Annotations for

A Biography of the Pixel

by Alvy Ray Smith

Each note is preceded by the book's page number and opening words of the relevant paragraph. [Math] indicates the presence of mathematics in the note that follows.

1:*Thou shalt not*: Also Deuteronomy 4:16–18 (King James Version): "Lest ye corrupt yourselves, and make you a graven image, the similitude of any figure, the likeness of male or female, the likeness of any beast that is on the earth, the likeness of any winged fowl that flieth in the air, the likeness of any thing that creepeth on the ground, the likeness of any fish that is in the waters beneath the earth."

1:*In the beginning*: *Wikipedia*, Cave of Altamira, accessed Feb. 15, 2020, cites uranium-thorium dating evidence that the paintings at Altamira were made over the period of about 22 to 36 thousand years ago. The cave was sealed off by a rockfall about 13 thousand years ago.

That the boar is a graven image comes from a precious copy, in my possession, of Henri Breuil and Hugo Obermaier, *The Cave of Altamira at Santillana del Mar, Spain*, Madrid: The Junta de las Cuevas de Altamira, The Hispanic Society of America, and The Academia de las Historia, 1935. The double boar image in this English edition is "Plate XLV. Walking wild Boar, painted over an earlier one," as painted by Henri Breuil. From p. 43: "Alteration: Some slight corrections of the legs, snout, ear and snout." Also p. 43 explains which parts of the image are indeed engraved: "Most of the back and hind legs, above the snout." And which parts scraped: "Belly, hind-quarters, backbone (a broken line with gaps) tusk and mouth, chest." The comments are accompanied by the picture shown in figure 0.3, labeled "Fig. 20. Engraved parts of walking wild Boar. Pl. XLV."

Figure 0.3

Breuil's famous paintings, including figure 0.1, are of course relatively modern representations of the actual cave paintings. Altamira is now closed to the public.

2:*Even as late:* On a commission from the then King of Spain, David created the paintings (there were five versions) from 1801 to 1805. The original (this one) was in Madrid, and came into possession of Napoleon's older brother Joseph Bonaparte (1768–1844) when Napoleon made him King of Spain, 1808–1813. Joseph took it to France when he abdicated, and then with him to the US, where he resided 1815–1832, mainly in New Jersey. So he *did* dare to move it to America. The US census, 1830, Chesterfield Twp., Burlington Co., NJ, lists Joseph "Bonepart," 60–70 [image online at https://www.familysearch.org/, which cites NARA Series M19, Roll 80]. The painting hung in Joseph's estate, Point Breeze, located at Bordentown, Burlington Co., NJ, and was in possession of American descendants until 1949. All versions are now located in Europe, and this one in particular at Château de Malmaison near Paris. [Date details from *Wikipedia*, Joseph Bonaparte, also *Napoleon Crossing the Alps*, and from *Appleton's Cyclopedia of American Biography* (1887), 1:311–312, online at https://www.ancestry.com/interactive/61360/47194_54729-00337.]

2:*Through all that*: Or what could constitute a sculpture, say Michelangelo's *David*, separate from its Carrara marble? The concept generalizes.

4:*That the Great*: The DVD went public in 1996 not 2000. It would be accurate to say, however, that is had debuted worldwide by 2000. [Corrected 22 July 2021.]

11:*There was a*: Hugo (1887), 179. These words are immediately followed by "and in some garret an obscure Fourier, whom the future will recall." Although "obscure Fourier" seems to fit the hero of this chapter, the second Fourier was probably Charles Fourier, a philosopher who was contemporary with Joseph. In that case, Hugo essentially got his prediction backward.

11:*The answer divides*: Snow (1961) most often called the two cultures nonscientists and scientists, or (literary) intellectuals and scientists, or at least once, artists and scientists. I take it to be the arts and humanities on one side, and science, engineering, and technology on the other, and abbreviate the two groups as the arts and sciences.

12:*This musical insight*: As a reminder, the Great Digital Convergence refers to the collapsing of all media types to just one, the bit. Digital Light is the general term for all things based on pixels, so all of computer graphics, all of image processing, digital cameras and video, computer and cellphone apps display, and videogames, to name some of its domains.

12:*Jean Joseph Fourier*: My principal source for Fourier is the excellent Herivel (1975) which, in turn, references Fourier's contemporaries Cousin (1831) and Champollion-Figeac (1844) and many French sources, including many previously unpublished letters by Fourier. I also appealed to

Bracewell (1965), Grattan-Guiness (1972), Gonzalez-Velasco (1995), and Dhombres and Robert (1998).

Benjamin Franklin's hat was actually made from marten fur, more akin to mink or sable than lowly racoon.

13:*At 13 he*: "Impaired by night studies," he wrote years later, "my health scarcely sufficed for the work my position required of me."

13:*The danger wasn't*: A contemporary stated that it was Fourier's lack of nobility that disqualified him from military advancement, but historians have disproved the claim.

14:*Bliss was it*: Wordsworth (1970), X:692.

14:*Fourier didn't have*: Later Fourier claimed that he had tried to resign and return to his true calling as a math teacher, but the local commune accused him of attempting to abandon his post. The letter purportedly backing up this claim has disappeared, however. The upshot was that Fourier remained a member of the local committee of surveillance, an integral part of the apparatus of the Terror.

15:*The next stop*: Wordsworth (1970), X:335.

17:*You've also met*: [Math] The standard 120-volt AC system in the US is often called a 110-volt system, a naming holdover from older times. The amplitude of the wave is about 170 volts. 120 volts is the average voltage delivered, where the average is taken to be the root mean square voltage. That is, $\sqrt{170^2 + (-170)^2}/2 = 170/\sqrt{2} \approx 120$.

18:*Notice one other*: There are two waves (dashed) in each row of figure 1.12. The two waves in the top row are identical in amplitude and frequency to the two waves in the bottom row. Only their relative positioning differs. In both rows the wave of lower amplitude is aligned with the left edge in the same way. But the wave of higher amplitude in the top row has its trough aligned with the top row's left edge. The point halfway between its trough and crest is aligned with the bottom row's left edge. To add one wave to another, at each horizontal point add the height of one wave above the midline to the height of the other wave (heights can be negative). The two sums (solid) are obviously different.

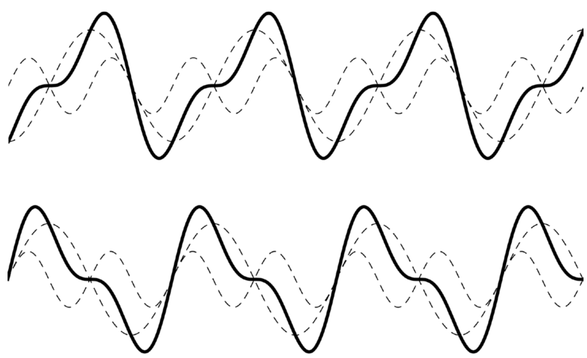

Figure 1.12

18:*We use the*: [Math] It's common to use both sine and cosine waves in Fourier applications, but a cosine wave looks exactly like a sine wave. It's a sine wave changed in phase (shifted left) by one-fourth of a cycle. So the one shape, of a (sine) wave, is all that's needed.

18:*A first glimpse*: [Math] This statement of Fourier's result will surely cause mathematicians to shudder. I put no limits on it; don't mention—for obvious reasons—functions, discontinuities, integrability, periodicity, linearity, convergence, or any other technical matter dear to our hearts; and subsume the integral under the term "sum." I'm justified in doing this, I believe, by a goal of making the sum-of-frequencies intuition inherent in Fourier's idea available broadly. I want readers to hear the symphony without knowing or caring about the stiffness of the first clarinet's reed.

20:*We understand these*: I felt an even more impressive sound in Sydney Harbour in early 2011. The Cunard Line's massive flagship, the *Queen Mary 2*, shook Sydney's entire Central Business District with a prolonged and mighty blast, its boombox made of skyscrapers. Thus the leviathan hailed—with a truly oceanic salute—her younger, smaller sister, the *Queen Elizabeth*, as she departed the harbor on her maiden voyage. Verified by Brenda Garcia, Cunard Line, email July 26, 2012.

21:*Just over a*: My principal sources for Bonaparte are Asprey (2000) and Asprey (2001). Bonaparte was born Aug. 15, 1769, in Ajaccio, Corsica. He called himself Napoleon after he became Emperor, a practice I tend to follow here.

21:*Bonaparte attended the*: Napoleon's Theorem is a pretty result in plane geometry almost certainly not proved by Napoleon (as sometimes claimed however). More likely it was named in tribute to his mathematical interest. [Math] The theorem is this: Construct equilateral triangles on the three sides of any triangle. The three centroids of these equilaterals always form an equilateral triangle.

23:*Bonaparte's hasty and*: Asprey (2000) takes a more positive view of Napoleon's actions while leaving Egypt, but makes it clear that he and Kléber were implacable enemies.

27:*Starting from the*: The angle of the line doesn't matter because Fourier's idea, in the two-dimensional case, takes angles into account.

28:*Jean-François Champollion*: Champollion had to work with a reproduction of the Rosetta Stone inscription, because the stone itself was in England.

28:*Fourier's special relationship*: My principal source for Champollion is Robinson (1975). Champollion, the decrypter of the hieroglyphs, is not to be confused with Fourier's biographer, Jacques-Joseph Champollion-Figeac, who was Champollion's elder brother.

30:*Fourier's big idea*: Angle is like phase in that it's important for implementation of Fourier's idea. But because it doesn't add significantly to the important intuition that all visual space is a sum of Fourier waves, I seldom mention it or relegate it to these notes.

31:*Fourier offers us*: Strictly speaking, a complete specification is a frequency, an amplitude, a phase, and an angle.

32:*Color information is*: The color receptors in the eye (the cones) are usually termed the long, medium, and short wavelength receptors instead of the old-fashioned (and inaccurate) red, green, and blue receptors.

Cellphones, televisions, computer and videogame screens emit light and therefore combine additively. The additive primaries are red, green, and blue. Paint and printers' inks absorb light and therefore combine subtractively. The subtractive primaries—called secondaries—are yellow, magenta (often misnamed red), and cyan (often misnamed blue). For our purposes, the additive system is of principal importance.

33:*So imagine the*: Strictly speaking, a color picture in Fourier terms is a sum of triples of waves, where each triple consists of three waves all at the same frequency, phase, and angle, but at three different amplitudes, one for each primary. The stuff of the waves is in all cases light intensities.

34:*Fourier's critics didn't*: It's jumping the gun a bit, but the difference between digital snapshots stored as TIFF (.tif) files and those stored as a JPEG (.jpg) files is that the former is a point-by-point storage of the light intensities of a picture while the latter stores a frequency representation instead.

36:*To posterity's mind*: Grattan-Guinness (1972) is a careful translation and analysis of Fourier's seminal 1807 memoir.

36:*One of the*: Fourier, "On the Temperatures of the Terrestrial Sphere and Interplanetary Space" (from *Oeuvres de Fourier* (1888–1890), 2:97–125). Jones (2017), 338, correctly attributes the lesser-known greenhouse effect discovery but misses Fourier's greatest contribution: "The physicist Joseph Fourier (remembered for his discovery of the greenhouse effect) became prefect of the department of the Isère."

36:*Lacking rigor in*: Grattan-Guinness (1972), 188–193, gives a careful account of the mathematical difficulties in Fourier's young theory and makes the strong point: "Fourier's formal processes, and the results that he obtained from them, were the great prototype for research throughout his century and into ours, and to have expected him to perceive the techniques of 'rigorization' which we now know partially because of the problems that these results had suggested *for the first time* in the development of mathematics is to apply entirely inappropriate criteria of adequacy and interpretation to the work under discussion."

39:*We don't know*: My principal source for Germain is Bucciarelli and Dworsky (1980), particularly chapters 7–8.

39:*The Academy of*: Napoleon died May 5, 1821; *The Eiffel Tower* (2012), lists Fourier at no. 67 on the Face Paris, Laplace at no. 9 on Face Trocadéro, and Poisson at no. 53 on Face École Militaire.

39:*Napoleon's death also*: Napoleon's exile to Saint Helena began Oct. 15, 1815.

39:*The political battles*: Martin Davis, email Jan. 7, 2013, observed that sleeping vertically suggests that Fourier might have been suffering from congestive heart failure.

39:*Fourier died of*: Fourier died May 16, 1830. His grave in Pére Lachaise is in the 18th Division, Avenue des Acacias, on the Casimir-Perrier roundabout. The lily, wave, and serpent motif is repeated twice on all four sides of the grave "box" surrounding his bust.

40:*The younger Grenobloise*: Champollion's grave in Pére Lachaise is also in the 18th Division, about 15 meters from Fourier's. Germain's grave is in the 16th Division, slightly hidden behind a tree, not far from Fourier's in the 18th.

40:*One of Germain's*: Bucciarelli and Dworsky (1980), 137, "Public attention had been fooled: this woman did not show up to receive an award which no one of her sex had, up until then, ever won." The French Academy has had a prize named for Germain since 2003 [see *Prix Sophie Germain* (2020)].

40:*Fourier's troubles are*: Grattan-Guinness (1972), ix.

42:*In mathematics something*: Gonzalez-Velasco (1995), 23–25, 36–44; Grattan-Guinness (1972), 188–193.

42:*Mathematicians must deal*: Bracewell (1965), 1–5; Grattan-Guinness (1972), 193.

43:*There was a*: Solzhenitsyn (2001), *The Gulag Archipelago*, 1:590.

44:*Just as the*: [Math] Formally, the wave is the mathematical function $sine(x)$, usually abbreviated $sin(x)$, and the spreader is $sin(x)/x$, also known as $sinc(x)$. It's easiest to think of x as degrees of rotation, stated in radians. So when $x = 90$ degrees, or $\pi/2$ radians, $sin(x)/x = 1/(\pi/2) = 2/\pi \approx .63$. When $x = 180$ degrees, or π radians, $sin(x)/x = 0/\pi = 0$. When $x = 270$ degrees, or $3\pi/2$ radians, $sin(x)/x = -2/3\pi \approx -.21$. When $x = 360$ degrees, or 2π radians, $sin(x)/x = 0/2\pi = 0$. And so forth. If x is negative $(-90, -180, -270, -360$

degrees), you get the same results as for x positive because a minus sign appears in both numerator and denominator. For example, when $x = -90$ degrees, or $-\pi/2$ radians, $sin(x)/x = -1/(-\pi/2) = 2/\pi$, and so forth. As x approaches 0 degrees, $sin(x)/x$ approaches 1. In fact, the math details show the nonobvious result that $sin(0)/0 = 1$ exactly.

44:*The spreader comes*: Kotelnikov (1933), 4. There are surely earlier pictures of the mathematical function itself. An earlier picture appears, but not in correct context, in Nyquist (1928), 294 (of the 2002 reprint). The Nyquist picture shows the function as the response to a specific circuit, not as a spreader.

45:*I first learned*: Gertner (2012), 135: "Some lawyers in the patent department at Bell Labs decided to study . . . why certain individuals at the Labs were more productive than others. They discerned only one common thread: Workers with the most patents often shared lunch or breakfast with a Bell Labs electrical engineer named Harry Nyquist." Shannon surely had dined with Nyquist.

Re the *bit*: Shapiro (2000); Brillinger (2002), 1569–1570; Tukey (1958). Shannon credited John Wilder Tukey, also of Bell Labs, with inventing the word as a contraction of *binary digit*. It was Tukey, by the way, no slouch at coinage, who gave us the word *software* too. Tukey is also noted for bringing the Fourier idea into the modern digital world, in an efficient way, as "the fast Fourier transform," using an algorithm created with J. W. Cooley.

In Smith (1981) I still referred to the theorem as the "Nyquist, or sampling, theorem."

45:*But that's just*: Stigler (1980) attributes it to Robert Merton. Merton actually elucidated the "Matthew effect" (derived from *Matthew* 25:29): famous scientists often receive disproportionate credit for their contributions, to the disadvantage of lesser known researchers who might have actually done the work. Gladwell (2008), 60, describes the naming process as “pinning tails on donkeys.”

Shannon carefully gave credit to mathematicians *and* to engineers and physicists—from the ideal world *and* from the real world, respectively. We’ve felt the sandpaper between these intellectual heritages before: Mathematicians Laplace and Poisson quibbled about Fourier’s big idea—and gave him a difficult time about it. Fourier, as a physicist, happily used it to solve a problem in the real world—the heat flow problem—as engineers and physicists have ever since. The sampling idea has followed a similar arc, and Shannon was sensitive to it. [Shannon (1949a) directly cites mathematician Whittaker [Jr.] (1935), engineers Nyquist (1928) and Bennett (1941), and physicist Gabor (1946).]

Nevertheless he was a bit cryptic about what he knew. For example, he certainly knew of Sir Edmund Whittaker’s relevant mathematical work, because he mentioned a paper by Whittaker’s son Jack. And he surely knew of Herbert Raabe and Raabe’s influential engineering professor, Karl Küpfmüller, because he mentioned two papers that refer to Raabe’s work, one of which refers to Küpfmüller. So why did he resort to such indirect references? [Whittaker [Jr.] (1935) cites Whittaker (1915); Bennett (1941) cites Raabe (1939); Gabor (1946) cites Nyquist (1928), Bennett (1941) (which cites Raabe (1939)), and Küpfmüller (1924). Bennett was a colleague at Bell Labs and published in the house organ.]

The elder Whittaker’s mathematics directly competed with Shannon’s. If you’re schooled in the forms of the Sampling Theorem, the shock of recognition after a look at Whittaker’s paper from 1915 is immediate. The spreader is there (but no picture). Twice the highest Fourier frequency is there. Shannon’s claim that the mathematicians used “other forms” is true for most of them, but not for Whittaker. [[Math] Here are actual examples: Whittaker (1915) interpolated $f(t)$ from $\sum_{k=-\infty}^{\infty} f(a+kw)\frac{\sin \pi(t-a-kw)/w}{\pi(t-a-kw)/w}$. Kotelnikov (1933) reconstructed $f(t)$ with $\sum_{k=-\infty}^{\infty} f(\frac{k}{2f_1})\frac{\sin \omega_1(t-\frac{k}{2f_1})}{\omega_1(t-\frac{k}{2f_1})}$. Shannon (1948) reconstructed $f(t)$ with $\sum_{k=-\infty}^{\infty} f(\frac{k}{2W})\frac{\sin \pi(2Wt-k)}{\pi(2Wt-k)}$. Someya (1949) reconstructed $f(t)$ with $\sum_{k=-\infty}^{\infty} f(\frac{k}{l}-t_0)\frac{\sin \pi l(t+t_0-\frac{k}{l})}{\pi l(t+t_0-\frac{k}{l})}$. I've made the summation index k and the function $f(t)$ in all four cases, but otherwise left the presentations essentially unchanged from the originals. The spreader—the form $\sin(x)/x$—is obvious in all cases. But most mathematicians, Whittaker (1915) excepted, tend toward the interpolation of $f(t)$ with form $\frac{\sin \pi t}{\pi}\sum_{k=-\infty}^{\infty}(-1)^k\frac{f(k)}{t-k}$. This form is equivalent to the ones above (according to Higgins (1985)), but the spreader is not obviously present. Into this camp fall Ferrar (1909), Ogura (1920), Whittaker [Jr.] (1935), and, by reference in Higgins (1985), Borel in 1898, and de la Vallée Poussin in 1908.]

More importantly, however, they were solving a different problem. Shannon was solving a communications problem: what's the best way to utilize an information channel, such as a telegraph or telephone line? The mathematicians, however, were interested in something completely different—curve-fitting: Given several points, what's the best way to fit a curve to them? They sought a meaningful curve that interpolated, or filled in smoothly, between the points. Interpolation is the reverse problem to sampling, which seeks to extract meaningful points from a given smooth curve. I'll revisit Whittaker (1915) more fully in a later chapter on splines (interpolation) where he's more relevant. Interpolation would not have led to the digital age, so Shannon may be forgiven for only indirectly acknowledging him. [There's a cottage industry in academia devoted to clarifying the conceptual genealogy of the Sampling Theorem. It has chased the origins back at least to French mathematician Emil Borel and a paper he wrote in 1898, “Sur l’interpolation,” and to Sir Edmund Whittaker in 1915. See Butzer et al. (2011); Ferreira and Higgins (2011); Butzer et al. (2010); Meijering (2002); Lüke (1999); Higgins (1985); Jerri (1977). Their work is thorough and careful, and I’ve depended a great deal on it. It led me to a host of papers I might not otherwise have discovered, and have depended on its translations or paragraph-by-paragraph analyses of the crucial French, German, Japanese, and Russian papers.]

But why the indirect approach to engineer Raabe? It’s clear from his 1939 paper that he understood the Sampling Theorem in all its practical engineering particulars. Importantly, however, he didn’t state it. That aside, Shannon’s real problem with Raabe was surely that he was politically dirty. Raabe had been a member of the Nazi Party in the recent war, and his teacher Küpfmüller had not only been a Nazi but an *Obersturmbannführer* in the SS. Raabe had worked on V-2 rockets with his friend and fellow Nazi Party member, Wernher von Braun. Nevertheless, US organizations were later to overlook the Nazi blemish and invite both friends to America. In the late 1950s Raabe would indeed come to the US, but in the late 1940s Shannon apparently thought it prudent to keep his distance—via indirect reference. [Gabor (1946); Maier (2007), 710; Raabe (1939); Bennett (1941); Butzer et al. (2010). We don’t really know Shannon’s motivations, but it’s possible that Shannon simply didn’t or couldn’t read the German papers. Küpfmüller arrived at some of the same results as Nyquist, including the “Nyquist” sampling rate, but in German so not well-known.]

What about Nyquist? Why did Shannon slip his older colleague’s name off the credits? Nyquist *did* state a sampling theorem in his classic paper of 1928: A signal consisting of samples taken at twice the highest Fourier frequency can be reconstructed from the samples only. Something from nothing. That's exactly the first half of the Sampling Theorem. And he showed how to recover the original signal from the samples, which is the second half. However, Nyquist fell short here. He failed to formulate the recovery in the elegant, succinct form of the classic Sampling Theorem, which we'll come to shortly. That's why Shannon only credited him with the Nyquist sampling rate of the Sampling Theorem, the twice the highest Fourier frequency part. [Nyquist (1928), particularly the introduction to the 2002 IEEE reprint. Nyquist's sampling theorem has to be equivalent to the Sampling Theorem, yet he failed to reduce it to that simplest form. Page 283 of the 2002 reprint shows the spreader as a mathematical function in his version of the sampling theorem. The relationship between this use of the spreader and the picture of one on his p. 294 is tantalizingly close, but isn't explicit.]

Incidentally, Nyquist wasn't his original name. He was baptized Harry Theodor Larsson, using the patronymic form common in Sweden and his father being Lars Jonsson, but to avoid confusion with another Lars Jonsson, Lars took the surname Nykvist, meaning "new branch," perhaps his clever joke. When Harry immigrated into the US at age 18 his new surname took its final form Nyquist [Åström (2003); Bode (1977); Harry Nyquist death certificate, Harlingen, Cameron Co., Tex., no. 26415, Family History Library microfilm roll 2243931, Salt Lake City, Utah].

46:*Despite the attribution*: Tchobanou and Udalov (2006), 177; Bissell (2009), 32. When I approached a Russian friend, Fyodor Urnov, in Berkeley about the purpose of what looked like an extra Cyrillic character in Kotelnikov's name, he explained that there are two "l" sounds in Russian and the extra character denotes which is intended. Then he said, "But why do you ask?" "I think he's responsible for the Sampling Theorem, not Claude Shannon," I replied, and Fyodor exclaimed, “Alvy, we all know this in Russia! We’ve never understood why Americans won’t say so.”

46:*Vladimir Aleksandrovich Kotelnikov*: Kotelnikova (2006), 727. Nataliya Vladimirovna Kotelnikova, Vladimir Kotelnikov’s daughter, is one of my primary sources for him, especially of his personal life. Unfortunately, she recently died, as I learned from Fyodor Urnov (see preceding note), who tried to contact her in 2013 on my behalf.

The Euler Archive lists the eight students of Euler, including S. K. [Semyon Kirillovich] Kotelnikov, “During 1752–1756, Euler provided quarters in his Berlin residence for these two students [Kotelnikov and Rumovsky]. In the translation of [a] book . . . Kotelnikov added an original survey of the principles of the differential and integral calculus—the first study in Russian on mathematical analysis.” Semyon (Cemën) is accented on the second syllable, but is sometimes transliterated as or Semen or Simon, neither of which encourages the correct accentuation.

See Herivel (1975), 154, 172, re Fourier and Euler. The Petersburg Academy was founded in 1724.

46:*Vladimir’s grandfather, Petr*: The university, founded in 1804, is now Kazan Federal University. Tom Lehrer famously spoofed Lobachevsky in song [*Lobachevsky*, 1953, https://www.youtube.com/watch?v=gXlfXirQF3A, accessed Apr. 4, 2020].

46:*The Kotelnikovs, with*: Kotelnikova (2006), 728–729.

47:*That challenge focused*: Kotelnikova (2006), 728–729.

47:*Great was the*: Bulgakov (2008); Kotelnikova (2006), 728–729.

47:*In 1924 Aleksandr*: Kotelnikova (2006), 729; Tchobanou and Udalov (2006), 172; Bissell (2009), 24. MEI stands for *Moskovskiy energeticheskiy institut*, often translated as Moscow Power Engineering Institute. There was actually an interruption in his continual service with MEI during World War II from 1941 to 1944.

47:*When he submitted*: Kotelnikova (2006), 730, states there were three papers in 1932 but mentions only the "carrying capacity of ether and wires" paper explicitly; Tchobanou and Udalov (2006), 172–173, states there were two. Nyquist excelled, and is remembered, in both carrying capacity and filters, but his fame resides in linear filters, not Kotelnikov's nonlinear filters. Nyquist's famous 1928 paper was "Certain topics in telegraph transmission theory," a title about as catchy as Kotelnikov's.

47:*In 1933, with*: Kotelnikova (2006), 731; Tchobanou and Udalov (2006), 173. Red October was Oct. 25, 1917, old style (Julian calendar), or Nov. 7, 1917, new style (Gregorian). Russia adopted the new style on Feb. 14, 1918, dropping the days Feb. 1–13. Народный комиссариат is transliterated Narodniy Komissariat, so all abbreviations for People's Commissariats begin with NK. The NKS was originally the NK for Posts and Telegraph. The infamous NKVD was the People's Commissariat for Internal Affairs.

48:*Between any two*: [Math] I conflate here physical reality with mathematical purity. Analog videotape recordings, from the real world, are *not* continuous in the mathematical sense. The physical videotape is coated with a fine ferromagnetic powder which carries the video signal. But a powder is discontinuous. Real sound waves aren't continuous either. At some level they are carried by the movements of air molecules. The human retina is composed of rods and cones, so is inherently discontinuous. Nevertheless, this is how engineering works. A mathematically pure idea is used to model the real world. In particular, the mathematics of Fourier and Kotelnikov are mathematically pure. Their applications to, for example, heat and Digital Light, make the leap that it's a good enough engineering approximation to take the real world as continuous when it actually isn't at some very fine level.

50:*With these questions*: The wave is positioned so that the big dots in the snippet occur over the wave's zero crossings—that is, the points where the wave crosses the zero line (shown in tiny dots). This happens twice for every cycle of the wave. [Math] The phase of the wave (its horizontal position relative to the snippet) is not necessarily that matching the sum shown by the snippet.

50:*Here's Kotelnikov's great*: It's probably obvious that it doesn't hurt to sample faster than twice the highest Fourier frequency. Sometimes in real-world practice there are technical issues that require it to be at least a little faster than twice. And there's a theoretical issue that requires sampling at just greater than twice. I avoid all these issues, since imparting the intuition of twice the highest Fourier frequency is what I wish to accomplish. However, I, from time to time, parenthetically remind readers of the "slightly greater than twice" that is strictly required.

[Math] The notion that discrete points can represent a smooth continuum is not new in mathematics. The easiest example is a straight line, which can be represented by just two different points on the line. The generalization is that any polynomial can be represented by only its roots—a quadratic by three roots, a cubic by four, and so forth. The distinction to draw with the sampling case is that nobody ever confuses the two points with the line, or the roots with the polynomial, whereas it's quite common for people to confuse samples with the thing sampled. Thanks to my friend and mathematician, Lenore Blum, for this example.

51:*The word* pixel: Conversations with Richard Lyon, about one year after this book published, revealed further details:

Lyon also tracked the origin of the phrase *picture element* itself. Perhaps the earliest use was in a U.S. patent filed June 10, 1911: Alf Sinding-Larsen, "Transmission of Pictures of Moving Objects," no. 1,175,313, patented Mar. 14, 1916: "In the graphical transmission of pictures . . . in which the duration of each movement is not limited, it is not difficult to establish such synchronism, but in the transmission of moving pictures, where every light point or picture element has to be repeated before the light impression on the eye has ceased, . . . such a motion system is very difficult to accomplish."

For further details, see *Wikipedia*, Pixel (accessed Sept. 27, 2022), with contributions by Lyon. For example, as regards Billingsley's first use of the term in print: "Billingsley had learned the word from Keith E. McFarland, at the Link Division of General Precision in Palo Alto, who in turn said he did not know where it originated. McFarland said simply it was 'in use at the time' (circa 1963)" [citing Lyon].

See also Zimmer (2016), which covers much of the same historical material while noting Google's choice of the word as a trademark name for its recently announced (2016) cellphone [*Wikipedia*, Google Pixel, accessed Sept. 28, 2022].

52:*The pixel directly*: Soxel and pixel both play on the *ics* in *sonics* and *pics* (*pictures*).

52:*A more serious*: Shannon (1949a), the original printing, carries a notation that the original manuscript was received July 23, 1940, so 1940 is sometimes given as the date for the paper, but the contents of that manuscript are unknown. At least one reference suggests that the 1940 is a misprint for 1948, and July 1948 does fit with a Jan. 1949 publishing date.

IEEE is pronounced "Eye-triple-eee."

The Fields Medal is considered the top prize in mathematics, often called the Nobel Prize of Mathematics. It does come with a cash award but it's far less than the monetary award of either the Nobel or Kyoto Prize, the latter also often compared to the Nobel.

53:*Shannon was a*: Gleick (2012), an otherwise excellent book on Shannon and information theory, doesn't mention Kotelnikov. FDR–Churchill communications, and the security of them or lack thereof, are discussed in Bauer (1997), 6, and Stafford (1996), 22.

53:*This is a*: See p. 448 in the 1998 reprint of Shannon (1949a). Shannon (1948) states the Sampling Theorem in section 19, "Band limited ensembles of functions," with a footnote that references Shannon (1949a), "to be published," for its proof. The second half of the earlier paper was published in Oct. 1948 and the later paper was published in Jan. 1949, so both were in the final stages of publication when the footnote was written.

54:*Here are the*: Gleick (2012) suggests a leakage might have gone the other direction. He has a section on Andrei Nikolaevich Kolmogorov's access to Shannon's 1948 paper in poor translation in 1953 and subsequent Russian development of information theory, particularly the statistical aspects.

54:*We can't help*: Kotelnikov (1933) was intended for presentation at a conference to be held in Moscow in 1933, but which did not take place. The papers of the conference were published anyway in 1933, but it's an obscure conference proceedings [Kotelnikova (2006); Bissell (2009)]. Shannon probably didn't know about Isao Someya's result of 1949, since it was surely being prepared more-or-less simultaneously with his own, and it was in Japanese, the language of another recent enemy [Someya (1949); Ferreira (2007)]. There has been a suggestion to change the name of the theorem to the WKS Sampling Theorem, for Whittaker-Kotelnikov-Shannon, but the name is unfortunately clumsy and omits some of the other players. Another suggestion is to drop all personal names and simply call it the Sampling Theorem.

55:*And here's the*: The parts of the curves below the line are negative so addition of their heights is actually a subtraction.

56:*A popular, practical*: [Math] Cubic means that the curve is described with third-order equations, of the form $f(x) = ax^3 + bx^2 + cx + d$. Intuitively, cubic means that the curve has two inflection points, so three parts. The spreader used here is called, by the computer graphics community, the Catmull-Rom spreader, although it has been known for a long time in the mathematics of interpolation by other names. Smith (1983) shows that it's a member of a class of spreaders.

[Math] Spreading a pixel is an example of what is called a *convolution* by mathematicians.

57:*Figure 2.15 shows*: If the bleeding edge were the ideal spreader then this would be a picture of the ideal pixel spreader, but we can't show it because it is infinite in both dimensions, and hence not useful in the real world.

The Visible Human Project of the National Library of Medicine is an example of a three-dimensional sampling process. In that case, the samples are called "voxels," and the voxel spreader is a generalization of the spreader for two dimensions to three, a *tri*cubic spreader. Voxels, of course, are not little cubes.

59:*The missing infinity*: The time dimension wasn't carried along in analog form in the old media. This is discussed in detail in a later chapter.

59:*So here's the*: At the annual Association for the Scientific Study of Consciousness conference in Krakow, in 2018, I explained the Sampling Theorem to Sascha Benjamin Fink as replacing pixels with a little blobs of infinity to restore the original continuum. He said, "*Blobs of Infinity* would be a good name for your book." I think not, but I do want to preserve the felicitous phrase.

60:*Another way to*: An exact plot of the two spread pixels would be against a black background. Since the picture is displayed here against a white background, as typical with ink displays, it's the complement of the curve that is plotted. In other words, valleys are plotted, not peaks. The left valley is not as low as the right valley.

60:*The two spread*: And a voxel is not a little cube.

61:*Stalin's Great Purge*: Solzhenitsyn (2001), *The Gulag Archipelago*, 1:408, with respect to the show trials of the period. The most serious years of the Great Terror are usually given as 1937–1938, but the second chapter, "The History of Our Sewage Disposal System," is a listing of known incarcerations during many purges over many years.

61:*Two tyrants for*: The four were Lazar Kaganovich, Andrei Zhdavov, Georgi Malenkov, and Lavrenti Beria. "These four were to combine some political capacity with satisfactory ruthlessness and to rise high in the State. Their roles in the Purge were particularly murderous" [Conquest (2008), 13–14].

62:*Malenkov's report to*: Kotelnikova (2006), 731–732; Wright (1941b). The Wright references have to be used carefully, as he represented the archrival (to Stalin) Leon Trotsky contingent.

62:*But Malenkov's importance*: There's not a hint of any relationship between them other than professional. Anything else would surely have been suicidal, but more importantly Kotelnikov had married Anna Ivanovna Bogatskaya in 1938. He had three children with her, and lived with her until her death in 1990 [Kotelnikova (2006), 730].

62:*Golubtsova had a*: Hamilton-Dann (1998), 16, 19, 22–25, 30–32, 36–38, 40, 47, 53, 65–66, 94, 295; Kartsev (1985), 61–62, 171; Nebeker (2009), 84; "Death of G. M. Krzhizhansovsky" (1959); Possony (1964), 38; Ruthchild (2010), 183; Nicolaysen (1990), 34, 62, 65, 206, 339; Wright (1941a). The Nevzorov sisters were daughters of Pavl Nevzorov and Lyudmila Pyatova. Gleb Maksimilianovich Krzhizhanovsky was an Academician and an outstanding power engineer. He would become the chief architect of the electrification plan for the country. Sophia married Sergei Pavlovich Shesternin. Olga married Aleksei Golubtsov, a staff teacher of the Nizhny Novgorod Military School, and begat Valeriya Golubtsova.

62:*Golubtsova was brilliant*: Chertok (1996), 2:96–108. Boris Evseyevich Chertok is my primary source on Golubtsova. He was a fellow student at MEI. He wrote, "This amazing woman was a talented, intelligent, and determined organizer. She fully deserved the title 'first lady' of the state, and in terms of her civic qualities, she personified the grand scale of the state. . . . [R]ecollections of her colleagues, former students, and daughter and sons paint a picture of a courageous woman with a generous heart, 'an amazing director,' and a loving mother *who determined the fate of many of our country's scientists*." [Emphasis added.]

Interview with Prof. Aleksandr Efimovich Sheyndlin, Hero of Socialist Labor, Lenin and Stalin Prizes, online at https://www.peoples.ru/science/professor/sheyndlin/, accessed in both Russian and Google's English translation Apr. 4, 2020. The English translation needs a little help: "Its [Her] role in the development of MPEI [MEI] is very large. She essentially built a modern institute. I met with her many times, it was not easy to deal with her—she was [a] domineering, smart, 'cool,' as they would say today, woman. . . . [Stalin's secretary Bazhenov] claims that Malenkov was made by his wife Golubtsova."

64:*Often display manufacturers*: There are really two parts to the display process, conceptually at least. Since the resolutions of a given image and a given display device hardly ever match, the first step is a reconstruction and resampling of the image to fit the resolution of the device. So that reconstruction step occurs in the hardware or software device driver with sophisticated spreaders. The resampled pixels are sent to the physical display. The second step is the excitation of the display elements (*not* pixels!) of the display device. Each such display element "reconstructs" the pixel sent to it by the shape naturally associated with that physical element—for example, the spread of ink at a spot on paper, or the pattern of glow of a phosphor on a screen, or the pattern of light emitted by an LCD cluster. Each display technology has a different "natural" spreader, some of them quite far from the ideal demanded by the Sampling Theorem, or even the good one represented by the bicubic spreader.

64:*"The idea* of: Solzhenitsyn (2009), *In the First Circle*, 92, said by prisoner Pryanchikov, explaining a scrambler to Abakumov of state security.

64:*Kotelnikov's paper—the*: Kotelnikova (2006), 731, and Bissell (2009), 29, have images of the rejection letter. Tchobanou and Udalov (2006), 173, says only, "In 1936 he went on his first business trip abroad to the USA." *New York, Passenger and Crew Lists (including Castle Garden and Ellis Island), 1820–1957*, https://www.ancestry.com/interactive/7488/NYT715_5807-0438, accessed Feb. 29, 2020, manifest of alien passengers for the United States immigration officer at port of arrival, for *S.S. Berengaria*, sailed May 20, 1936, Cherbourg, France, arrived New York, NY, May 24, 1936, list 13, line 16: Vladimir Kotelnikov, age 27, male, single, engineer, reads and writes

Russian, nationality Russian, born Kazan, Russia, passport visa 321, issued Moscow, May 13, 1936, last permanent address Moscow, Russia, nearest relative in Russia: "Father .V. [*sic*] Kotelnikov Gorochovsaia [*sic* Gorochovskaia?] 29 10 Moscow," final destination Russia via New York, passage paid by the Soviet government, never before in the US, to visit Amtorg Trading Corp., 261 Fifth Ave., New York, NY, length of visit 60 days [and misc. other information, such as 5'9" height, fair complexion, brown hair, gray eyes].

65:*But Amtorg was*: "The Amtorg Trading Company Case" (1965), 1, "In 1931 the attention of the cryptanalysts of the Signal Intelligence Section, Office of the Chief Signal Officer, turned their attention to the traffic of the Amtorg Trading Corporation, a Soviet affiliate operating in New York City. | This project had its *raison d'etre* in an investigation conducted by Representative Hamilton Fish of New York into Communist propaganda in the United States," 2, mentions the one-time pad.

Morris Cohen, the spy who gave US atomic secrets to the USSR, had a cover job at Amtorg. *Arthur Fielding* (2010), "During recuperation in Barcelona, he [Cohen] was recruited by the KGB and sent to a spy school where he was assigned the covername LUIS. After returning home, Cohen was activated and given a cover job at AMTORG, the Soviet Purchasing Commission in New York," and "One of Zarubin's intelligence officers in America perfectly placed and qualified to work the atomic assignment was Semyon Semyonov. Semyonov was an asset of the illegal station operating out of AMTORG and served as Morris Cohen's control officer"; Romerstein and Breindel (2000), 206, "Vassiliy Zarubin returned as *Rezident* and reactivated some of the agent network. Morris Cohen worked at the Soviet trade organization Amtorg and was part of the reactivated network." See also Zelchenko (1952).

65:*Or perhaps he*: Kotelnikov's report wasn't publicly published until 1999. Tchobanou and Udalov (2006), 173–174, "This paper [Kotelnikov's 1941 cryptography paper] was published only in 1999 by Scientific Research Committee of Cryptography Academy of Russian Federation during the celebration of 90 years of V. A. Kotelnikov"; Shannon (1949b), the first footnote states, "The material in this paper appeared originally in a confidential report 'A Mathematical Theory of Cryptography' dated Sept. 1, 1945, which has now been declassified"; Molotkov (2006), mentions Kotelnikov's 1941 classified paper. Kahn (1996) says there's no such thing as an unbreakable code or cipher, the one exception being a "one-time system," which is a superset of the one-time pad.

65:*Kotelnikov must have*: Kotelnikova (2006), 732; Tchobanou and Udalov (2006), 174.

65:*During the battle*: Kotelnikova (2006), 732; Tchobanou and Udalov (2006), 173–174. They were both Stalin Prizes of the 1st degree.

65:*When the lab*: Kotelnikova (2006), 732, 734. She said, "It is probably this that was the decisive factor that made it possible for Kotel'nikov, in his position as head of a top-secret project, to escape from the NKVD system to MEI." (The English transcription of Kotelnikov's name from Russian sometimes includes an apostrophe as a "soft sign" to indicate that the preceding 'l' is palatalized in Russian. It's often omitted in English transliteration.)

66:*Success was dangerous*: Ings (2016), 312–314, "Beria's special prisons or *sharashki* solved at one stroke the two besetting difficulties of Soviet industrialisation . . ."

66:*The Marfino sharashka*: Kotelnikova (2006), 733–734; Solzhenitsyn (2009); Dexter and Rodionov (2012), "name NII–2 MPSS, location Moscow (Marfino), branch ELEC, . . . , details telephone cipher or scrambling equipment and communication technologies, formed

10/9/46 . . . , address Moscow, Vladykinskoe sh., now Komarova, 2, later 127106, Moscow, Botanicheshkya [*sic*], 25 ," also "name Laboratory No. 8, or Marfinskaya laboratoriya, location Moscow (Marfino), associated units KB, branch ELEC, . . . , details Marfinskaya laboratoriya; telephone cipher or scrambling equipment and communication technologies, formed 10/9/46 . . . on site of former theology college and later children's prison; used prisoners; Solzhenitsyn described it in 'V Kruge Pervom [The First Circle]' and worked here till 1950, . . . , address Moscow, Vladykinskoe sh., now Komarova, 2, later 127106, Moscow, Botanicheshkya [*sic*], 25."

Winokur (1973), 113, "The two house churches dedicated to St. Pantaleon the Martyr and the Icon of the Virgin 'Assuage My Sorrow' inside the orphanage at the former Monastery of the Epiphany in the village of Marfino have been transformed into a 'sharashka' (special prison and research institute), which has since been immortalized by Solzenicyn [*sic*] [to whom the book is dedicated] in *First Circle*."

Solzhenitsyn (2009), *In the First Circle*, 74, "The blue light over the four-paneled door set in the vaulted entrance shed a dim light on a dozen double bunks, fastened together in pairs and arranged fanwise around the large semicircular room. This room, probably the only one of its kind in Moscow, was twelve good masculine strides in diameter. Up above, there was a spacious dome, at the base of a hexagonal tower. Around the dome were five elegant arched windows. The windows were barred but not 'muzzled' (fitted with inverted awnings), so that in daytime you could see the wilderness that passed for a park on the other side of the highway." Probably the second floor of the tower, not the top one.

67:*Chelnov had been*: Solzhenitsyn (2009), *In the First Circle*, 217, 218. I've removed parentheses around the second sentence of the first quotation for easier reading. Chelnov in the novel, however, was a prisoner (zek). Nevertheless he was a very special one: "The weightiest argument for this concession [no overalls] was that Chelnov was not a permanent Marfino zek but an itinerant zek; once a corresponding member of the Academy of Sciences and director of a mathematical institute, he took his orders from Beria in person and could be dispatched to any sharashka confronted by a particularly urgent mathematical problem. Having solved it in outline and showed his hosts how to complete the calculation, he would be transferred elsewhere."

67:*Vladimir Kotelnikov, a*: Dudley (1939); Kotelnikova (2006), 731; Tompkins (2011), 70, 122–130, mentions Kotelnikov on p. 122. Ironically, Dudley was, according to Tompkins (2011), 130, an anti-Communist of the extreme, Joseph McCarthy, variety. Interestingly, Dudley had demonstrated the vocoder at Harvard in 1936, the year of Kotelnikov's US visit.

67:*What? What d'you*: I used Solzhenitsyn (2009), *In the First Circle*, 92 (chapter 17), for the translation of this passage. It's a statement by a prisoner (zek) named Pryanchikov who is reporting directly to Abakumov. I have dropped the confusing quotation marks for ease of reading. The epigraph follows almost immediately. Solzhenitsyn (1996), *The First Circle*, chapter 16, translates it this way, where the quotation marks are correctly maintained: "'Artificial speech device?' Pryanchikov winced, 'Nobody ever calls it that. It was given that clumsy name to make it sound as if we weren't copying a foreign invention. We use the English word "scrambler."'"

68:*Then continue to*: Kotelnikova (2006), 734.

68:*Within a short*: Chertok (1996), 2:106–108; Chertok (2006):761–762; Dexter and Rodionov (2012), "name OKB-1 NII–88, location Kaliningrad (Podlipki), now Korolev, Moscow obl., branch AERO, . . . , details opened 26/8/46 . . . , director S. P. Korolev dir./des. 1946–66 . . . ." 200

German rocket specialists came to NII-88 after the war. OKB, *Opytnoe konstructorskoe byuro* (Experimental design bureau), was the official name of a sharashka during the Soviet era.

68:*The MEI "collective*: Kotelnikova (2006), 734–735. This included stints in mud huts dug into the steppe, near the remote missile testing grounds, "to have someone responsible in case something went wrong."

69:*Some "computerspeak" is*: [Math] The short form is: n bits can store 2^n values.

69:*Here's a case*: My display has a maximum brightness of 300 standard units (candelas per square meter). The chart is the DICOM Grayscale Standard Display Function which gives the number of "just-noticeable differences" between grayscale values for displays of a given brightness, stated in the standard unit [*Digital Imaging and Communications in Medicine* (2004)].

70:*We have analyzed*: Meyer and Moran (2007), 778. There has been a furious attack on the Meyer and Moran paper. For a modern update of the state of this research, see Reiss (2016). See *The Super Audio CD Reference* thread that attempts to debunk it. Without commenting on this attack, it should be noted that my presentation of the adequacy of 16 bits *assumes* that there really is no part of human hearing that exceeds 20,000 cycles per second. There is evidence that this isn't true, however. The 20,000 cycles per second applies for (young) human hearing at full volume, but it seems that human hearing may be better at low volumes and hence require sampling at more bits for proper representation (and hence possibly exceeding what a CD can handle). Another source of possible CD inadequacy is "inter-aural" distinction. Apparently some humans can distinguish arrival times at the two ears down to (on the order of) 10 microseconds, implying a hearing response of some sort distinguishable at (on the order of) 100,000 soxels per second (which supports the SACD sampling rate). The point here is not CD versus SACD. It's that if you exceed the sampling rate required by the human ear—whatever it is, including all phenomena—then digital suffices for an accurate reproduction when executed correctly.

It's worth noting that parts of visual perception are analogues to the parts of audio perception mentioned above. For example, human brightness perception increases dramatically at very low light levels—giving us our good night vision. And so-called Vernier measurement is based on the ability of humans to perceive at a higher spatial resolution when two scales of lower resolution are slid relative one another.

71:*Yesterday evening we*: Kotelnikov (1961), 129, from an interview with Kotelnikov in 1957, predicting the future of radio in 50 years. He goes into further detail, explaining that the friend's image appears in great detail on the device, and how they perused a map together on the device to plan a journey, and how they followed a football game on their devices as they traveled. He further predicted widespread use of computers, and mentioned voice translation in particular. He based his projection on his prediction that radio waves of higher and higher frequency (shorter and shorter wavelength) would make it possible to have millions of simultaneous conversations going on simultaneously. Athough he clearly saw the marriage of the phone and the television, he did not foresee the marriage of the phone and the computer, in this article anyway. Two of his predictions have not yet come true: wireless power distribution, and meteorites destroyed by radio beams should they be on a collision course with Earth.

71:*Kotelnikov visited the*: Dickson (2001), 98–99, 130; NASA's *National Space Science Data Center*, for Sputnik info.

71:*He was there*: Evans (2012), 37; Ezell and Ezell (2010), 182–188.

71:*Spearheading the space*: Tchobanou and Udalov (2006), 176–177. There were twelve editors. The earlier Pioneer–Venus mission from the US had not mapped the northern polar region. The Pioneer mission began in 1978, and the *Venera* missions in 1983 and 1984. Schmadel (2003), 231, "(2726) Kotelnikov . . . Discovered 1979 Sept. 22 by N. S. Chernykh at Nauchnyj. Named in honor of academician Vladimir Aleksandrovich Kotel'nikov {1908– }, Soviet scientist, radio engineer and vice-president of the U.S.S.R. Academy of Sciences. Radar observations of Mercury, Venus, Mars and Jupiter conducted under his supervision were of help in correcting the value of the astronomical unit, in determining the period and the direction of the rotation of Venus, and in understanding the physics and dynamics of these planets."

72:*The frequencyspeak intuition*: The unpleasant artifacts of poor use of the Sampling Theorem are called *aliasing*. This strange name comes from the notion that the too high frequencies, that should have been removed before sampling, come back to haunt us at a lower frequency. That is, they take on the alias—as in fake name—of a lower frequency. They sneak in at a frequency we can perceive although they should rightfully be at a higher frequency that we can't. Their illegality is almost always unsightly. Luckily these criminals can always be caught. I further discuss aliasing elsewhere in the book.

73:*We hereby report*: *The KGB File of Andrei Sakharov* (2005), 193–196. The report was cosigned by Academician G. K. Skriyabin. Among the Politburo members signing the decision to publish the statement were Brezhnev and Andropov. A footnote stated, "So far as is known, all five academicians survived the affair unscathed, despite their refusal to cooperate."

73:*I think I*: Ginzburg (1991), 282.

73:*Indeed Ginzburg and*: It's true that Kotelnikov no longer had his protectors in place. Chertok (1996), 108, "In 1957, after sacking a group of his former colleagues from Stalin's Politburo, Khrushchev sent Malenkov into exile in Kazakhstan . . . . Golubtsova could have stayed in Moscow, but she and her children followed her husband. She did not return to Moscow until 1968. She completed her journey on Earth in 1987, and was buried in Moscow at the Kuntsevskaya Cemetery"; Russia: the quick & the dead, *Time Magazine*, July 22, 1957, "Georgy Malenkov was the man Stalin chose six months before his death in 1953 to step into his bloodied jack boots. But last week pudgy Georgy Malenkov, like hundreds of thousands of Communists before him, was on his way to banishment in Asia's outer reaches." Though Malenkov and Golubtsova were back in Moscow before 1975, they had no remaining power.

73:*I was curious*: Bissell (2009), 32, interview in 2003. Kotelnikov held the position for eight years, 1973–1980.

75:*The parallels between*: Kotelnikov (1933), the introduction by translators Bissell and Katsnelson; Bissell (2009); Bykhovskiy (2009); Tchobanou and Udalov (2006). Bell invented the telephone, and was the seventh president of the AIEE, one of the parent organizations of the IEEE.

75:*On Kotelnikov's ninety-fifth*: Tchobanou and Udalov (2006), 177; Lantsberg (2004); Pollock (2005); Chertok (2006), 765. Shannon died Feb. 24, 2001.

Putin pronounced, "Professor Kotelnikov has the right to be recognized as the Coryphaeus of Russian science," in praise strange to Western ears but not Russian. It's from *coryphaeus*, the leader of the chorus in ancient Greek drama. A Stalin epithet during his personality cult years had been "Coryphaeus of Science," so Putin's accolade was a significant reassignment of credit.

Ings (2016), 173, “So Russia’s scientists lost their two most powerful patrons, and Stalin became as a consequence a sort of *über*-patron around whom, like it or not, they were all obliged to gather. By the end of the 1930s they were calling him ‘the Great Scientist’, and ‘Science’s Coryphaeus’: the leader of the band.”

77:*Tom Stoppard, Arcadia*: Stoppard (1993), 51–52, with several lines omitted for prose flow.

77:*He was born*: Turing, S. (2012), by Turing’s mother Sara; *Biographical Memoirs of Fellows of the Royal Society* (1955); and Hodges (1983), which is my principal source for Turing. He was born 3 yrs. 9 mos. 17 dys. after Kotelnikov and 3 yrs. 10 mos. 7 dys. before Shannon.

78:*Then suddenly, in*: The most significant intelligence product (decrypted messages) of Bletchley Park was codenamed Ultra. The official historian of British wartime (WWII) intelligence, Sir Harry Hinsley, said, “Ultra was the main reason why the British were able to reduce the depredations of the U-Boats in the Atlantic in the second half of 1941.” Also, “My own conclusion is that it shortened the war by not less that two years and probably by four years—that is the war in the Atlantic, the Mediterranean, and Europe.” Hinsley served at Bletchley Park 1939–1946. Turing did not crack the Enigma code alone.

78:*Topping that revelation*: Although illegal, homosexuality was of little concern to English academics, who quietly accepted it. But Turing was arrested for having sex with Arthur Murray, who was not an academic and out of work. Turing had stepped outside academia, perhaps with too much confidence bred from the acceptance within.

The official inquest stated that cyanide poison was self-administered while the balance of his mind was disturbed [Sara Turing (2012), 117 (Sara’s book was first published in 1959); Copeland

(2012), 285, note 6, also cites *The Times*, June 12, 1954]. The official inquest papers have been destroyed, which is standard practice after 15 years.

The association of Turing's apparent suicide with the poisoned apple scene in Disney's *Snow White and the Seven Dwarfs* (1937) has often been made. Turing saw the film in 1938 and recited the film's couplet, "Dip the apple in the brew | Let the Sleeping Death seep through," many times. See Hodges (1983), 149. But the apple was never tested for poison.

79:*Biographer Hodges, himself*: Hodges (1983), 487–492, discusses the apparent suicide at length—the pros and cons of its actually happening—but baldly states (p. 487) that "on the evening of 7 June 1954, he killed himself." He quotes the coroner's report, "I am forced to the conclusion that this was a deliberate act," as reported in the *Daily Telegraph*, June 11, 1954, and the local newspaper, June 18, 1954. Half an apple with several bites taken from it was found next to his bed, but the apple was never tested for cyanide [Hodges, 488].

A post mortem medical examination report from June 8, 1954, the day Turing's body was discovered, performed at the mortuary in Wilmslow, gives the cause of death as shown by the examination to be, "Asphyxia, due to Cyanide poisoning. Death appeared to be due to violence." In further remarks, "I was present at the house of the deceased when a solution of a cyanide (identified by characteristic smell) and a bottle of Potassium Cyanide in solid form were found. The smell of the solid was identical with the smell of the organs, and no other chemical smells the same." Signed by Dr. Bird. The smell is described in several places as "of bitter almonds." [From a digital photo of the postmortem report on display on a video monitor at the South Kensington Science Museum, London, courtesy of George Dyson].

The argument continues in every direction—Turing committed suicide, he staged his suicide as an accident to protect his mother, it actually was an accident, the government assassinated him as a security risk, an apple was or wasn't involved, he was depressed from the hormones, the hormones were already a thing of the past, he was happy at the end, he was miserable at the end—and will surely never be settled to the comfort of all, especially conspiracy theorists. Sara Turing (2012), 114–121, adheres to the accident, or clumsiness, case. Copeland (2012), 223–234, presents the case for assassination very carefully, not coming down strongly for any of the three possibilities: suicide, accident, or assassination. The only definite conclusion is that he died of cyanide poisoning.

I dined next to Sir John Dermot Turing at Kings College, Cambridge, Apr. 28, 2017, at a celebration of his uncle, Alan Turing. Dermot expressed support of the theory that Alan's death was a suicide staged as an accident to protect his mother (Dermot's grandmother). Dermot has written a biography of his uncle [D. Turing (2015)]. Dermot is the 12th Baronet of the Turing Baronetcy of Forveran, Aberdeenshire, a Baronetage of Nova Scotia, founded about 1638 by King Charles I. (According to Marie Fraser, *Baronets of Nova Scotia*, www.electricscotland.com/canada/fraser/baronets_novascotia.htm, accessed Apr. 4, 2020: "There are still about 100 Baronets of Nova Scotia in existence, many of them descendants of those who once owned land there—land which they never set foot upon." She lists "Turing of Foveran" as family 48 of 109, granted the baronetcy in 1638. It's a curious story.)

79:*In 1950s America*: Hodges (1983), 71, mentions that Turing toyed with visiting Russia as a student but didn't do so, and he relates (p. 73) this telling story: "The Cambridge communists took upon themselves something of the character of a fundamentalist sect, with the air of being saved, and the element of 'conversion' met in Alan Turing the same skepticism as he had already turned upon Christian beliefs. With his fellow skeptic Kenneth Harrison he would mock the communist line."

79:*The Apostles, a*: David Champernowne was asked to "help" the Communists, but he didn't [personal conversation with David's son, Arthur, a personal friend and Digital Light colleague.]

Burgess was one of the Cambridge Five spies for the Soviet Union. It also included Anthony Blunt, Donald Maclean, and Kim Philby. Maclean defected in 1951 with Burgess. Philby and Blunt weren't detected until the 1960s. Maclean may have been homosexual; Blunt definitely was. The "fifth" Cambridge spy was John Cairncross, also an Apostle and also of Bletchley Park, but he wasn't identified publicly until after Turing's death, and almost certainly wasn't homosexual.

79:*Everybody agrees that*: Copeland (2012), 223–234, points out that the computer Turing was using at the time, at Manchester, was also being used for secret British atomic bomb calculations, and that the threat of Communist spies was creating hysteria in England and the US.

79:*It's a sad*: Welch issued his condemnation on June 9, 1954, in the Army-McCarthy hearings before the Senate Permanent Subcommittee on Investigations, chaired by Sen. McCarthy: "Little did I dream you could be so reckless and so cruel," intones the impassioned Welch in a filmed record. "Have you no sense of decency, sir? At long last, have you left no sense of decency?" It was the beginning of the end for McCarthy.

79:*The British government*: Leavitt (2006), 18, for the end of the law which criminalized unspecified "acts of gross indecency" between adult men in public or private.

Some Englishmen still haven't come to terms with Turing. I was dismayed on a visit to Manchester (July 4, 2013) to Sackville Park to view Turing's statue. This is the only public acknowledgement of him in Manchester proper (but there's a blue plaque in nearby Wilmslow where he died). His eyebrows were painted brown, his lips red, and his fingernails purple. Someone had apparently urinated on the crotch of his metal pants. Clearly his homosexuality was more important to some people there than the fact that they were there at all. In a further dampening of the dismal scene, pigeon droppings obscured the plaque explaining who he was. The reason for the disfigurement was probably the proximity of the LGBT community to the park and statue, separated from it only by a canal. And the presence of that community in Manchester is perhaps a more fitting tribute to Turing than the statue anyway.

The Guardian announced on July 20, 2013, the probability that the UK government would finally pardon Turing. Then on Dec. 24, 2013, Queen Elizabeth issued a rare pardon under the "Royal Prerogative of Mercy," which said she was "Graciously pleased to extend Our Grace and Mercy unto the said Alan Mathison Turing and to grant him Our Free Pardon posthumously in respect of the said convictions." As reported online at https://www.nbcnews.com/news/world/queen-pardons-computing-giant-alan-turing-59-years-after-his-n241, Dec. 23, 2013, updated Dec. 31, 2013, accessed Apr. 4, 2020.

79:*Fourier's French Terror*: On a visit June 24, 2013, I was startled by the prison camp look of Bletchley Park. If you mentally remove the estate mansion, then what remains are rows and rows of miserable huts. The wartime estate plans show this clearly. And if that weren't enough to evoke prison camp thoughts, there were construction fences around many of the huts. They were being refurbished as part of national museum plans. The fences weren't barbed-wire fences, but it was rather easy to imagine them so. Nevertheless, Bletchley Park was no sharashka. People came and went freely. They weren't sentenced to it for life.

But the manor house isn't absent. In fact, it's rather jarringly present, its architecture a jumble. I found it useful to imagine that the big house was a row of several smaller houses, each with unique architecture, chock-a-block along a residential street.

80:*Seymour Papert, Mindstorms*: Papert (1980), viii.

80:*A computer, like*: Countless here means countably infinite—the digital kind of infinity. You can count the number of musical compositions but you'll never finish.

81:*The other, very*: Large number names in this book are in so-called short scale. Short scale means that the names are applied to multiples of 1,000. Long scale means that names are applied to multiples of 1,000,000. Thus in short scale, a million is a thousand thousands; a billion is a thousand millions; a trillion is a thousand billions; etc. In long scale a billion is a million millions; a trillion is a million billions; etc. In particular, in short scale as used here, a quadrillion is 10^{15}, a thousand trillions, but in long scale a quadrillion would be 10^{24}, a million trillions. Short scale dominates in English-speaking countries.

Eleventy-eleven skydillion is a silly number of impossibly immense size fashioned from several sources and a bad memory. *Walt Disney's Uncle Scrooge* comic books star Scrooge McDuck (created by Carl Barks), world's richest duck. Many estimates of his worth appear in the pages of these comics. I remembered one such estimate as several skydillion but the "number" used, in issue no. 5, was actually skyrillion. My father teased me as a child with "eleventy-eleven," but many had first contact with "eleventy" in the first chapter of J.R.R. Tolkien's *Lord of the Rings*, where Bilbo Baggins famously celebrates his eleventy-first birthday in the opening lines.

81:*Repeating a task*: A wordier but popular alternative is to call programmers and engineers "software engineers" and "hardware engineers," respectively.

82:*In a nutshell*: Moore's Law details are presented in the next chapter.

82:*By its very*: I first wrote this paragraph in 2010. I've had to add two orders of magnitude to it since, the Moore's-Law increase that took place during the intervening time.

83:*–Thomas Usk, The*: Usk (ca. 1385, ed. 2002), II.7.71–73. This was long misattributed to Chaucer until about 1863. Al-Khwarizmi → *algorithm*, *algorism* → (French) *augrime* → (English) *augrym*, *augrim*. A tight translation: *Although a cypher in algorism has no might in signification of itself, yet it haveth power in signification to others.* A loose translation: *A zero in the decimal number system means nothing when standing alone, but has great significance when standing with others*. Compare 0 to 1000000.

84:*And if it*: A full intellectual history of the concept of computation would go back at least to Leibniz. He contemplated a notion like Turing's in the 18th century, but Turing brought the idea home. Charles Babbage tried to build a mechanical calculator in the 19th century and proposed a more sophisticated machine called The Analytical Engine, which was never built. Some claim that his famous fan, Lady Ada Lovelace, daughter of the poet Byron, was the first programmer since she sketched one for Babbage's nonexistent machine. Much more impressive, however, was her observation that Babbage had glimpsed a machine that was beyond mere numbers. They just didn't have the words or theory yet. That took Turing. See also Haigh and Priestley (2015) and Wolfram (2015) for deeper analyses of Lovelace's role.

85:*Geoffrey Chaucer in*: Chaucer (1391, ed. 1880) used the phrase "nombres in Augrym" in his *Treatise on the Astrolabe*, I.9.3, by which he meant Arabic numerals in decimal notation. The system was actually Indian, but we call it Arabic because of al-Khwarizmi who introduced it to the Arabic world, from which the West learned of it. Al-Khwarizmi also influenced modern terminology another way. He wrote a book with a long Arabic title that included the word *al-gabr*, translated into Latin as *algebrae*, hence our *algebra*.

Al-Khwarizmi was native to the city of Kharazm—that's what his name meant, the guy from Kharazm—located in the part of the old Persian Empire that is now Uzbekistan. Kharazm is located near the (former) Aral Sea.

86:*But Hilbert asked*: Hilbert and Ackerman (German 1928, 1938; English 1950), 112–124.

87:*In the scholarly*: The basic fact is that a father passes his YDNA (DNA of the Y chromosome) directly to his sons, who pass it to theirs, and so forth. To compare the YDNA of an ancestor to that of a living male descendant requires that you know the ancestor's YDNA. How might you know that—short of macabre exhumation? If you know, by scholarly proofs based on extant records, that a living male descends from the ancestor of interest, then you know that the ancestor's YDNA must match the living male's. That's the theory anyway, assuming no mutations of the YDNA during its passage through many generations. However, there generally *are* such mutations. By using the YDNA of several living males, each formally known to descend from the (common) ancestor, the mutations can sometimes be accounted for and the ancestor's YDNA exactly recovered. (I have done so for an ancestor who immigrated from England in 1633 to Massachusetts. See http://alvyray.com/Riggs/printpapers/EdwardRiggsSignature_publishable.pdf.)

87:*In England in*: Anderson (2013), 30, quotes Newman claiming, "I believe it all started because he [Turing] attended a lecture of mine on foundations of mathematics and logic in which I had mentioned . . . that what is meant by saying that the process is constructive is that it's purely . . . mechanical . . . and I may even have said a machine can do it." Anderson cites an unpublished interview with Newman by C. R. Evans, 1975.

87:*Student Alan Turing*: Copeland (2012), 1–2, clarifies that what was usually reported as Turing's stammer was in actuality something more like an "Ah . . . Ah . . . Ah . . ." which he used to keep someone from interrupting. His mother [Sara Turing (2012), 63] suggested that his mind was too fast for his tongue. Brian Randell, email Aug. 8, 2014, "I was told by someone who had known Turing well that Derek Jacobi's acclaimed performance as Turing in *Breaking the Code*—which I saw during its initial London run—was uncannily accurate, *except* that Jacobi used 'the wrong kind of stammer'."

88:*Newman urged Church*: [Math] It wasn't just Turing and Church who came up with the essential idea. Emil Post and Stephen Kleene came up with two other equivalent conceptualizations at about the same time. Post's *canonical systems* (and his later *tag systems*) seem the closest in "industrial" spirit to Turing's [Post (1936); Arbib (1969), chapter 5]. Kleene's *recursive function theory* is more abstract, like Church's [Kleene (1936); Arbib (1969), chapter 6]. (Jacques Herbrand and Kurt Gödel are sometimes co-credited with Kleene.)

Turing outlined the equivalence of his system to Church's in an appendix to Turing (1936). He published a full proof in Turing (1937).

Of incidental interest in the context of this book is a surprising paper by the same Kleene. Kleene (1947) was based on his research during World War II and declassified in 1946. It concerns an aspect of Fourier and sampling theory, with a figure containing (the absolute value of) the ideal spreader of the preceding chapter.

88:*The two approaches*: Farmer and Henley (1903), 6:368.

89:*Turing wasn't the*: Post was the first to notice this [Post (1947), 7]. Davies (2004) pointed out (circa 1947) "programming" errors in Turing's 1936 paper, and corrected them. Donald Watts

Davies went on to invent and name packet switching, fundamental to the internet today [Hafner and Lyon (2006), 64–67]. He was also listed as co-inventor of the patent for the Ace computer with Turing (and with Michael Woodger), application date May 4, 1950.

Davis [not Davies] (2004), 115, in his introduction to a reprint of Turing (1936), says, "This is a brilliant paper, but the reader should be warned that many of the technical details are incorrect as given." Hodges (1983), 392, recounts a later buggy programming effort by Turing.

The word *computation* is much older than Turing. It was the word that described what human computers did. In Nov. 2017, Jon Doyle of North Carolina State University pointed me to Holman (1895), titled *Computation Rules and Logarithms*, itself almost certainly not the first use of the term. This book was not obscure, reprinted at least fourteen times, 1895–1918 (and again in 1942 and 2014). When I say that *computation* was Turing's word, I mean that he used it rather than *lambda calculus* or *recursion* or some other less intuitive term from the equivalent mathematics of Church, Post, or Kleene. Doyle pointed me to *Wikipedia*, History of the Church-Turing thesis (accessed Apr. 4, 2020): "The reader [of Turing's "On Computable Numbers"] must bear in mind a caution: as used by Turing, the word 'computer' is a human being, and the action of a 'computer' he calls 'computing'; for example, he states 'Computing is normally done by writing certain symbols on paper' (p. 135). But he uses the word 'computation' in the context of his machine-definition." In fact, Turing did use *computation* to describe what his machines do: "It is my contention that these operations include all those which are used in the computation of a number" [Davis (2004), 118].

89:*And he was*: Leavitt (2006), 186–187, 196.

89:*Turing sailed to: New York, Passenger and Crew Lists (including Castle Garden and Ellis Island), 1820–1957*, image online https://www.ancestry.com/interactive/7488/NYT715_5877-0225, accessed Feb. 29, 2020, manifest of alien passengers for the United States immigration officer at port of arrival, for [*S. S.*] *Berengaria*, sailed Sept. 23, 1936, from Southampton, arrived New York, NY, Sept. 29, 1936, third-cabin passenger, list 10, line 30: Alan Turing, age 24, male, single, research[er], reads and writes English, nationality Britain, born London, England, visa NQIv.208, SEC.4(e), issued London, Sept. 17, 1936, last permanent address Cambridge, England, nearest relative in England: "Father Julius Turing, 8, Ennismore Ave Guildford ENG," final destination The Graduate School Princeton University NY [*sic*], length of visit "Until Sept 29, 1937" and "Expires 8/12/41" [and misc. other information such as 5'10" height, ruddy complexion, brown hair, blue eyes].

89:*A real nexus*: Dyson (2012), 52–53, 88–89. The IAS (Princetitute) and Princeton University were such close neighbors, in fact, that until 1939 they shared the same building, Fine Hall, at Princeton University.

92:*And so on*: Dan Garcia at the University of California at Berkeley wrote a simulator for this machine and discovered some short starting sequences that halted after several dozen steps. For example, the program example shown will halt after 78 steps with 4222444444 on the tape, the hole over the leftmost 4, and in the southeast orientation. It's not an interesting computation, but it does halt.

[Math] Programming the device is difficult. First you would design an Emil Post tag system (not a Turing machine, but equivalent to one) to implement your algorithm. Then you would encode the Post system into the symbol set of the business card machine, and also the data for it, according to Rogozhin (1996), whose theory is behind the business card design. Then you would have to decode any result obtained from the symbol set of the business card machine.

92:*This hasn't been*: Turing's machine was completely software, unless you count the brain running it as hardware. The business card design has actually been realized in hardware—in heavy card stock and also in thin metal. The card stock version was handed out to all 8,000 Freshmen entering the University of California at Berkeley, fall term of 2013, along with a copy of Dyson (2012).

92:*In the 1930s*: Turing, S. (2012), 70, "The most that Alan told me about his war work was that he had about a hundred girls under him. We knew one of these 'slaves' as he called them." Turing had already published his paper on Turing machines a couple of years prior to his working with computers at Bletchley Park, so the ultimate appeal is to Turing himself [Turing (1936), 135–140, in the Davis (2004) version]. "The behaviour of the computer at any moment is determined by the symbols which he is observing, and his 'state of mind' at that moment (p. 136)." "We may now construct a machine to do the work of this computer (p. 137)." Re tea breaks: "It is always possible for the computer to break off from his work, to go away and forget all about it, and later to come back and go on with it (p. 139)."

The computer Turing meant is human, and use of the masculine pronoun was the practice at the time, regardless of the gender of the majority. It was Davis (2000), 148, who suggested that "she" be the preferred form, and historically accurate considering the majority, when discussing Turing's time.

92:*There are four*: There are several equivalent formulations. Davis (1978), 246, for example uses in place of our one generic instruction, several instruction types, including print *x*, go left or right, go to step *i* if *y* is scanned, stop.

93:*You might glimpse*: Rogozhin (1996), 231–233. The design of the business card machine is mine and Dan Garcia's, based on a suggestion from Tom Griffiths then at the University of California at Berkeley, but the underlying rules and the proof of universality are Rogozhin's. He called it UTM(4, 6), a universal Turing machine with 4 states and 6 symbols. [Math] This machine is strongly universal, meaning that only a *finite* non-blank configuration may exist on the tape initially. This was the original meaning of *universal* and the one I adhere to.

93:*Turing's master stroke*: That a Turing machine captures what we mean by a systematic, or mechanical, process, or an algorithm, has withstood the tests of time and of other mathematicians for decades now. See subsequent note on the Church-Turing Thesis.

94:*Robert A. Heinlein*: Heinlein (1997).

95:*See the annotation*: There are lots of ways of doing this. Here's just one. It's folded to fit onto this page but is actually one-dimensional:

(f04Lf,14Lf,23Rf,32Lf,40Rf,50Rb) (b05LB,10Rb,25LB,34Rb,4H,52Rb)

(F05Rf,11RF,24Rb,32RF,4H,51Rf) (B01LB,10RB, 23LF,34RB,43LB,52RB)

There are four pairs of parentheses, one pair for each state, or orientation, of the business card. Each pair of parentheses is identified with one of these four states. For example, the first pair has an f as its first symbol. This means that this pair of parentheses holds the six rules for the f orientation.

Inside each pair of parentheses, and listed just after that first symbol, are encoded versions of the six rules on the card for that orientation, separated by commas. For example, the first rule inside the first pair of parentheses (and just beyond the first f there) is 04Lf. This is the code for the first rule of the business card machine in state f, where 0 represents the blank, 1 through 5 represent themselves, and L represents the left arrow. So 04Lf encodes the rule that says, if there's a blank in the hole, then change it to a 4, move left one square, and stay in state f—that is, don't change the orientation of the card. The sixth rule is 50Rb: If there's a 5 in the hole, then erase it, move right one square, and change to state b—that is, flip the card over to its back orientation. The only other code is H, which simply means halt (e.g., the fifth rule of the second set of rules).

95:*Turing's first trick*: The fact that our example machine A, the business card machine, is itself a universal machine doesn't matter. The technique works for *any* Turing machine.

I've glossed over an important detail of the encoding. What if you don't have enough symbols on your universal machine's tape to encode all the rules of a given Turing machine A? Well, you could use pairs of symbols to encode the rules, or triples, etc., however many you need. Suppose, for example, you had a U with only six symbols but you need 27 symbols to encode a particular machine A. Pairs of six symbols can represent 6^2 or 36 symbols which is plenty to handle the 27 you require. The encoding of A just about doubles in length, but it's still one-dimensional.

95:*At this point*: Actually Turing didn't do it this way. But he could have, so Turing in this description is metaphorical. What he actually did was to zipper two tapes together, one to hold A's encoded description and the other to hold A's encoded tape. In other words, he used every other square, or tooth, of the universal machine's tape to hold A's description, and the intervening teeth were A's tape. This is unnecessarily complex. It's clearer, and equivalent, to use side-by-side half-tapes.

[Math] The only catch with the side-by-side configuration is that, whereas A's tape is infinite in both directions, the universal machine described here only allots it a half-tape, infinite in one direction only. But mathematically a half infinite tape is equivalent to a doubly infinite one. In other words, for every Turing machine A with a tape infinite in both directions, there's an equivalent one A* that uses a half infinite tape. So to simulate A with a universal machine of the two half-tapes configuration, as here, simulate A* instead. Minsky (1967), 129–130, suggests that the way to do this is to fold the infinite tape on itself and let alternate squares represent the two half tapes, using a zippering idea like Turing's.

95:*The bold **0***: As before there are lots of ways of doing this too. Here's just one:

(f04Lf,14Lf,23Rf,32Lf,40Rf,50Rb) (**b**05LB,10Rb,25LB,34Rb,4H,52Rb)

(F05Rf,11RF,24Rb,32RF,4H,51Rf) (B01LB,10RB,23LF,34RB,43LB,52RB)

|00000005155**0**000000.

96:*Then it would*: [Math] This is still not a full design, but it's taken to a higher level of detail. Suppose U starts scanning the leftmost square of its input string. That means the first symbol it sees on its tape is the leftmost left parenthesis. To simulate the machine encoded by the description that follows that (symbol, U must discover what state the simulated machine is in. That is, it must find the set of rules marked by a bold **f**, **b**, **F**, or **B**. It can do this by scanning right along its tape and inspecting the symbol just after each (symbol that it finds. After starting it will find the **b** and "know" that the current state of the simulated machine is b and the current set of parentheses contains the corresponding six rules for that state. Then it must find what symbol is currently scanned by the simulated machine. To do that it must then scan right to find the vertical bar | demarcating the right half-tape. Then it must scan along the encoded data of the simulated machine there until it finds a bold symbol. On its very first pass it will therefore find the **0** and know that the simulated machine, now known to be in state b, is scanning a 0. Then U will scan back to the left until it finds the **b** and hence the rules corresponding to the current state. Then it will scan right to find the rule 05LB which is the one that the simulated machine must currently execute, the rule that starts with a 0. So U now knows that it must change the blank (0) to a 5 and move the simulated scanner one square left. So it scans right along its tape to find the | then goes to the **0**. It changes it to 5 and moves one square left and changes the 5 there to a **5** to mark its new simulated position. U's tape now looks like this:

(f04Lf,14Lf,23Rf,32Lf,40Rf,50Rb) (**b**05LB,10Rb,25LB,34Rb,4H,52Rb)

(F05Rf,11RF,24Rb,32RF,4H,51Rf) (B01LB,10RB, 23LF,34RB,43LB,52RB)

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U now has to simulate a state change from b to B as demanded by the current rule. It scans left to find the **b** and converts it to a b. Then it looks for the (B and converts the B there to **B**. U's tape now looks like this:

(f04Lf,14Lf,23Rf,32Lf,40Rf,50Rb) (b05LB,10Rb,25LB,34Rb,4H,52Rb)

(F05Rf,11RF,24Rb,32RF,4H,51Rf) (**B**01LB,10RB, 23LF,34RB,43LB,52RB)

|000000051**5**5000000

U has now simulated one complete step. U moves its head to the leftmost symbol on its tape and starts the process again.

96:*A modern computer*: The observation is called the *Church-Turing Thesis*. It's something that cannot be proved. It's name honors both Turing and Alonzo Church, Turing's PhD adviser, who had an equivalent idea slightly before Turing. Generations of mathematicians have come at it with every attack imaginable and have not found it wanting. For example, you might think that a Turing machine with more tapes, more heads scanning a tape (in "parallel"), or with higher dimensional tape, might be more powerful than the simple one presented here. In every case, it's been proved that, although there might be greater speed with such improvements, there was no increase in the number of things that could be computed. Post, Church, Kleene, and others came up with completely different mathematical systems for the concept underlying Turing machines, but all their approaches were proved equivalent to his. In other words, they didn't increase the number of computable things either.

97:*How many programs*: There's a countable infinity (or digital infinity) of programs. This isn't strictly true for a real-world computer which has to be finite, but you can always add more memory—another chip or another tape or another disk, say.

98:*John had been*: Whitman (2013), 1–2, 7, 16–17, 50, 52, 54, 60, where Marina von Neumann Whitman is John's daughter; Dyson (2012), 54.

The photograph in *Life* magazine [Feb. 25, 1957, 96] is a cropped version of this shot, originally made by the Kolb Brothers at the Grand Canyon.

98:*Von Neumann became*: Von Neumann didn't invent this architecture alone, despite its name. Herman H. Goldstine, Arthur W. Burks, John Presper Eckert, and John W. Mauchly were other members of the team. Von Neumann's name alone appeared on an early draft report of the architecture, so he often unfairly gets all the credit.

Von Neumann invented another field in computer science, with Stanislaw Ulam, called *cellular automata* theory. He left an incomplete book at death called *The Theory of Self-Reproducing Automata* [von Neumann and Burks (1966)]. My PhD dissertation, *Cellular Automata Theory*, at Stanford University in 1969 was inspired by and extended this book.

98:*He was a*: There are many stories about von Neumann's prowess. Herman Goldstine, who worked on one of the earliest computers with von Neumann wrote about his skills in Goldstine (1972), 167. Lothar Nordheim, theoretical physicist, attributed to von Neumann the "fastest mind I ever met" [Goldstine (1972), 171]. Jacob Bronowski, writer and host of the television series *The Ascent of Man*, "He was the cleverest man I ever knew, without exception. And he was a genius." [Bronowski (2011), 323–327]. Edward Teller, physicist, principal in the development of the H-bomb, "If a mentally superhuman race ever develops, its members will resemble Johnny von Neumann," and "He was incredibly fast. Beyond him, we have never seen." [Dyson (2012), 45, 326].

98:*Hilbert's Second asked*: More generally Gödel proved that a system that was robust enough to support arithmetic couldn't be both consistent (no contradictions possible) and complete (all truths derivable). So if you want to avoid contradictions, then your system can't be complete. But if you want every truth derivable in the system, then you have to accept that some falsities can be proved true in it too.

Gödel's result surprised the math world, including Hilbert himself, but delights many mathematicians because it suggests that "mathematical intuition" plays a role in what they do. They don't want an essentially mechanistic way to derive math—even arithmetic.

100:*Von Neumann didn't*: Eniac was a programmable electronic machine but it wasn't a stored-program machine and it wasn't universal. It was a hardware implementation of a Turing machine but not of a universal Turing machine.

Eniac is usually written ENIAC since it was originally an acronym meaning Electronic Numerical Integrator And Computer. But Eniac has become the name of the machine, so I promote its acronym to a full name in this book and do so also for all other machines with similar names, their acronyms long forgotten, if indeed they were ever acronyms.

100:*Like Turing, von*: Turing received an OBE (Order of the British Empire) for war service, but what it really represented went unannounced.

Bernstein (2010), 36–50: Fuchs and von Neumann witnessed the Trinity Site A-bomb test in New Mexico in 1945. Fuchs passed the technical information about it (the plutonium bomb subsequently dropped on Nagasaki) to the Soviets, who implemented a copy of it as their first A-bomb. In 1948 he passed the Fuchs-von Neumann triggering mechanism for H-bombs to the Soviets, who did not use it for their first H-bomb.

A book published while this book was in final production—Ben MacIntyre, *Agent Sonya: Moscow's Most Daring Wartime Spy*, Crown, 2020—provides a thoroughly entertaining but accurate and detailed history of how and why Klaus Fuchs supplied full western knowledge of the atomic and hydrogen bombs to the Soviets. Agent Sonya was his handler for much of it.

101:*There was a*: Hodges (1983), 95, 117–132, 144–145. Von Neumann might have been unaware of Turing's computation result in 1937 because he failed to mention it—a large omission—when describing Turing in a reference letter that year. Instead he stressed two areas of math where his and Turing's interests overlapped, but not including computation. Perhaps Turing was just too shy to force the issue with von Neumann, but it's a puzzle that Newman, who also knew von Neumann, didn't press it either, or so it seems. At any rate, by 1938 von Neumann definitely did know (p. 145). And that's the year that he offered Turing a job at the Princetitute, although the assistant's job he offered Turing might not have originally entailed computation.

Gödel himself was at the Princetitute off and on until permanently there in 1939. So it seems unlikely that von Neumann could have been long unaware of Turing's result since he was in Princeton, was obviously familiar with fundamental logic, knew Gödel, knew Church, knew Newman, and attempted to hire Turing then and there. And Gödel was a Turing fan.

Nevertheless, supporting a delay in von Neumann's appreciation of Turing's result, Church claimed that he (Church) and von Neumann never discussed the basic foundations of mathematics "because von Neumann had lost interest in the subject" [Aspray, interview with Eugene Wigner, 1987]. This is consistent with his departing the field of logic after trying to improve on Gödel's result. But von Neumann certainly knew the field and ultimately didn't fail to appreciate Turing's result and give him credit.

I honor as the first stored-program computer the one nicknamed Baby, which first computed in June 1948 at the University of Manchester. This is usually the computer given credit as first, but there is dispute about that role. There is a recent series of papers that contends that it was an American machine, a modification of Eniac (which I term Eniac+), that was the first, beating out Baby by a month or two. Some, but not all, of these claims are discussed in the next chapter.

101:*Bletchley Park was*: The first big breakthrough in cracking Enigma came from Polish cryptographers, who passed what they had discovered on to Bletchley Park personnel. Prominent among them were Marian Rejewski, Jerzy Rózycki, and Henryk Zygalski.

101:*The trial and*: Turing did not build a Bombe, despite the movie, *The Imitation Game* (2014). Nor was one of them named Christopher, for Turing's childhood love. Nor did Turing get the idea of a computer from the Bombe. He had defined the stored-program computer several years before Bletchley Park.

103:*Turing had led*: Copeland (2006), 157–158. Tunny was the Bletchley Park code name for the Lorenz cipher machine. Fish was the code name for the decrypted product of Tunny. The Colossi were built chiefly by engineer Thomas "Tommy" Flowers. Bill Tutte made the fundamental mathematical advance that broke the Tunny code, or Lorenz cipher.

103:*And Turing indirectly*: Copeland (2006), 380–381, "The algorithms implemented in . . . Colossus depended on this simple but brilliant observation [Turingismus]. In that sense, the entire machine-based attack on Tunny flowed from this fundamental insight of Turing's." Tutte's final breakthrough was inspired by it.

104:*Churchill and Roosevelt*: The vocoder's inventor, Homer Dudley, applied for its patent in Oct. 1935. Kotelnikov openly acknowledged his debt to Dudley, in his search for a solution to secure radio communications during the German invasion of Russia—ironic because Dudley was extremely anti-Communist, of the Joseph McCarthy right-wing extreme variety. Kotelnikov was in Manhattan while Dudley was perfecting the device there. Kotelnikov at Amtorg Trading Co. was just blocks away from Dudley at Bell Labs, but Kotelnikov's visa expired in late July, just shy of Dudley's public debut of the vocoder in September at Harvard. Tompkins (2011), 48, 81; Dudley (1964), abstract, "A program of active research on the vocoder was initiated in July 1934. The first public demonstration of the vocoder was at the Harvard Tercentenary in September 1936." Kotelnikov had departed America before then. He had arrived on May 24, 1936, on a 60-day visa. Kotelnikov was at Amtorg, 261 Fifth Ave. Dudley and Shannon (and later, briefly, Turing) were at Bell Labs, 463 West St., a couple of dozen blocks away.

Kotelnikov's vocoder system for frontline communications was working by 1942. Germany's surrender conditions would be discussed over it in 1945. The X System, or Project X—officially called SIGSALY—went into service in 1943. Conditions of German surrender were discussed by Churchill and Truman on it in 1945. See Tompkins (2011), chapters 2 and 3. Another secret project, the Manhattan Project, was alternatively known as Project Y.

104:*The fact that*: Hodges (1983), 245–246; Tompkins (2011), 42; *Judges* 16 (King James Version), Delilah was Samson's lover but in the pay of the Philistines. She quizzed him about the source of his awesome strength, and he misled her three times. Finally, under intense daily pleading "until his soul was vexed unto death" (Judges 16:16), he finally revealed the real secret. The Philistines paid off Delilah, cut off Samson's hair (while asleep in her lap), blinded him, and imprisoned him.

Turing wasn't a good engineer, it seems, despite his efforts. Bletchley Park engineer, A.W.M. Coombs: "Turing was a brilliant mathematician but he was a rotten engineer, you know. His ideas for making the machine, the engineering ideas, God help us! But he was brilliant as a philosopher and a mathematician and . . . as a seer of the future" [Anderson (2007b)].

104:*Now we invoke*: [Math] The Sampling Theorem used here is a generalization, called the *band-pass* version, of that presented in the preceding chapter. It assumes that there's a lowest frequency f as well as a highest frequency F. The sampling rate required in this case is twice the bandwidth, or $2 * (F - f)$, samples per second. This is the same as we've used before if f is 0 cycles per second. Kotelnikov proved this stronger version in 1933, and Shannon published it again in 1948. For our vocoder example, each band need only be sampled at 600 samples per second, whereas the full voice signal in our example would have to be sampled at 6,000 samples per second.

The actual X System used voice frequencies from 250 to 2,950 cycles per second—that used by the telephone—divided into ten bands of bandwidth 25 cycles per second each. Each band was sampled at 50 samples per second. So the sampling rate for each band was the one required by the

Sampling Theorem, but the ten bands totaling 250 cycles per second didn't actually cover the full band (2,700 cycles per second) of given voice frequencies. It must have sounded awful, and anecdotes report that it did.

105:*The surprise in*: [Math] Turing's version assumed the highest voice frequency was 2,000 cycles per second and he sampled it at 4,000 samples per second, again in accordance with the Sampling Theorem.

105:*The vocoder is*: Auto-Tune is a proprietary product and name of Antares Audio Technologies. Similarly Photoshop is a proprietary product and name of Adobe.

105:*But computers do*: A good intuition to have: Any software algorithm can be made to go fast by implementing it in hardware For example, a machine that does nothing but implement the addition algorithm can be made to go extremely fast, but it can do nothing else. When we talk about hardware and software, we usually mean with respect to a general-purpose, or universal, computer. A computer simulates, via a program, any algorithm. We implement the computer in hardware to make those software simulations extremely fast. But each one of them could be made to go even faster by directly implementing it in hardware. Most computers have a few algorithms, like addition, dropped into hardware to make them go especially fast, but such *adders* aren't necessary for a machine to be a computer.

There may seem to be a contradiction between the earlier claim (1) that hardware is simple while software contains all the complexity, and the claim just made (2) that hardware and software are equivalent. The resolution is that (1) applies only to hardware for a general-purpose, stored-program computer. In other words, the hardware in that case is devoted to the implementation of the equivalent of Turing's universal Turing machine. This doesn't invalidate (2) which is about hardware of a much broader variety, namely hardware for implementation of *any* software, not just a universal Turing machine equivalent. Any arbitrary very difficult piece of software can always, theoretically by claim (2), be realized in special-purpose hardware, but that hardware will be as complex as the software it implements.

106:*Many think that*: In actual fact, a computer isn't completely deterministic at each step if it's allowed to operate asynchronously—without benefit of a clock—as some are, or partially are. If the computer's control is asked to arbitrarily choose one of two stimuli that arrive simultaneously, what's it supposed to do? This is more generally known as the problem of Buridan's ass in philosophy, first raised by Aristotle. So the machines considered here operate strictly against a clock, in the sense of strictly one operation per tick allowed. The ticks are assumed separated in time although not necessarily spaced exactly by a certain duration.

106:*Remember that Turing's*: Turing is usually thought to have named and proved the halting problem, but he didn't. He proved something else, that the *printing problem* is unsolvable. This is the problem of determining whether a Turing machine starting with a blank tape will eventually print some specific symbol, say a 1, on its tape. It was Davis (1958), 70, who coined the term *halting problem*, explicitly stated it, and proved it [see also Copeland (2012), 241, note 14]. The unsolvability of the halting and printing problems are proved the same way. Davis, in fact, proved them side by side. Since Davis (1958) was an early and influential text on Turing, it's a common error to assign the halting problem to Turing rather than to Davis. For a pleasant presentation of the unsolvability of the halting problem, see Davis (2000), 159–160.

There are, in fact, a countable (digital) infinity of unsolvable computations, the two above being the most famous. The unsolvable problems for Turing machines are a theoretical concern. In the real world, memory is bounded and hence theoretically all possible outcomes can be determined. But the numbers are so large that the task is usually infeasible—computation times larger than the age of the universe, for example.

106:*So a computer*: To show that some programs are solvable, suppose your program had one instruction: (1) go to step 1. Clearly this program will not halt. You know it. That is, you can decide that this program, regardless of its input data, will never halt. Similarly suppose your program consisted of this one instruction: (1) stop. Again you can easily determine that this program, on any input data, will always halt. It's the highly-nested, many-branching, multi-looping complexes that, in general, cannot be tamed by any algorithm. That's what the undecidable halting problem tells us. There's no systematic way to make sense of the convoluted structure of a computation to determine, just by looking at it, whether the program will halt or not.

107:*One of the*: Lavington (2012), 82, discusses the conditional branch instruction of Turing's original computer design.

107:*Donald E. Knuth*: Knuth (1968), first paragraph of the preface of vol. 1.

107:*Programming is the*: The complete title of Turing's paper was "On Computable Numbers, with an Application to the *Entscheidungsproblem*."

108:*The separation of*: [Math] There are generally two human-oriented ways to write programs. One uses mnemonic codes to stand for the unreadable string of symbols the computer needs. Mnemonic codes form what is called *assembly language*. It's not the *machine language* that the machine understands, but it's not far removed. An *assembler* is a program that converts assembly language to machine language. Typically one assembler instruction converts to one machine instruction. The other way to write programs, the usual way, is to write in a so-called *high-level programming language* which is almost English-like. Then a *compiler* program converts that high-level program into an assembly language equivalent, or directly into machine language. Each statement in a high-level language may convert into many assembly or machine language instructions. The handiest thing about a high-level language (like C) is that the programmer doesn't have to know how a particular piece of hardware works. The compiler for that machine has to know, but not the programmer.

There are high-level languages with keywords not in English—importantly, there's a Chinese C++—but the most popular ones use English keywords.

108:*But back then*: George Dyson was granted special access to the archives while researching his book *Turing's Cathedral* [Dyson (2012)], the definitive work on von Neumann and Julian Bigelow at the Princetitute. He generously shared these documents with me.

108:*In a memo*: Dyson (2013), memorandum for Frank Aydelotte (director of IAS, the Princetitute), from John von Neumann, has these additional mentions: "simple methods for planning the 'setting up' of any problem; no setting of switches or plugging . . . , so that the machine sets itself up fully automatically," and "I planned, and am developing further, the 'setting up' and the logical control methods for both devices."

See Copeland (2004), 383, for Turing's use of "set up" in a 1947 lecture: "When any particular problem has to be handled the appropriate instructions for the computing process involved are stored in the memory of the Ace [Turing's first hardware computer] and it is then 'set up' for carrying out that process." It appears that what Turing means by "set up" is only that the instruction table is appropriately located in the memory of Ace. The design of the instruction table is the creative part.

109:*A letter dated*: Dyson (2013), letter to Frank Aydelotte, from John von Neumann.

109:*Then it happened*: Dyson (2013), minutes of meeting no. 2, Electronic Computer Project, from the office of V. K. Zworykin. Present also at the meeting were J. A. Rajchman, Zworykin's main engineer, and Tukey who coined the words *bit* and *software*. The last sentence quoted from the minutes is just another way to say "the rules listed are the instruction table of a universal Turing machine."

109:*The von Neumann*: An anecdote that demonstrates von Neumann's rather surprising shortsightedness about computation is this from pioneer programmer Don Gillies, via Martin Davis (personal communication, Oct. 2013). Von Neumann would write programs in mnemonics. For example, a mnemonic instruction might look something like this: Add x [to] y. The computer couldn't understand such a mnemonic instruction. To convert it to an equivalent string of bits that the computer could actually use is called *assembly* [cf. preceding note]. Von Neumann used graduate students to do the assembly, a torturous task. Gillies offered to write a program to make the computer do the conversion, a program we would now call an assembler. Von Neumann responded annoyed that Gillies proposed to "use a scientific tool to carry out a secretarial task." Clearly then, at that early time, von Neumann still thought of the machine as principally a number cruncher, a calculator, rather than a symbol manipulator. He, however, didn't deny the nonnumeric capabilities. He just couldn't foresee their importance. Turing, meanwhile, was already thinking about computation in mathematical logic and artificial intelligence.

109:*So in late*: Copeland (2004), 388, 390, 391, for Turing's use of *programming* in the 1947 lecture. In a discussion of the process of loading an instruction table (that is, a program) into the memory of a machine and then starting it, he talks about performing a series of checks to ascertain that everything is as it should be before starting the computation. Then (p. 391): "The programming should be done in such a way that the Ace is frequently investigating identities which should be satisfied if all is as it should be." So *programming* here appears to be the set of procedures one follows to set up, or install, a program in a memory prior to actually running it—a flight check, so to speak, before actually taking to the air. However, his first use of the word (p. 388) seems closely akin to what we now mean. It's used in the context of looping through instructions and using a conditional branch instruction to exit the loop.

Grier (1996), in a paper about the verb *to progam*, chased down the deeper origins of the verb, but was clear that the early uses weren't what we now mean by it. John Mauchly worked with J. Presper Eckert, on the almost-computer Eniac, then was joined by von Neumann. Eniac was not programmable but it used the term *programming* the following way: Its central control unit was called the master programmer and it sent control signals down program cables to invoke different parts of Eniac. This is the way Mauchly used it in 1942 [Mauchley (1942), 330–331], perhaps the first use of it in a computer context at least. The term was used in radio broadcasting in 1923. It was also used by the military in the War (WWII) in a way implying "to assemble" or "to build a complicated operation out of simpler actions." Von Neumann was close to the military so was probably familiar with that use of the term.

109:*Sir Charles Sherrington*: Sherrington (1942), 178.

110:*Bits aren't required*: Shannon (1956). There's a price to pay for this improvement. The cost of reducing the number of symbols to 2 is an increase in the number of states of the tape scanner. Shannon's equivalent of our universal business card machine would have about 100 states, versus our 4, but we can do better. There's a universal Turing machine with only 2 symbols and 15 states.

So its program of 30 rules is longer than ours but its alphabet is smaller. It's still a simple machine—*deceptively* simple in light of its ability to compute anything that's computable. Neary and Woods called it $U_{15,2}$, and it's strongly universal [Neary and Woods (2009), 120–123]. It's hard to imagine a business card implementation with 100 (or even 15) orientations of the card, so some other realization of "state" would be necessary.

Shannon (1956) also proved a more surprising result. For a Turing machine with, say, *n* states, where *n* can be any number—like eleventy-eleven skydillion—there's an equivalent one with only 2 states. The cost is a monstrous increase in the number of symbols.

Shannon was the first to use *bit* in print, but he never used it as a memory unit. He used it in his information theory as the basic unit of information. For example, the capacity of a communications channel is measured in bits.

111:*It's easy to*: Even Eniac was used for nonnumeric computations. After hours Nils Aall Barricelli used it to simulate evolution of "organisms" [Dyson (2012), 225–242]. Barricelli used numbers to represent his "organisms," but they weren't numbers. He was looking for patterns of reproduction and evolution. He did, however, use a numeric rule for reproduction: If a cell numbered *m* were to reproduce in a cell, and if a cell numbered *n* were to reproduce there too, then the collision would be resolved as follows. Add *m* to *n* and subtract the value, say *p*, already in that cell. But the rule seems rather arbitrary, intended to make a "mutation" that is in the same numeric ballpark as the other organisms. A nonnumeric rule would probably suffice as well. If Barricelli had had a graphic display, he surely would have used it. Instead he had to transfer his output tediously to paper to see it.

112:*But in a*: In computer chips today voltages are typically in the range 1 volt or less, so you can think of a 1 as a voltage of 1 volt and a 0 as a voltage of 0 volts, and not be far off.

113:*But a truly*: Hodges (1983), 78.

113:*Perhaps the most*: Woolf (2018), entries Apr. 24, 1929, Sept. 1, 1929, Sept 2, 1929, Nov. 30, 1929, Jan. 4, 1931, Sept. 2, 1931, Jan. 17, 1934, Oct 6, 1935, and others in 1934.

113:*Lyn and Max's*: Newman, W. (2002), 1–3.

114:*There grew between*: S. Turing (2012), xxi, in foreword by Lyn (Irvine) Newman.

114:*But Lyn's lasting*: The Bletchley Park bookstore sells an Alan Turing Edition of the game Monopoly. It's based on a hand-drawn Monopoly-like board created by the young William Newman. The original drawing is part of the Bletchley Park museum collection. Its board features Cambridge locations and a diagonal bar that doesn't exist in official Monopoly. The story is that Turing played this game with young William, who defeated the great mathematician.

117:*Sir Frederic "Freddie"*: Reported in documentary film, Manchester Baby: world's first stored-program computer, 2013, produced by Google, from a 1976 interview.

117:*Simon Lavington, British*: Live interview, Manchester Baby: world's first stored-program computer, 2013. Lavington acted the part of Kilburn, removing a virtual pipe from his lips, delivering the statement, then firmly replacing the pipe in his mouth. Lavington asked the question in 1966.

118:*Williams gave us*: Intentionality is an important requirement of Digital Light. Computers have long used lights on their consoles to indicate the status of specific internal bits. Conveniently these indicator lights are arranged in rectangular arrays. But there is no intention that that array of lights be a picture. It could equally well have been one long row of lights. We don't include such accidental arrays of lights as part of Digital Light.

By the same argument, we don't count a blinking array of lights as a computer animation if there is no intention of a stream of coherent two-dimensional pictures. Such blinking arrays of lights represented the computer, along with spinning magtape reels, to the public at midcentury—but were not Digital Light. Again, a one-dimensional row of lights would carry the same information.

The late Russell Kirsch is sometimes said to have created the first digital image—see, for example, his obituary in the *Washington Post*, Aug. 13, 2020—but his "first" image (of his baby son) was created in 1957, almost a decade after First Light on Baby in Manchester in 1947. He did contribute to the misconception that pixels are little squares by forcing the display of each digital value of his son's photo to have rectangular shape.

120:*It's an old*: Throughout this chapter I state that something is first, or second, etc., and sound quite categorical about it. It's a stylistic choice to avoid constant resort to the wiggle words "perhaps," "probably," "might be," "arguably," etc., which I would have to use in a scholarly account. The account here should make it clear that such an exact ordering is impossible at this time in the history of computers and of Digital Light. I have elected to give my reasons and use simple rules applied consistently and then let the reader decide. An example of one such rule is that for priority dates. Often the early dates simply weren't recorded, so were later estimated, sometimes long after the fact and with biased intent. My rule is to be conservative and take the latest of a range of such dates as "the" date, which might easily be wrong in light of future evidence. In short, I expect to be found wrong in some cases, but I suspect that I'm not far off. But that's little consolation to a group, or a university, or a country, who dearly wants to "win."

120:*In the 1960s*: Bletchley Park museum exhibits use the term "semi-programmable computer" for what I'm calling an "almost-computer" here. From the previous chapter, it's clear that a computer doesn't have to be electronic, but now they all are. Electronics are fast, and the whole point of computers is to make computation fast. Also, by insisting that computers be electronic I can prune away from further consideration the electromagnetic contenders (such as Zuse's machines in Germany) and the paper tape contenders (such as IBM's SSEC, aka Poppa). They are important in the history of the concept of computer but not Digital Light. As an extreme case, the business card machine of the preceding chapter is a hardware implementation, in a sense, of a computer, but having made that point, we now turn to the Amplification that makes computers practical computers. From here on we want to exclude the business card machine and things like it from what we mean by a computer. The easiest way to do so is to insist that a computer be electronic.

Re the Zuse Z4, consider Rojas (1999), 4: "But the main difference between the Z4 on the one side, and the Z1 and Z3 on the other, was the inclusion later of conditional branching in the Z4. After the war, the Z4 was moved from Berlin to Bavaria, where it stayed in a barn for almost four years. Prof. Stiefel from the Technical University of Zürich heard of the machine and after visiting Zuse, decided to rent the computer for his university. He asked Zuse to include conditional branching in the instruction set, a second punched tape for numbers and to use a typewriter to print out the results. The machine was refurbished and conditional branching was added. The new instruction worked in the following way: when the contents of register R1 was negative, the control unit skipped all following instructions until a special code ('start') was found in the punched tape. In this way it was possible to jump over sequences of instructions, i.e., those constituting the not—taken branch of a conditional instruction in the source code." So a Z4 program was on paper tape, a mechanical device, and Z4 wasn't a stored-program computer. The delivery of Z4 (enhanced) to ETH Zurich occurred in 1950 [*Wikipedia*, Z4 (computer), accessed July 5, 2018, cites a Rojas article (in German)].

121:*The Brits aren't*: Copeland (2012), 104, 107; Copeland (2006), 301. Tommy Flowers, main hardware engineer of Colossus, built it starting in 1943 and had it running at Bletchley Park in Feb. 1944. He built it at the Post Office Research Station in Dollis Hill, in the northwest part of Greater London. That a large electronic machine could function reliably, as did Colossus, was an important lesson for builders of early computers. Turing in particular was highly influenced by the Flowers success.

One of the lessons from a theoretical study of universality [Minsky (1967), 255–259] is that it doesn't take much to make a machine universal. A couple of registers (small multibit memories, holding, say, one word) and two operations, including a conditional branch instruction, do it. There were some early machines that apparently were converted to universal ones in a jury rigged sort of way, once it was understood that universality was to be the distinction that counted. Historians still have to sort all this out.

121:*But those room-sized*: By the war's end there were nine giant Colossi in operation tended by a flock of Wrens—members of the Women's Royal Naval Service (WRNS). There were nearly 2,000 Wrens at Bletchley Park by the end of the War, operating Bombes and Colossi [Copeland (2012), 64, 113–116].

121:*Freddie Williams moved*: *Frederic Calland Williams (1911–1977)* gives his radar experience during the War years at Telecommunications Research Establishment (TRE), in Malvern, UK. One of his radar systems was manufactured by Ferranti Ltd. of Manchester, beginning his relationship with that firm. "He visited the U.S.A in 1945 and again in 1946 in connection with the Radiation Laboratory (MIT) Series. Here he learned of attempts to use cathode ray tubes for [analog] data storage. In June 1946 he also visited the Moore School of Engineering, home to the ENIAC."

Kilburn (1990), "Freddy Williams went to the States about 1945 and 1946 to contribute to a set of radar books that were being written [the MIT series]. He saw at Bell Labs some experiments on the cancellation of ground echoes in radar which involved moving signals from a cathode ray tube. . . . Freddy came back to TRE about August/September time and in '46 he started to set up this sort of system with a view to trying to store digital patterns. By December he had stored one digit at TRE!"

However, Williams and Kilburn (1949), 100, give a slightly different credit: "As far as we know the discovery that signals symptomatic of previous scanning could be observed on an ordinary cathode-ray tube was made accidentally at the Radiation Laboratories, Boston, U.S.A." Many other details can be found in Copeland (2011), Part 1.

121:*Just before his*: The actual electronic techniques used by Williams to read, write, and change a spot on the screen of the tube involved clever use of what had been considered an undesirable characteristic of cathode-ray tubes, a secondary emission of electrons from the face of the tube. He utilized secondary emissions, overlapping charge wells on the surface of the screen, and an electron collector plate over the screen to perform the tasks. (The collector plate was porous so that you could still see the screen through it.) But just as the nasty details of displays in the modern world are of no concern to the user of those displays, so these details are ignored here. An excellent source for details about the Williams tube development is Copeland (2011), Part 1.

Was that display of a single bit Digital Light? Williams's intention was to store a bit, not to make a picture. He didn't care whether the state was 0 or 1, so long as it was properly stored. He didn't even care whether he could see it or not. It *was* some primitive form, a zero-dimensional digital image, but spread ever so slightly into two dimensions by the single spread pixel. Similarly, a one-dimensional row of spread pixels constitutes a slightly higher-order form, also spread ever so slightly in the second dimension by the spread of the spread pixels. But generally, Digital Light doesn't refer to mere images but rather to those that are the result of human intention to make—or take—a two-dimensional picture. In other words, Digital Light assumes digital images that have two-dimensional spatial coherence.

122:*Kilburn's 1947 report*: Again, intention is fundamental to Digital Light. Digital Light *pictures* require two-dimensional coherence. It's arguable that every display of Baby's memory contents was a digital image and hence should be classified as Digital Light. But the lack of two-dimensional coherence of the bits in the usual display disallows the term. The mothering engineers apparently didn't care that the bits could be arranged into digital pictures, since they failed to do so for months, or perhaps years. (Excluding the major exceptions, of course, I call First Light and the very next picture, before Baby was complete.) They only cared to know from them what the contents of single words were, where a *word*, of 32 consecutive bits, was the next higher level of organization of Baby's memory, above the bit. Baby's 32 words could have been effectively presented in 32 separately housed one-dimensional arrays of 32 lights each. This was an intrinsically one-dimensional display problem. It's only an accident that the Williams tube forced those individual lights, or word lights, into a rectangular array. Any arrangement of word monitors would have worked equally well.

I toyed with restricting a *digital image* to mean an arbitrary array of spots, without intention of being a two-dimensional *digital picture*, and omitting it from Digital Light. But "digital image" is such a common term that I found it almost impossible to adhere to the distinction, and certainly not in conversation. I do, however, consistently omit unintentional two-dimensional arrays of spots from Digital Light.

Digital memory is required for Digital Light. A computer isn't required, although that's nearly always the case in the modern world. And a digital memory in the modern world is nearly always that of a computer.

Digital Light doesn't require that an image be representational, nor that it be derived from continuous models or from the real world by sampling. For example, an image created with pixels individually selected by an artist with no guidance from a formal model of the real world or of an imaginary world is Digital Light. The original paint programs created images of this nature if the artist so chose. So colors could be selected abstractly, or emotionally, or with no purpose whatsoever.

The problem becomes moot if a display is a graphics display only and not a memory or a monitor of a memory. Every image on a graphics display is intended to be a picture and hence part of Digital Light.

A provocative email exchange with New Zealand computer historian Jack Copeland [emails, July 2014] helped me to sharpen and clarify what exactly I mean by Digital Light.

122:*Kilburn created First*: Since no collector plate obscures the images in these photographs, the tube was used in write mode (storage mode) only—that is, as a monitor not a memory. Kilburn claimed, "The digits [bits] are represented by charge distributions which exist on small areas of a c.r.t. screen, the charge distributions being arranged in the form of a two-dimensional array. This array is produced by a television type of raster, in which the digits of a line, and the lines of the raster, are scanned sequentially, each digit corresponding with a 'picture element'." See Kilburn (1947), section 2, or Williams and Kilburn (1949), 82.

122:*Kilburn created the*: For perspective, 16 by 16 is the size of a single square in an earlier image (in the Sampling chapter)—the one of fourteen pixels incorrectly magnified by 16 using the dirty pixel replication trick.

122:*Kilburn's purpose—clearly*: Williams (1975), 327, "The store was quickly developed to the state where one tube could store over one thousand digits [bits] (see Fig. 2)." Fig. 2 of the paper is the picture I've called First Light. On p. 328, Williams continued, "With this store available, the next step was to build a computer around it." See also Kilburn (1947), sections 1.4, 1.5, 4.2, 6. See also Williams and Kilburn (1949), a more formal presentation of Kilburn (1947), with his adviser's name inserted as first author.

Dai Edwards, email July 16, 2013, emphasized that the first two pictures were to test the Williams tube statically, then Baby was built around it to test the tube dynamically. See also Lean (2010), 68–69.

122:*The sober, suitably*: The computer science department building at the University of Manchester is now housed in the Kilburn Building. Kilburn became a Fellow of the Royal Society in 1965.

Freddie (Frederic Calland) Williams became a Fellow of the Royal Society in 1950 and Sir Frederic in 1976.

125:*But there's no*: Lean (2010), 87, interview with Dai Edwards, "there were a few people around, potential users, who were in the desperate state that actually needed the computer." Dai Edwards, email July 16, 2013, "However for some time the urgent topics of interest were to provide larger capacity storage, to deal with the problem of software generation, training people to use the digital computers, making the operation of computers more user friendly, providing better techniques of getting information in and out of the computers, making the system more reliable and as fast as possible, providing a computing service, etc. Picture presentations in these early days 1948–1952 would have required suitable software being developed and there seemed to be more pressing problems at this time. There did not seem to be anybody around then who was keen to tackle this issue." Email from Chris Burton, June 24, 2013, "[Geoff] Tootill [another early Manchester team member with Edwards] has made it clear that they were still working in an ethos of wartime 'crash programmes' where they did not spend much time relaxing." Presumably, other facilities had similar priorities at the time.

125:*Making pictures was*: Another "frivolous" activity with early computers was making sound or music if there was a speaker attached. See note 152:*Strachey's draughts program*.

125:*The Baby rebuild*: Chris Burton, correspondence of June 24 and Sept. 13, 2013, "A member of my team who built the 'Baby' replica was the first to come up with a moving image for the replica in [about July] 1997. We were all astonished! When we ran a programming competition a year later there were several entries [starting about Mar. 1998] exploiting the same techniques." Burton arranged for my visit to Baby at MOSI.

The upper 22 rows of the monitor displaying the scrolling PIXAR are 22 different one-dimensional images (each an image of one 32-bit memory word), while the bottom 10 rows are a two-dimensional picture (on an array of 32x10 spread pixels)—an animated picture at that. Each image of a memory word would be Digital Light of a more primitive form than the picture of the word PIXAR. Either that, or just disallowed, as we do here, because of no pictorial intent.

125:*It's still not*: Many groups omitted here would have to appear in a full intellectual history of the computer—but not of Digital Light. Leibniz, Babbage, and Lovelace have already been mentioned in a note of the previous chapter. Some omissions of more recent efforts are these: The Atanasoff-Berry machine of Iowa was an early electronic non-programmable calculator—so not a computer. J. Presper Eckert and John Mauchly might appear to be omitted but are treated here as part of the von Neumann group mentioned often [see also note 135:*Edsac's first cry*]. More accurately, Eckert and Mauchly worked on Eniac and were joined there by von Neumann. They next worked alongside von Neumann on Edvac but then went their separate ways, eventually leading to the influential Univac line [see note 127:*Programming is the*]. Aiken's machine at Harvard (the IBM Automatic Sequence Controlled Calculator) was electromechanical and had no conditional branch instruction. Zuse's machines, funded by the Nazis in Germany during the War and ferreted out of Berlin to the Americans in the last days of Hitler, were mechanical or electromechanical, and not stored-program (used paper tape [see note 120:*In the 1960s*]). But the point is that none of these other efforts contributed to the history of early Digital Light, so far as is currently known. Other such groups are omitted for similar reasons, or are treated in the text (Eniac, Colossus), or are mentioned in further notes.

126:*Software contributors who*: Biological mothers build bodies, physical stuff, and fathers contribute code only, DNA. But this metaphor quickly bogs down. Multiple mothers and fathers are a problem with it. And there's that gender reversal problem with the words *hard* and *soft*. And the fact that fathers of a field generally convey a heavier import than we want to imply. So I won't pursue it further.

127:*Programming is the*: Other Edvac team members were Herman Goldstine, Arthur W. Burks, J. Presper Eckert, and John Mauchly. Only von Neumann's name appeared on the Edvac report, despite the others. Von Neumann perhaps gets too much of the credit. Eckert and Mauchly, in particular, were serious players. They proceeded after leaving the Edvac project to build the Binac computer and then the Univac line of computers. The first Univac is often taken to be the first commercial computer in the US, the second in the world, but some claim that Binac was first [see note 135:*Edsac's first cry*].

127:*T. S. Elliot*: T. S. Eliot, *The Hollow Men*, 1925. The Shadow has been taken to be "whatever may turn a person from completion, from fulfillment, from contentment," but I use it here only to represent the gap between an idea and an actual object. It represents the tower versus stinks conundrum. [Quotation from Russell E. Murphy, *Critical Companion to T. S. Eliot: A Literary Reference to His Life and Work*, New York: Facts on File Inc., 2007, 257.]

131:*The von Neumann*: Turing didn't explicitly state in the Ace report that its architecture was equivalent to his universal Turing machine, but it's hard to imagine that he could have intended otherwise. There's a surviving fragment that makes it clear that such was his intention: Copeland (2005), 455–456, in a transcription of Turing's discarded notes, "In 'Computable numbers' it was assumed that all the stored material was arranged linearly . . . This was the essential reason why the arrangement in ‘Computable numbers’ could not be taken over as it stood to give a practical form of machine.” Then Turing proceeded to analyze addressing schemes to overcome the linear list problem. The problem is like that of digital storage in the last century which sometimes used magnetic tape for mass storage external to a computer, but random-access memory (RAM) for quick storage internal to a computer. They both work, but scrolling mechanically through a linearly organized magnetic tape is tediously slow compared to electronic, random access to main memory.

Copeland (2004), 383, a transcription of Turing’s 1947 Ace lecture: “We may say that the universal machine is one which, when supplied with the appropriate instructions, can be made to do any rule of thumb process [a systematic process in our terminology]. This feature is paralleled in digital computing machines such as the ACE. They are in fact practical versions of the universal machine.” See also pp. 378–379.

Dyson (2012), photographs insert, 136ff, contains a photo of the much-used bound copy of Turing’s “On Computable Numbers” at the Princetitute with this caption: “The Institute for Advanced Study’s copy was consulted so frequently it became unbound.”

Randell (1972), re von Neumann’s acknowledgement of Turing’s precedence, quotes American physicist Stanley Frankel, “I know that in or about 1943 or ’44 von Neumann was well aware of the fundamental importance of Turing’s paper of 1936 ‘On computable numbers . . . ,’ which describes in principle the ‘Universal Computer’ of which every modern computer (perhaps not ENIAC as first completed but certainly all later ones) is a realization.”

131:*Turing’s architecture differed*: A plan of Turing’s architecture isn’t instructive. A *register* is an especially robust small memory (holding say 32 bits), meant for frequent use. The von Neumann architecture specifies at least one register often called an Accumulator (because it accumulates partial results). Turing's architecture specified 32 registers, so a plan view would have 32 little boxes labeled register boxes of various names. Turing's registers included an accumulator and, in particular, a *stack pointer* (not Turing's term). Turing also proposed using a 1,024 bit delay line as a *stack* (not Turing's term) to handle hierarchy [see the next two notes]. His stack pointer worked in conjunction with the stack. There's nothing special about simply having more registers, but the purpose of the stack pointer is special, because it shows that Turing was aware of the profundity of hierarchy. He provided hardware support for it.

131:*Creating a software*: A program thus becomes a list of names of subroutines (mixed with instructions not placed in subroutines). Programmers say that they *call* a subroutine by using its name in a program. When the computer gets to such a name it jumps to the part of memory that holds the actual sublist of instructions that is the corresponding subroutine. The stack pointer, and the stack it points into, are the mechanism for keeping track of this possibly quite elaborate nested jumping.

131:*The programmer still*: Subroutines are actually much more powerful than this. What's particularly nifty about them is that they don't have to be stored in memory in the order that they are used. (This is where the metaphor of the book breaks down: The book's parts still have to appear in order.) Subroutines can be located in memory anywhere that's convenient—in the order written, say, instead of the order used. The purpose of the stack is to remember where in a program to return to when the computer jumps temporarily to the part of memory that holds the called subroutine. How does the computer know where to return to when done computing the subroutine? The return location is placed on the top of the stack (and the stack pointer points to it). It's like being in a long ticket queue at the airport when you decide to take a quick coffee break. You ask the person before or behind you to "hold my place, please" until you return. After you get your coffee, you know where to return to because it's marked with that person.

When the computer has finished execution of the subroutine's instructions, it needs to return to the last known place in the program that made the subroutine call, so that it can resume from there. The stack pointer points to the location in the stack that holds the address of the place to return to. (So the stack pointer tells you where to look in the stack for the name of the person holding your place in line. You call his name and he raises his hand, so you know exactly where to go to complete ticketing.) There is a stack of these return addresses because a subroutine can have subroutines of its own. (Suppose you need to take a toilet break while standing in the coffee line. You ask a person to hold your place there, in the coffee line. Her name goes on the stack above the name of the person in the ticketing line. And the stack pointer is made to point to her name in the stack.) The computer has to be able to return to the right place after the execution of nested subroutines, so there is a return address on the stack for every level of the nesting hierarchy. The return address for the most recently called subroutine is on top of the stack of addresses and gets used first (and then deleted from the stack). It helps to imagine hundreds of thousands of calls to subroutines, perhaps nested to a depth of several hundred layers, to understand the importance of hardware assist.

And there is another profundity of subroutines. A single subroutine can be used many times by one program, called from many different places in the program. Subroutines can also be used by different programs. They can be stored in libraries of often used subroutines that are then available to other programmers.

132:*Surely Turing's architecture*: Carpenter (1993), 231.

132:*Sir Charles Darwin*: Turing's 1946 report on Ace [Turing (1945), Copeland (2005), ch. 20] was begun in Oct. 1945, probably completed before the end of 1945, and formally presented Mar. 19, 1946 [Simon Lavington, personal communication, Sept. 2013]; see also Copeland (2005), 369. Eniac was announced Feb. 14, 1946, but J. R. Wormersley of the NPL had already seen it in America, and the Edvac report. He had met Newman and had read Turing's "On Computable Numbers." It was he who recruited Turing and convinced his superior at the NPL, Darwin, to hire him [Hodges (1983), 305–307].

132:*One problem was*: Hodges (1983), the chapter "Mercury Delayed"; Copeland (2005); Lavington (2012), 13, 80. Another problem was probably Turing's confusion of architecture with design. In other words, he worked at a surprisingly low level, close to the implementation details. His Ace report included long calculations on delay line physics, circuit diagrams, and a cost and space budget. In particular, the memory he specified for Ace was the delay line, which could only be accessed sequentially. If it held 1,024 bits, then the computer could only get at them in the order they came out of its end. This led to all sorts of clever design choices (not Turing's) that made the machine fast but also led to obscure and difficult realizations. Since these realizations were ads for the architecture, the architecture didn't fare well (assuming it was available for consumption, which it apparently wasn't). Pilot Ace didn't ultimately use Turing's design [Copeland (2005), 114].

132:*Pilot Ace became*: Baby was formally the Small-Scale Experimental Machine at the University of Manchester. Ace was the Automatic Computing Engine. Turing worked mainly on Pilot Ace, the prototype of Ace, although he did write the programming manual for Ace.

My timeline follows. It's not to be taken as gospel. It's derived mainly from Lavington (2012), Copeland (2004), and Goldstine (1972). 1. Baby, June 21, 1948 [UK]; 2. Eniac+, Sept. 18, 1948 (possibly July 12, 1948) [US] [not Eniac]; 3. Edsac, May 6, 1949 [UK]; 4. [Manchester] Mark I, Apr., May, or June 1949 [UK, so in a dead heat with Edsac, but the dates are varied and soft, so I give the nod to Edsac]; 5. Binac, Aug. 1949 [US, but this is controversial, with proponents claiming it ran Feb.–Apr. 1949, and opponents claiming it never ran [see also note 135:*Edsac's first cry*]]; 6. Csirac, Nov. 1949 [Australia]; 7. Seac, May 1950 [US]; 8. Pilot Ace, May 10, 1950 [UK]; 8. Swac (Zephyr), Aug. 1950 [US]. This illustrates the uncertainty of early computer dates. The jockeying for position hasn't settled yet. It's clear, however, that 1948–1950 was the crucial period.

It's not clear where Whirlwind (often called Whirlwind I) at MIT should be placed. The date given for it is usually Apr. 1951, when it finally went fully online, but a careful reading of the Whirlwind Bi-Weekly Reports for 1947–1951 shows that a lot of programming of this machine in early stages of its development began before 1951. For example, the report for Aug. 19, 1949, has this entry: "An important milestone was passed on August 9th when the first program was run in the Whirlwind I computer, using central control, test storage and the arithmetic element. A few days later five registers of flip-flop storage were added and a program was successfully run which used all 32 storage registers which were available. . . . This program has been in the machine for several days and on several occasions has run for a period of 45 minutes without errors" [Whirlwind Bi-Weekly 889, Aug. 19, 1949]. This was not the final configuration of the Whirlwind, but seems an important event nevertheless. [See also note 136:*To look at.*] If we call the lesser machine, using only the temporary "test storage," Whirlwind– ("Whirlwind minus"), then Whirlwind–, Aug. 19, 1949, appears in the list above in position 5 or 6. Charles Adams recalled (Adams (1987), 787–788), "By 1950, the central processor was in operation, but due to difficulties with the specially-designed electrostatic storage tubes which were to provide the main memory, our only hands-on experience with Whirlwind for many months involved the use of a so-called test storage . . . with each bit represented by a toggle switch."

As before, I promote all acronyms to names here. For reference, however, Edsac was the Electronic Delay Storage Automatic Calculator. Binac was the BINary Automatic Computer (and Univac the UNIVersal Automatic Computer). Csirac was the Council for Scientific and Industrial Research Automatic Computer. Swac was the Standards Western Automatic Computer (for the National Bureau of Standards (NBS) at Los Angeles), and Seac was the Standards Eastern Automatic Computer, also for NBS.

Harry Huskey worked on Turing's Ace design in 1947, trying to simplify it, but his work was stopped. He reported that "morale in the Mathematics Division has collapsed" [Lavington (2012), 13]. He referred to the Mathematics Division of the National Physical Laboratory (NPL) where some of the work on Ace was carried out.

132:*Before he left*: Since Turing had created the architecture for Ace, he could and did write a programming manual for it—and hence for its prototype, Pilot Ace. Thus he was a software contributor to both machines. [Copeland (2004), 368–369]. The story is actually more complex than indicated. Deuce was the first machine derived from Pilot Ace, delivered in 1955. Ace (or Big Ace, as it was called) was finally begun in 1954 and delivered in 1958. Also, Pilot Ace as actually realized differed substantially from Turing's design.

See note on Turing's use of *programming* in the previous chapter, and Copeland (2004), 388.

133:*Baby was born*: Williams and Kilburn, 1948. As usual in the contentious history of computers, not everybody agrees that Baby was first. See the discussion of Eniac+. An excellent source for details about Baby is Copeland (2011), Part 2.

133:*Baby's first program*: Lavington (1998), 17, mentions Turing's early Baby code, a long-division routine. It was corrected by Geoff Tootill, so Tootill was another software contributor to Baby. Chris Burton, who rebuilt Baby, says about Tootill, in a communication of Sept. 9, 2013, re the construction phase of the original Baby, say Oct. 1947 to June 1948: "He probably did as much design work as Tom K[ilburn] in that period, and he and Tom spent all their time on the project. FCW [F. C. Williams] had other duties so was more supervisory in an admin sense. Technically the machine was designed and built and made to work predominantly by Kilburn and Tootill." So Tootill was a hardware contributor to Baby too [see Williams, Kilburn, and Tootill (1951)].

133:*But Williams and*: Williams (1975), 328. Supporting this argument is Anderson (2004), 39, "While the conception of the Baby may thus be traced back to Bletchley Park, it was by no means a one-man effort. The Manchester machine was a by-product of the theoretical genius of Alan Turing and the embodiment of principles enunciated by him in 1936. However it would not have come about without the drive and skill of Max Newman. . . . On the implementation side, the contribution made by Freddie Williams in developing the CRT memory was absolutely crucial and the accomplishments of Tom Kilburn were, if anything, even more important." Kilburn (1949), "I wish to acknowledge my indebtedness to Prof. M.H.A. Newman, and Mr. A. M. Turing for much helpful discussion of the mathematical requirements of digital computing machines."

Countering this somewhat is testimony of Prof. David "Dai" Edwards [Lean (2010), 58] that Williams was simply being generous: "he was very generous in his acceptance of what other people had contributed, and I think this comes through in later life after he'd done this work on computers and it was way behind him, he was interviewed by various people and of course they asked about Turing—you know, what Turing and Newman had contributed. And he would make a generous comment like he knew nothing about computers and Newman and Turing had explained to him about there were addresses which did, you know, this, that and the other, and so they were very helpful. But, you know, his article in the first Royal Society paper actually said all that—you know, referred to these addresses and all that approach, so it's actually down in black and white. And the actual contact and contribution that Newman made, I think was very limited but very specific and very direct, certainly in the first instance." Dai was an early member of the Manchester computing laboratory, joining Sept. 13, 1948 [Lean (2010), 60]. The Royal Society paper was published in 1948, so was probably written after Newman joined Manchester but before Turing did.

134:*Kilburn's PhD dissertation*: See Kilburn (1947) bibliography. Another possible Turing influence was the Ace report he wrote in 1945–1946 [Copeland (2005), ch. 20]. Kilburn's criticism of Ace might have been aimed at its storage device (a delay line) not its architecture. Another possible von Neumann source could have been the *Preliminary Discussion of the Logical Design of an Electronic Computing Instrument*, by Arthur Burks, Herman Goldstine, and John von Neumann, issued June 28, 1946, about the Maniac at the IAS (Princetitute).

The first meeting between Williams and Turing perhaps didn't go well, which might also have caused Williams to lean toward the Yanks. On Nov. 22, 1946, Turing tried to tell Williams, an accomplished engineer, how to design pulse circuits and sparks flew [Lavington (2012), 96].

Another source of confusion at Manchester was Turing's title. Newman hired him as Assistant Director of the Computing Laboratory, but it was an empty title. Oddly there was never a Director.

And Baby was built in a room called the Computer Laboratory. It appeared that Turing was in charge of Baby, but he wasn't.

Actually Baby was built in the Magnetism Room of the Department of Electro-Technics (later Electrical Engineering), which was dubbed the Computer Laboratory in the Williams and Kilburn (1947) note to *Nature* [Chris Burton, personal communication, Sept. 2013].

134:*Baby thrived and*: On the other hand, computer historian Brian Randell, in an email of Aug. 8, 2014, reminds us that "[Newman and Turing] had, almost uniquely among post-war computer pioneers, crucial first hand knowledge of the success with which digital electronics had already been used to produce reliable semi-programmable computers, of a size and complexity comparable to that planned for the first post-war computers." This experience was derived from their time at Bletchley Park.

Mark I is more fully named Manchester Mark I to distinguish it from Ferranti Mark I. Lavington (1998), 17–18, mentions that "a version was working about Apr. [1949]." The problem in dating Mark I seems to be a result of the machine's being a moving target, its specifications changing fluidly. The range Apr.–June 1949 is used by a variety of sources, so I've chosen June conservatively for this book.

134:*Mark I soon*: The February date was for the delivery to the University of Manchester. The public unveiling was in July. *The Guardian*, Manchester, July 9, 1951, conflated Newman and Williams, referring to Williams as F. C. Newman. Madam was an alternative name for both Mark I [Lavington (2012), 38] and Ferranti Mark I [MOSI, Ferranti Archives, "officially opened for operation 27 July 1951 Received publicity as Madam (Manchester Automatic Digital Machine)"]. There is contention about whether Ferranti Mark I was the first commercial computer, with a Zuse (German) machine, Z4, claiming priority and also the Univac from Eckert and Mauchly. We can be fairly certain that Madam was the first commercial machine that featured digital pictures. Turing's programming contributions were made with the full-time help of Cicely Popplewell [*Alan M. Turing (1912–1954)*].

134:*Mutual enmity very*: Copeland (2012), 132, cites a memo from Turing in the Turing Archive at http://www.alanturing.net/turing_womersley/, accessed Apr. 4, 2020.

134:*And Wilkes wrote*: Lavington (2012), 25, 81–82; Hodges (1983), 352–353. Maurice V. Wilkes was made a Fellow of the Royal Society in 1956, became Sir Maurice in 2000, and was made a Fellow of the Computer History Museum in the US in 2001. He was awarded the Turing Award (!) in the US in 1967. The official description of his award is incorrect, claiming that Edsac was the first stored-program computer.

The mutual disrespect is supported by an interview with David Hartley by Alan Macfarlane [Macfarlane (2017)], from the transcript: "33:5:09 At that time I remember nothing being said about Alan Turing; Turing was not a person who belonged to the maths lab in any sense; he didn't get along well with Maurice anyway; the heart of it was that Turing was a mathematician and Maurice was an engineer, although he had been a mathematician and they both sat the Tripos at the same time; I think Maurice always thought he got a better mark than Turing did; so Turing was hardly talked about in the maths lab in my day; he is talked about now as the subject has grown and so on, but Turing wasn't part of my life or the labs life in those days; he did influence Maurice but not necessarily in a positive way; they didn't like each other, they were very different sorts of people; Maurice's interest in life was to build computers to use them for doing computation which was far from what Turing wanted; I don't know how to analyse that but it is all history of course."

Hartley's doctoral adviser was Wilkes. Harry Huskey recommended that Hartley write compilers. Hartley, with Christopher Strachey and others, developed the programming language CPL, which became BCPL (which was the first high-level language we used at the New York Institute of Technology), then BCPL led to B and then C at Bell Labs. Hartley ran the University of Cambridge Computing Service, 1970–1994. See Macfarlane (2017), transcript section 34:51:07, which mentions Huskey and Strachey, and section 45:00:16, which mentions CPL, BCPL, B, and C.

135:*Edsac's first cry*: Edsac's birthdate comes from the image of a journal entry [Edsac99, Lavington (2012), 28]. There's an argument that Binac, another machine begat by Edvac, was the first American computer, becoming operational in Aug. 1949, slightly after Edsac. It was built by J. Presper Eckert and John Mauchly, who first worked on Eniac, then on Edvac, then started their own company which commercialized Univac (begat by Binac). The problem is that there's controversy about whether Binac ever actually became operational. Its customer, Northrop, was displeased with the product. See [Stern (1979)] for details and the argument for its being counted as a first.

135:*I attended the*: The gist of the Edsac team's argument was this: Baby was just a toy, built to test the Williams tube; Edsac was serious. Edsac does have a good claim to being the first complete computing service. It was where many of the most basic programming ideas were first developed, and promulgated in the influential book by Wilkes, Wheeler, and Gill (1951). The Whirlwind Bi-Weekly Reports mention exchanges with the Edsac team on software issues, particularly subroutine packages.

Lean (2010), 90, in an interview with Prof. David "Dai" Edwards of the Manchester team, Edwards says, "Wilkes thought it was hilarious as it were that, you know, we described this as a significant event, but—but we think it was."

135:*In America, von*: Some would argue that von Neumann gets too much credit in this suggested summary. Other Edvac fathers were Herman Goldstine, Arthur W. Burks, J. Presper Eckert, and John Mauchly. As mentioned previously, only von Neumann's name appeared on the Edvac report, despite the others. Von Neumann was quite aware of Turing's 1936 paper and gave it enthusiastic support as fundamental [Copeland (2005), 115]. And Turing's Ace report of 1946 (probably completed in late 1945) mentioned the slightly earlier Edvac report, to close the circle.

135:*As if Maniac*: Edvac was the Electronic Discrete Variable Automatic Computer. Maniac was the Mathematical Analyzer, Numerical Integrator, and Computer, named to make fun of this naming style for computers. Johnniac (not shown in the chart), built by the Rand Corporation in 1953, was the similar joking acronym for John von Neumann Numerical Integrator and Automatic Computer. And Emerac in Twentieth Century Fox's *Desk Set* was the Electromagnetic MEmory and Research Arithmetic Calculator.

135:*But the naming*: George Dyson, email Apr. 22, 2013, stated that the IAS objected to their machine being called Maniac, but Los Alamos didn't mind using the name for the sibling machine built there about the same time. The engineers solved this problem by referring to the IAS machine as Maniac–0 and the Los Alamos machine as Maniac–1—off the record, of course. Publicly the Los Alamos machine was Maniac and the IAS machine was, awkwardly, "the IAS machine."

Whitman (2013), 50, "The party at our house had as its centerpiece an ice-carved model of the computer, which my father dubbed the MANIAC but later was given a less playful designation as the IAS machine." Author Marina von Neumann Whitman is Johnny's daughter.

136:*Von Neumann noticed*: Herman Goldstine (1972), 233, "During 1947 von Neumann realized that the lack of a centralized control organ for the Eniac was not an incurable deficiency. He suggested that the whole machine could be programmed into a somewhat primitive stored-program computer. He turned the task over to Adele Goldstine, who worked out such a system and passed it along to Richard Clippinger . . . He and his associates made certain emendations and put the final touches on the idea, and on 16 Sept. 1948 the new system ran on the Eniac. Although it slowed down the machine's operation, it speeded up the programmer's task enormously. Indeed, the change was so profound that the old method was never used again." This "somewhat primitive" stored-program computer is called Eniac+ here since it was an improved version of the old Eniac. Goldstine, however, earlier in the same book, p. 196, gives Edsac credit for being the first stored-program computer. Perhaps he was invoking a "seriousness" requirement, "somewhat primitive" being in the same league as babyhood. Eniac was originally at the Moore School in Philadelphia, but the Eniac+ conversion was completed at the Aberdeen Proving Ground in Maryland.

The latest paper about (what I call) Eniac+ as I approach publication of this book is Neukom (2019), which dates the improved machine to Sept. 16, 1948, using Goldstine's date, and concludes with this statement: "The revised ENIAC was one of the first computers in the US to employ the principle of the stored program. The very first such computer, of course, was the Manchester Machine at the University of Manchester in England, first operated on 21 June 1948, a few months before the revised ENIAC." This paper too argues the origin of the stored-program concept only among computer engineers, missing Turing's primacy.

136:*Goldstine's date would*: Haigh et al. (2014), Part 2, 48. See also Haigh et al. (2016). Not only is this a battle in the Brits versus Yanks tradition, but also apparently in the stinks versus tower tradition. Haigh et al., Part 1, also deny Turing credit for the stored-program concept, presumably because it wasn't hardware.

In their analysis of the stored-program concept, Haigh et al. consider a machine that merits attention as a possible non-electronic computer, the IBM SSEC (Selective Sequence Electronic Calculator) from Jan. 1948 which used paper tape as its main memory. Bowden (1953), 174, suggested, "It was probably the first machine to have a conditional transfer of control instruction." This machine was known popularly as Poppa [see note 120:*In the 1960s*].

136:*But in a*: George Dyson, email Aug. 16, 2017, shared a photocopy of the Ulam letter to von Neumann, dated May 12 (not 10), 1948. The program was the famous Nicholas Metropolis Monte Carlo method.

George Dyson, email Oct. 25, 2017, forwarded this excerpt from a letter from von Neumann to Carson Mark, dated Mar. 13, 1948: "The Monte Carlo problem is set up and ready to go. We were promised that we can begin revamping the ENIAC for our purposes on Monday, March 15th, but there has again been a delay which I think will only be one week. It looks now that Nick will be in Aberdeen beginning March 22nd, and that if the ENIAC is 'reorganized,' which I think should not take more than two weeks, the work on Monte Carlo can begin soon." It's hard to know exactly what this means, but it seems to fix the minimum birth date of Eniac+ at two weeks past Mar. 22, 1948, or about Apr. 6, 1948, if the first running of Monte Carlo is defined to be its birthday. But we can't tell from this letter if the two weeks estimate was accurate. Apparently not, considering the later Ulam letter.

136:*To look at*: Goldstine (1972), 324, describes an international computer conference held in Paris in 1951, with 25 countries represented. In a remarkable appendix, "World-wide Developments," 349–362, he details activities in 16 countries in the 1940s and 1950s, about 10 of which include 1953 or earlier. Bowden (1953), ix: "A rough count showed that about 150 digital computers are being built at this moment, most of them in universities and other research establishments." This is a remarkably complete book on the early history of computers. A serious omission was the developments at Bletchley Park, because the Official Secrets Act blocked them. Another excellent source is Lavington (2012). His book (pp. 8–9) succinctly summarizes many of the early developments, and gives dates. Copeland (2004) also provides many early developments and dates. Also see Dyson (2012) and Davis (2000), 177–183.

Whirlwind (formally called Whirlwind I) begat Whirlwind II which was never completed but which begat Sage. Whirlwind, made of vacuum tubes, also begat TX-0, its transistorized version. TX-0 begat TX-2. (TX-1 was overly ambitious and was abandoned.)

The Whirlwind computer is "officially" dated to Apr. 1951, but it had been in development from Dec. 1947. The date of the first Whirlwind bi-weekly report was Dec. 15, 1947, and the last was Dec. 21, 1951 [Whirlwind Bi-Weekly 185 and 1361]. Mention is made of a final report being due in the Whirlwind Bi-Weekly 1209, Apr. 27, 1951, but the nature of the bi-weekly reports doesn't change around that date. However, the project archives contain this interesting record for July 7, 1949: "The first program using electrostatic storage [intended to be its main memory, as opposed to "test storage"] with the rest of Whirlwind was run July 7th. One of the simple display problems was used and an error-free run of 1¼ hours was made before the program was removed" [Whirlwind Bi-Weekly 875, July 8, 1949]. Although the machine still had many problems at this early date, many programs were run on it in the late 1940s, as reported in the bi-weekly reports. [See note 132:*Pilot Ace became*.]

137:*The actual number*: The "googol" misspelling story is almost "too good to check," but it's backed by Hanley (2003), citing Google cofounder Larry Page: "'But we realized BackRub [as a search engine name] wasn't the world's greatest name,' Page said. Instead, he and [his cofounder Sergei] Brin looked through Web sites and URLs before finally stumbling across a list of very large numbers. The word "google" was at the top. | A friend later pointed out, however, that the number is actually spelled "googol." But the misspelling had two o's and ended with 'le' so they decided to stick with it, Page said. Plus, the Google domain name was still available."

[Math] The number of patterns in a computer with a memory of 1,024 bits (Baby, for instance) is 2^{1024}, which is roughly 10^{309}. We don't have names for most numbers that large (a 1 followed by 309 0s). A googol, 10^{100}, however, is in the ballpark. A googol cubed is 10^{300}, and $10^{309} = 10^9 10^{300}$. So 1,024 bits can store about a billion googol-cubed patterns. But 1,024 bits is a very small computer memory. Modern computers are approaching exabyte memories, with on the order of 8×10^{18} bits. The number of patterns is 2 raised to that number, or about 10 raised to the 10^{19} power. That's far greater than a googol, or 10 raised to the 10^2 power, but far smaller than a googolplex, or 10 raised to the 10^{100} power.

139:*Luckily, an important*: Early cathode-ray tubes normally used electric field deflection. If the ray passes between two plates with a voltage between them, then the ray's charged particles are attracted toward one of the plates. It bends and the amount of bending depends on the voltage between the plates. One set of plates controls left-to-right bending, another up-down.

139:*With the aiming*: Another name for calligraphic display is *vector* display. In math a vector is a line that goes from one point to another. It has a direction, in other words, and it can be any direction. A vector display is free to draw a line from anywhere on its screen to anywhere else. The letter S, for example, could be drawn as a sequence of short vectors along the path shown on the left (figure 4.8). If there was a short break between each vector, then the result might appear as the S on the right.

Strictly speaking, dot displays that could be written in random order form a separate hardware display category. The dots of a dot display are often, if not always, located on a grid, like a raster display, but not addressed in raster order. I class them here with calligraphic displays because of the random order (vs raster order). Hardware people don't so classify them.

139:*Another kind of*: Raster displays can write only horizontal lines, only left to right, at regularly spaced vertical positions. Raster-order scanning requires that the cathode ray return from the end of one row to the beginning of the succeeding one. The beam is turned off while this happens, so nothing is seen (no phosphors are caused to glow) during the return sweep between rows.

A famous form of raster display is old-style, or pre-digital, television which used a cathode-ray tube with magnetic aiming. The energy of the cathode ray varies as it moves along each row, and the brightness follows suit along the row of phosphors illuminated by the ray. When the whole rectangle is painted out, very fast (1/30th of a second, say), one sees a two-dimensional field of varying brightnesses—a picture—lingering there.

The vertical spacing of a raster array of spots doesn't have to match the horizontal spacing. In fact, in the early days, they often didn't match, a cause of many headaches. That is now a thing of the past. Equal spacing in the two dimensions is very convenient.

141:*The calligraphic versus*: Although calligraphic displays are diminished in this biography of the pixel, we don't abandon calligraphic *style* computer graphics and shall consider it at length. The distinction is that it's represented conceptually inside the computer—in Creative Space—in smooth, continuous, omnidirectional fashion, but no longer delivered visually to us that way in Display Space.

I agree with reader Richi Chopra (email of Oct. 6, 2022) that the last sentence of this paragraph should be improved to: "The Sampling Theorem made raster display with spread pixels as beautiful as calligraphic display with smooth strokes."

141:*Zworykin's group designed*: Dyson (2012), 68–69, 103, 148. Rajchman originally intended that Selectron would store 4,096 bits, but he reduced its capacity for engineering considerations to 1,024.

142:*The Williams tube*: Bletchley Park had Max Newman's visitors book on display (on June 24, 2013, when I visited), for visitors to his Manchester home. The page on display listed Norbert Wiener (who coined the word *cybernetics*), Alan Turing (three times), and Garrett Birckhoff (leading algebraist and friend of von Neumann, with high interest in computers), among others. At the bottom of the page just under the last Alan Turing visit on the page, on July 2–5, 1948, was Julian Bigelow followed by Mary M. Bigelow (his wife), on July 19, 1948.

143:*The story Williams*: As told by computer historian Simon Lavington in Lavington (1998), 22. He also recounts how the trip was to be all expenses paid by IBM. A UK company (NRDC, the National Research Development Corporation), which was set up to license government research to industrial partners, found out about the trip. They frantically got in touch with Williams as he was about to sail and told him not to accept IBM's money, that they would pay for everything. He remained loyal to Britain in all dealings with IBM, which eventually licensed the Williams tube for use in its first commercial computers, including IBM 701, its first.

Watson became chairman of IBM in Sept. 1949. He created the "THINK" slogan in 1911, and it became pervasive in the 1930s.

143:*The collector plate*: The working details of Baby (and hence the Baby rebuild) are courtesy of Chris Burton, emails of July 2014. Many other details can be found on the *Computer 50* website.

143:*Another cathode-ray tube*: Baby actually had three Williams tubes, one each for the memory, control, and accumulator of its von Neumann architecture. The monitor could be switched to display any of the three. Similarly, the Yanks' Maniac featured 40 Williams tubes, but it also had an uncovered tube—a Williams tube without a read circuit—that could selectively monitor any one of the other 40.

144:*The Yanks' Whirlwind*: The intended Whirlwind memory tube was to be an adaptation of a tube designed by Andrew V. Haeff. It was Williams-like in that it stored bits on a CRT screen, but it used multiple beams for different modes instead of one beam in multiple modes. Where the Williams tube's single beam did reading, writing, and refreshing, the Haeff tube had a read beam, a write beam and a "flood" or "holding" beam. The Whirlwind team had many problems with this storage device and ultimately went instead with the first core memory, built of small magnetic loops, or cores.

From the outset the Haeff tube was also intended to be a memory for a computer. It was first announced in popular magazines, *Electronics* [Haeff (1947a)] and *Popular Science* [Haeff (1948)]. The latter informal presentation contains a photograph of the Haeff tube displaying a picture of "The Memory Tube" in handwriting on a card, but it gives no details other than that the signal originated in a television-like, or analog, mode. It has an illustration showing how the Haeff tube might trace out the letters PS as dots in apparently calligraphic order, but it states that the reading beam moved in zigzag, or raster order. There was apparently no computer behind it. The formal presentation in a learned journal, also in 1948, doesn't contain pictures. It does state that that the tube design was "suitable for use as a memory device in an electronic computer" but was "still in the development stage." See Copeland et al. (2017) for further details on the Haeff tube, and see Copeland and Haeff (2015) for more on Haeff.

144:*Because it took*: The temporary test storage device for Whirlwind consisted of 32 words (16 bits each) of toggle switches and five words of vacuum-tube memory organized into so-called flip-flop circuits holding one bit each [Adams (1987), 787–788].

144:*Here's an unheralded*: Photograph no. F-751, "WWI on Demonstrator/Static Display," nearest date above May 20, 1949, in the archive spreadsheet, nearest date below June 2, 1949, in box 2, folder 1 of the MITRE Corp. Whirlwind photographic archive, Bedford, MA.

145:*To determine which*: Taylor (1989), slide 3, p. 20, "We started in 1948 with 256 points of light," "So we invented the light gun . . . This was late '48 or early '49," "By erasing selected spots [with the light gun] the MIT logo was formed." Then confusingly, "The dates on the back of these [unspecified] slides are 1947 and 1948," so 1947 can't apply to the "MIT" picture. This was followed by a story about Edward R. Murrow visiting "In 1949, or '48" to see his name similarly picked out with the light gun. But Gilmore (1989), slide 3, p. 40, "I started my computing career as a system programmer at the MIT Digital Computer Lab in October of 1950. Working under the guidance of Charlie Adams, I developed the early mnemonic and symbolic assembly programs for the Whirlwind Computer." The Gilmore testimony directly contradicts the Taylor evidence which dates the Adams-Gilmore collaborative graphics (bouncing ball) at 1949 (cf. note 155:*The players would*), bringing all the Taylor stated dates into question.

A visit Oct. 11, 2016, to the Whirlwind photographic archives, held at MITRE Corp., Bedford, MA, with archivist Krista S. Ferrante, revealed the actual dates as follows: Taylor's slide 1 is F-637, ST Reliability tester display A, box 1, folder 8, undated [but 1949 is estimated by me and Krista Ferrante]; slide 3, the "MIT" slide, is F-1485, Light Gun in Operation, box 2, folder 8, Apr. 8, 1952; slide 5 is F-1070, Quartic Curve with Axes, box 2, folder 4, May 18, 1950; slide 6 is F-1416, Bouncing Ball Display, box 2, folder 8, Dec. 13, 1951; slide 7 is F-1940, Bouncing Ball Display, box 3, folder 5, dated between May 28 and June 10, 1953; slide 8 is F-1396, Antenna Display Intermediate Condition, box 2, folder 7, Dec. 3, 1951; slide 9 is F-1406, Antenna Display Final Condition, box 2, folder 8, Dec. 3, 1951. So all pictures in the Taylor talk date to 1950–1953 [with the exception of F-637 with estimated date of 1949], not 1947–1950. The two antenna pictures are from a thesis by "Dom Combelec" according to Taylor (1989). He was actually Donn Combelic [Whirlwind Bi-Weekly 1233, June 22, 1951, p. 17, and 1290, Sept. 28, 1951, p. 24].

On this same MITRE we determined that the Murrow visit was in 1951. Evidence was picture F-1414, "Hello Mr. Murrow" Display, box 2, folder 8, Dec. 13, 1951. The documentary of Whirlwind aired on Murrow's *See It Now* program of Dec. 16, 1951, backs this up [Murrow (1951)].

Note added 29 Apr. 2021 (book in production but not yet published): Guy Fedorkow contacted me about a Whirlwind interactive graphical program he has simulated (Fedorkow (2021). It is based on report M–1343 (Israel (1951)), dated 3 Dec. 1951 (but contains a chart dated 21 Dec. 1951), which describes the display of two dots, one a target aircraft, the other an interceptor aircraft. A user selects, with the Whirlwind light gun, which dot is to be the target and which to be the interceptor. The report suggests that the program was working in "the early summer of 1951." And it mentions report E–2024 re the light gun. Guy verifies, from the Whirlwind biweekly report

M–1250, that there was such a report: "E–2024, 'Light Gun', H. J. Kershner, June 28, 1951." These dates narrow the timeframe around early interactive graphics on Whirlwind. This is to be compared to the 15 May 1951 date on Strachee's draughts program in England (but which might not have yet been graphical on that date). Clearly, interactivity was being entertained at about the same time in both places.

146:*Whirlwind– programmers, led*: Norman Taylor wrote, in Whirlwind Bi-Weekly 899, Sept. 16, 1949, 1, "The computer using test storage is essentially complete . . . | The addition of Special Display equipment to the system made possible the plotting of several simple curves on an oscilloscope. As the computer solved the value of discrete points on a family of parabolas, each point was plotted on the display oscilloscope. This display demonstrates an important means of output and a very effective method of using a digital computer to give essentially continuous information to an observer. The same technique was employed to display powers of x. The speed of WWI is notable in these demonstrations. The parabolas were plotted in about 1/30th of a second a 3 power of x in 1/60th of a second. Some 500 points were plotted for each sweep of the scope totaling respectively 15,000 and 30,000 calculations and plots per second for the two problems."

MITRE Whirlwind archive photos back this up: box 2, folder 2, F-841 and F-842, Oct. 5, 1949, show x, x^2, and x^3 for small and larger increments. There were then many plots. For examples—that don't repeat any in the note above—see F-873, Dec. 5, 1949, dampening factor; F-898, Dec. 28, 1949, driving functions and responses; F-921, Feb. 20, 1950, cubic curve with axes; F-973 and F-974, Mar. 6, 1950, computed surfaces [!]; F-1297, Mar. 19, 1951, polynomial roots; F-1395 and F-1405, Dec. 3, 1951, antenna display initial and final conditions; F-1413, Dec. 13, 1951, 7th degree polynomial; F-1415, bouncing ball display, Dec. 13, 1951, all in box 2, folders 2–8. Also, Box 3, folder 5, F-1490, between May 28 and June 10, 1953, superimposed bouncing balls with hole in floor.

146:*Most of the*: Pictures F-973 and F-974, Mar. 6, 1950, display computed surface, box 2, folder 3, in the Whirlwind archives. These are not surfaces of three-dimensional objects, which occupies modern computer imagery. They are families of mathematical curves displayed using a third dimension for the parameter that varies. There is no perspective.

148:*The oscilloscope was*: A typical graphics workstation as late as the 1970s had three displays, a text display, a calligraphic display, and a raster display.

An oscilloscope, in the normal use of that term, is an indispensable design tool for electronic engineers, used to display waveforms—typically oscillating regularly as do Fourier waves—at various points in a complex circuit. The Whirlwind use of the word implies that engineers on that project adapted such a tool for display of a computation. Although an oscilloscope can calligraphically paint out continuous analog curves, Whirlwind– pictures indicate that its oscilloscope display was used solely to draw dots along continuous curves, apparently at equal time intervals or equal parameter intervals but not necessarily at equal spatial intervals.

Gruenberger (1967), 106, "To the best of the authors' [F. V. Wagner and J. LaHood] knowledge, the earliest 'proper' graphic output [not via a printing device], directly from a digital computer, was successfully produced by the Whirlwind at MIT, in late 1949. A five-inch laboratory CRT scope was used. Charlie Adams displayed, on X/Y coordinates, the solution to a differential equation." First Light, on Baby's disply in 1947, clearly predates this.

Adams (1987), 787–788, "By 1950, the central processor was in operation, but due to difficulties with the specially-designed electrostatic storage tubes which were to provide the main memory, our only hands-on experience with Whirlwind for many months involved the use of a so-called test storage . . . with each bit represented by a toggle switch." He goes on to say, "Output . . . [comprised] more importantly, a device unique to Whirlwind among early machines and crucial to its air defense applications—a cathode-ray-tube (CRT), the beam of which could be deflected to arbitrary *x* and *y* coordinates by output instructions."

148:*Harry Huskey intended*: Image courtesy of the Computer History Museum, Mountain View, CA, dated by the museum ca. 1949, gift of Mac McLaughlin, object ID: 102710661. Huskey was installed as a Fellow of the CHM in 2013.

148:*I met Dr.*: The meeting at the museum was brief, but I also met Harry's son Doug. Email from Doug Huskey, Aug. 25, 2013, "Dr. Huskey says that the Zephyr image was turned on manually bit by bit as an early test of the tube before it was fully functional. He was the one that toggled it in, and thinks it was between 1948 and 1950, probably closer to 1948." And, "In fact, in reconstructing the sequence Dr. Huskey thinks it was in the later part of 1948 that they made the image."

149:*The Yanks' Selectron*: The Selectron image (figure 4.15) was found by George Dyson in what appears to be two pages of an internal RCA report ca. 1948. We don't otherwise have a citation for that report. George courteously shared the report and picture with me.

149:*J. Presper Eckert*: Eckert et al. (1950) contains the digital image in figure 4.28 recorded off the face of his cathode-ray tube memory (complete with glare), of rather poor quality [I've enhanced it slightly], captioned "Photograph of 1,200 spots." I don't call it Digital Light since there was no intention that it display a two-dimensionally coherent picture. It's purpose was to show the contents of a linear array of computer words, so it could just as well have been an array of separated one-dimensional rows of lights, or even one long one-dimensional row of lights. Imagine a separation of, say, five inches between each two rows of the following image. It conveys the same information to the engineers as to the state of the memory bits.

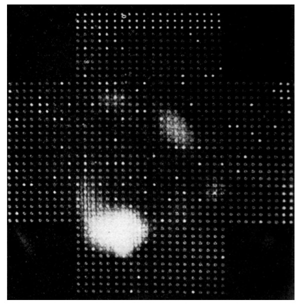

Figure 4.28

The text of the paper (first presented in Mar. 1949) suggests that this was from work done "almost four years earlier," about 1945, but the date is soft. The paper mentions, "Work very similar in nature to the developments described in this paper has been carried on in England under the direction of F. C. Williams of the University of Manchester."

The curious cross-shaped spot layout is similar to an image in Bowden (1953), 148, but the spots in that case are located on an unusual triangular grid. Its date isn't established, other than before the 1953 publication.

I thank Jack Copeland who brought Eckert's work to my attention in an email of July 2014.

150:*Although Eckert failed*: Lukoff (1979), 88, "My electrostatic memory test rig was now wired to operate as a memory instead of being an open loop test device. It worked! I was able to select any of 1024 positions, push a button and enter a circle around a dot to represent a '1.' Initially, the '1' was remembered for seconds. With some adjustments it became minutes, and with much sweat the information could be stored for hours. . . . One morning I had entered my initials, H L [Herman Lukoff], into the memory to initiate an endurance test. After several hours I went out to lunch. . . . We concluded that electrostatic memory was not reliable enough to use in a computer system. The results of our work culminated in a presentation by Pres[per Eckert] at the IRE convention in March, 1949, and the publication of a paper in the Proceedings of the IRE of May, 1950 [Eckert et al. (1950)].” Jack Copeland, email Aug. 3, 2014, informed me of Lukoff’s work, and dated the creation of Lukoff’s image to after Dec. 1948, when a preprint of Williams and Kilburn (1949) was mailed from Manchester to Eckert’s group.

150:*Participants at the*: *Proceedings of the 1951 AIEE–IEE Conference*, 59, 71. Wilkes presented the Edsac at the same conference. He showed a movie which demonstrated the visual monitor tube of Edsac, but there is no record otherwise of what it showed. The discussion (p. 83) suggests that it was used only to check the memory and its operation. The Whirlwind paper was presented by Robert Everett, who engineered the machine with Jay Forrester (who was also present at the conference).

Chris Burton, correspondence Sept. 13, 2013, “The Edsac display (three side-by-side CRTs) showed the contents of a mercury tank on one tube, and the content of two internal registers on the other two.” Burton is technical leader of the team building a replica of Edsac at Bletchley Park. He previously led the team that built the replica of Baby at Manchester.

Archivist Krista Ferrante verified Oct. 20, 2016, that the Whirlwind picture is photograph F-1413 in the MITRE Whirlwind photographic archives, in box 2, folder 8, title Polynomial, 7th Degree, date Dec. 13, 1951. The proceedings version shown has the “F-1413” cropped. Whirlwind Bi-Weekly 1326, Oct. 26, 1951, 19, mentions a new subroutine for generating letters and digits on a 5 by 5 array and then on a 6 by 5 array, consistent with the Dec. 1951 date of the conference.

151:*This composite of*: *The Manchester Electronic Computer* (1952), 13. Dai Edwards, email July 16, 2013, “This shows on the left half of the display data that has been fed into the memory from paper tape, e.g., some part of the program. On the right half of the display some ticks are shown in dot form which indicate that on feeding the paper tape in a second time that the same information was received in the memory. This essentially is checking the correct operation of the paper tape input system. I believe this program was produced by Dr [Dietrich] Prinz but I am not 100 percent sure."

151:*Games have been*: The idea that play drives innovation is developed in a 2016 book by Steven Johnson, *Wonderland: How Play Made the Modern World*.

152:*Christopher Strachey ("Stray chee"*): Link (2012), 23, "In a letter dated 15th May 1951, Strachey wrote to Turing: 'I have completed my first effort at the Draughts . . . At this point, the algorithm already had 'input and output arrangements'." This letter is in folder C22 of Oxford's Bodleian Library Christopher Strachey archive [Strachey (1950–1952)]. Folders C20–C26 are labeled "Ace | draughts-playing program 1950–51" but C20, C21, and C23 contain nothing about draughts. C24 is labeled "Ace Coding Programme | (Incomplete)," and C25 "A.C.E. Draughts | Current Programme," and neither contains any dates. C26 contains several "Deuce [child of Ace] Program" programming printed sheets and several "Ace Pilot Model Programme" printed programming sheets, and no dates.

The draughts archive continues in folders C27–C33. C27 and C28 are draughts coding sheets from the Manchester University Computing Machine but none are dated. C29 is titled "Draughts | M. O. C. [probably should be M.U.C. for Manchester University Computer, a popular abbreviation then] Programmes | and Notes etc. | game —." It contains several program listings dated "31/7/52" on coding sheets preprinted with "Manchester University Computing Machine." It also contains a flow diagram which has one circle labeled "Display" and another "Print Message" and another “Record Print Move” (which is connected by an arc to “Display”). This is on the back of scrap paper and is paperclipped to another scrap page dated (on its front (original) side) May 31, 1952. The final bundle (paperclipped section of a folder) in C29 contains three listings dated in pencil “1/8/52”, “10.7.52”, and “9.7.52.”

C30 contains two sets of six photographs of “Photographs of the monitor tube display during a game of draughts. | These are best viewed at arm’s length.” A bundle is faced with a note saying “Examples of draughts as played by the machine” and contains a listing “11.7.52.” The next bundle contains a listing dated “21.8.52.” The final bundle has this note, “The complete programme for draughts as printed out by the computer,” followed with many listings, each dated “10.7.52.” C31 contains the undated draft of Strachey’s paper “A programme for making a calculating machine play draughts.” On p. 38 of this 45-page paper (not including figures) is this paragraph, headed “Complete Programme for the Ace.” C32 contains the draft of Strachey’s paper “Logical or non-mathematical programmes,” which was eventually presented in the Proceedings of ACM Meeting at Toronto, Ontario, pp. 46–49, Sept. 8–10, 1952. C33 contains a bound notebook that Strachey took to the Toronto conference. It has this note, “Sept 3 Arrive Toronto | To University . . . Doubtful if machine will be able to run Draughts.” [Toronto had a Ferranti Mark I]. He also noted that Eckert [of Eckert and Mauchly] complained that Williams had taken ideas from them on a visit and then patented them in the UK.

Hodges (1983), 446–447, 477, seems to place the first running of the draughts program at Manchester between August and November 1951, but the dating is unclear, except for this note: Strachey’s “draughts program was much developed and played throughout the summer of 1952.”

Link (2012), 24, "The software very probably constitutes the first usage of a graphical display in a computer program." Copeland (2004), 356–357, "The state of the board was represented on the face of a cathode-ray tube—one of the earliest of computer graphics."

Strachey also wrote the programming language CPL (influenced by Algol 60), which became BCPL, which became B, which became C, which became C++. BCPL was the first high-level programming language used at NYIT, the New York Institute of Technology. I was handed a magnetic tape copy of BCPL there, without a manual, by someone I don't remember. I was familiar with BCPL from exposure to it at Xerox PARC and was able to reverse engineer the copy to determine what its manual must be. Then NYIT adopted C wholeheartedly in the late 1970s. The group now known as Pixar took its love of C from NYIT to Lucasfilm and then Pixar. Pixar still (2020) runs on C and its descendants (e.g., C++).

152:*"He had written*: Van den Herik (2012), 42.

152:*Strachey's draughts program*: There was a speaker attached to Ferranti Mark I, so Strachey programmed it to play a tune when a game of draughts was completed. It played *God Save the King*. In the autumn of 1951, the BBC captured a recording *God Save the King*, *Baa Baa Black Sheep*, and *In the Mood*, played by Ferranti Mark I. This wasn't the first computer music, however. The crown for that achievement went to Australia's Csirac which reputedly played *Colonel Bogey* six months earlier. See and hear Fildes (2008). Copeland (2012), 164, states that Turing wrote a tutorial on how to make this crude kind of music in Manchester near the end of 1950, so perhaps Turing was first here too.

152:*Chess was never*: Claude Shannon, 34, arrived with his wife at Southampton from New York, Sept. 19, 1950 [*UK and Ireland, Incoming Passenger Lists, 1878–1960*, image 405 of 458 online at https://www.ancestry.com/interactive/1518/30807_A001268-00737, accessed May 16, 2020, Claude E. Shannon, 34, mathematician, aboard *SS Queen Mary*]. They departed from Liverpool to New York on Nov. 11, 1950 [*UK and Ireland, Outward Passenger Lists, 1890–1960,* image 421 of 538 online at https://www.ancestry.com/interactive/2997/41039_b001981-01096, accessed May 16, 2020, Claude Shannon, 34, executive, aboard *SS Media*].

152:*Two close contenders*: Wheeler (1992), 28, "The cathode-ray tube display of the store . . . made it easy to keep an eye on a selected area of the store. Programmers could watch the size of any significant counter in the store—for example, the size of the integration step. Of course, this soon led to experiments with games and pattern recognition. In his PhD thesis in 1952 Stan Gill describes a simple 'learning process' program. A vertical line was drawn which could have one of two gaps opened. A horizontal line was drawn opposite the gap that the program predicted would open. The light beam of the tape reader could be interrupted by the player to open the top gap—otherwise the lower gap opened." Martin Campbell-Kelly in an email July 28, 2013, verified that the thesis was a Cambridge thesis published in Nov. 1952.

In Douglas (1992), Sandy Douglas wrote, probably about the same game, "Stan [Gill] at that time was experimenting with a game involving pattern recognition, which involved a sheep approaching two gates, only one of which was opened after a 'decision point' had been reached. . . . To play such games one needed a way to manipulate the gates, and a display to show what was happening. The display on Edsac showed a bit pattern formed from 16 lines of 35 bits. Each word was 35 bits and 16 words could be displayed simultaneously. Thus by filling up 16 words appropriately a 'fence' could be drawn & 'gates' shown in it. The state of a gate could be controlled by one's program inspecting the state of the photo-electric reader used for input. One state resulted from the beam being interrupted & the other when no interruption occurred. This took the wave of a hand across the beam to accomplish."

153:*Alexander Shafto "Sandy"*: Douglas wrote the program (probably in 1952) to illustrate his 1954 PhD thesis at Cambridge on man-machine interaction, *Some Computations in Theoretical Physics*, which contains a listing of the program and two images from it. The image is from Campbell-Kelly (2000), 409. Martin Campbell-Kelly, in an email July 9, 2013, described the user interface to noughts and crosses: "In the original program one had to wave one's hand over the photocell of the tape reader when a tracking spot appeared in the display." From Campbell-Kelly, email July 10, 2013, "The evidence for dating is that the Edsac had a telephone dial installed in March 1953, and OXO [noughts and crosses] definitely precedes that date. I have some correspondence with Douglas which says he got the idea from an earlier program written by Stanley Gill. Douglas guessed it was 1952 but his memory was vague."

154:*The Brits had*: Pilot Ace apparently didn't have a monitor. Jack Copeland, in an email of July 2014, reported after looking for evidence of digital imagery in the Pilot Ace development, "Disappointing news: the Pilot ACE ray tracing program generated numerical output only."

Jack Copeland, emails of July and Sept. 2014, told me of a movie of "dancing dots" by Williams and Kilburn, presumably from Baby. If this was just changing memory values, then I would call it a sequence of digital images but not Digital Light. I invoke the lack of 2-dimensional coherence as cause for rejecting their dancing dots as an early computer animation in Digital Light. They had no pictorial intent. A one-dimensional display would have been just as meaningful.

154:*There may have*: Martin Campbell-Kelly, in an email July 9, 2013, stated, "There was at least one other display program [on Edsac], of an animated highland dancer. The code no longer exists I believe."

155:*I'll go with,*: This is slide 6 in Taylor (1989). See note 145:*To determine which* for details.

155:*I bother with*: Here is a description from a history of the game *Spacewar* by one of its creators, J. Martin Graetz (1981), 60: "Bouncing Ball may be the very first computer-CRT demonstration program. It didn't do much: a dot appeared at the top of the screen, fell to the bottom and bounced (with a 'thok' from the console speaker). It bounced off the sides and floor of the displayed box, gradually losing momentum until it hit the floor and rolled off the screen through a hole in the bottom line. And that's all." This seems to describe the bouncing ball as an animation, complete with a sound effect. But it reads as if it's hearsay to Graetz who started at MIT after Whirlwind. And the ball bouncing off the sides and floor of the displayed box, and rolling off the screen, doesn't fit the evidence.

But on Aug. 13, 2018, at the annual Siggraph conference in Vancouver, B.C., Fred Brooks showed the bouncing ball photograph (the June 1953 version) and said that there was a "thunk" sound at each bounce. He also said that the sound was different if the ball went through the hole. When I quizzed Brooks afterwards, he testified he'd seen the bouncing ball move and heard the sounds—in 1953. Brooks was the highly respected director of the programming team of IBM's System 360 and professor of computer science at the University of North Carolina.

New evidence added June 22, 2022: The bouncing ball moving in time can actually be seen at the temporal locations 6:12–6:26/37:08 of an old BBC TV production called, *Painting By Numbers*: https://ia600408.us.archive.org/11/items/paintingbynumbers/paintingbynumbersreel1.mp4. It matches the Graetz description earlier in this note, except there is no bouncing off the walls: The dot's position was calculated, presumably as fast as was possible then, and displayed. Then the next position, and so forth. Dot positions were not rewritten, so each dot disappears quickly due to phosophor decay, leaving the slightest trail for a very brief time. Sometimes the dot falls through a (presumed) hole in the floor. Is this an animation? Yes, although it is unclear if the dot writes occur at regular intervals. Unfortunately, there is no date on the original film footage used. The TV show itself was produced about 1982 (Pong was published in 1972 and the sequence about it states that "ten years ago . . .").

155:*The players would*: This is slide 7 in Taylor (1989). It is F-1940, Bouncing Ball Display, box 3, folder 5, dated between May 28 and June 10, 1953. The game is not mentioned in the June 1951 Whirlwind report [Saxenian (1951)]. Adams (1987), 787–788, "Probably the most widely seen demonstration of Whirlwind, before electrostatic storage bec[a]me operational, used the CRT to display the solution to the differential equation describing a ball bouncing on a horizontal axis, repeated at successively-increased horizontal speeds until it hit a hole in the floor and fell through." Fred Brooks stated in his 2018 presentation that this picture was a record of multiple traces of the bouncing dot.

Gilmore (1989), slide 3, p. 40, "Charlie Adams' bouncing ball demo program . . . was probably the first significant use of the computer display screen. | The program was 32 words in length and its instructions and constants were contained in 28 16-bit toggle switches [perhaps those mentioned two paragraphs above] and four electronic flip-flop registers. It plotted the simultaneous solution of three differential equations and inspired the MIT mathematical and engineering students to do likewise as they struggled to use Whirlwind computer in their thesis work." Gilmore (1989) states that he started at Whirlwind in Oct. 1950 [cf. note 145:*To determine which*].

Gruenberger (1967), 106, "Shortly thereafter [he claimed late 1949], one of his [Adams's] associates, Hrand Saxenian, programmed the famous numerical integration of a ball bouncing across the floor and eventually (if the initial conditions were properly selected) disappearing through a hole in the floor." The Saxenian error is due to a report written by him in 1951, a programming manual for Whirlwind, that included the bouncing ball program [Saxenian (1951), 55].

155:*The published code*: Weisberg (2008), chapter 3, p. 5, "Adams wrote a short program that displayed a bouncing ball on the display. This was done by solving three simultaneous differential equations. A little later, probably in late 1950, Adams and Gilmore wrote the first computer game. It consisted of trying to get the ball to go through a hole in the floor by changing the frequency of the calculations." As demonstrated, the date was more likely mid-1951 for the bouncing dot, and as late as mid-1953 for the "game" version. MIT people have called it the first videogame, but the 1953 date, the earliest bona fide date I've found so far, belies that claim.

Bug in the published book: "4.21" in this paragraph should be "4.20" (note added Aug.10, 2021).

156:*Edward R. Murrow's*: Video at https://criticalcommons.org/Members/ccManager/clips/mits-whirlwind-computer-debuts-on-see-it-now-with/view, accessed Apr. 4, 2020. This on-air show was probably not the Murrow demonstration mentioned by Taylor (1989) [cf. note 145:*To determine which*]. The original still, from the Whirlwind archive at MITRE Corp., is F-1414, "Hello Mr. Murrow" Display, box 2, folder 8, Dec. 13, 1951. I made the simulated animation frame.

157:*The mathematician Martin*: Martin Davis, email Oct. 18, 2013. Ordvac (ORdnance Discrete Variable Automatic Computer) was built by the University of Illinois for the Ballistics Lab. Davis (1958) was one of the establishing textbooks of the theory of computation. He is mentioned numerous times in the annotations of the Turing chapter (3). He and Virginia are friends and neighbors of mine in Berkeley.

157:*In the same*: *Merwin Biography*. Merwin was at IBM 1951–1965 and was president of the IEEE Computer Society at his death in 1981. Maniac came online at Los Alamos in Mar. 1952. I recorded the George Michael version about 1999. The Forrest version is from A. Robin Forrest, *War and Peace and Computer Graphics: From Cold War to Star Wars*," a PowerPoint presentation, Nov. 2013, backed with an interview by me of Robin in London, Sept. 5, 2016. The quoted claim was made about Williams tube graphics at Manchester.

159:*Well, they were*: The Jacquard loom from the early 19th century famously used wooden cards with punched holes to control the weaving pattern. The resemblance to the punched cards of early computers suggests that the Jacquard loom was an influence on the modern computer. It really had nothing to do with computation but rather with data input. But the assumed resemblance to a computer might suggest that the loom cards held a binary code that created a two-dimensional picture, the cloth itself. In this metaphor, the portion of a thread bounded by its neighboring threads in both warp and weft would be the "display element." So, indirectly anyway, each card coded one line of thread display elements. And it was a (partial) memory for that pattern.

But inspection of how a Jacquard loom works reveals problems with the metaphor. The card holes caused some warp threads to be raised selectively from the plane of the others. Then a weft thread would be shot, with a shuttle, between the two sets of warp threads so separated by the hole mechanism. The raised warp threads would then be returned to the original planar position, ready for the next "instruction" from a loom card. So, in general, there was no one-to-one code for each thread display element. Nor was there any color information in either warp or weft. As with the sampler example, there is only a slim intellectual path from Jacquard cloth to Digital Light. [*Wikipedia*, Jacquard loom, accessed Aug. 13, 2019, contains an excellent detailed description of how the loom worked.]

160:*By our definition*: A code existed for each character and also for carriage return (moving the printing head back to the beginning of the line) and for line feed (advancing the page by one line). A teletypewriter, as opposed to a typewriter, separates these two operations. So overprinting is accomplished by sending a carriage return at the end of a line, but not a line feed. Then the next line of characters prints over the preceding line. This can be done any number of times.

Nick England, email Aug. 11, 2019, provided this information about M*adonna*: "Some person [presumably Meyer Hill] typed in the original on a teletype keyboard and simultaneously punched it onto paper tape. Might have involved some trial and error and editing to get it right. Digital data and digital storage. Then at Christmas time transmitted it (digital tape reader) over the AP digital network to lots of other people who printed it on their teletype printers and punched tapes to keep their own digital copy. All digital but no computers involved in 1949 [or 1947]. Store and forward messaging networks with punched tape as the storage medium."

160:*The question is*: The Baudot code (or Baudot-Murray code), as it came into widespread use, coded "A" as 11000 and "Y" as 10101. There was no connection between numerical value of the code and position in the normal alphabetic listing. There certainly was no corelation with the perceived grayvalue of the character [*Wikipedia*, Baudot code, accessed Aug. 12, 2019].

161:*Hundreds, perhaps thousands*: An extensive collection of teletype art has been made available by Nick England at http://artscene.textfiles.com/rtty/, accessed Apr. 4, 2020, with this description: "In this collection, all manner of art is represented: cartoon characters, landscapes, slogans, holidays, pin-ups, and even some attempts at photograph-quality portraits. Some of these date back definitively to the 40s, with many of them showing up in the 60s, 70s and 80s." Nick also recommended the explanation offered by John Sheetz online at https://www.youtube.com/watch?v=c1Beg5qb4is, accessed Apr. 4, 2020, of the workings of the teletype art radio underground.

The almost-computer Colossus had a teletype. Might someone have made, say, a bar chart with it? I've been unable to discover evidence of such activity, yet it's hard to imagine somebody not doing so and, characteristically, not telling anyone about it. In an email from Jeremy (Jerry) McCarthy to Nick England, Aug. 10, 2019, and to me, Aug. 18, 2019: "However, if you mean, are there any examples of Colossus itself generating anything other than straightforward alpha numerical text, laid out in columns, and then printing it on its teletype, then I'd doubt it; the programmability of Colossus is very limited, after all." McCarthy, among other things, built a replica of the Cyclometer, the first Enigma-cracking machine, developed by the Poles [see *British expert builds Enigma cracking machine*, http://scienceblogs.de/klausis-krypto-kolumne/2016/07/10/britischer-experte-baut-enigma-knackmaschine-nach/, accessed Apr. 4, 2020]. He is now working with Chris Burton on a rebuild of Edsac.

161:*The teletype art*: A related system is the Bartlane system, used first in 1921 for trans-Atlantic picture coding and transmission, which was invented in 1920 by Mr. Bartholomew [thought to be Harry G. Bartholomew] and Maynard D. McFarlane of London. It used a Baudot tape with five positions to record the tonal values (intensities) at each location in a helically scanned photograph. Each position was binary—a hole punched or no hole punched. But according to descriptions—for example, in McFarlane (1972) and at http://www.hffax.de/history/html/bartlane.html, accessed Sept. 28, 2022—the five positions encoded six intensities (coded 0 through 5) rather than 32. That is, binary encoding was not used. At the receiving end, a light beam was passed through the holes in a facsimile of such a tape and imaged a brighter or darker spot depending on how many holes it passed through, not their arrangement.

The Bartlane system is certainly part of the intellectual history of the pixel, and should properly precede the position of teletype art in that history. I do not call its values pixels by the same argument that I use for teletype art in the main text.

I was alerted to the system's existence by Richard Lyon, notable in these pages as author of the history of the word *pixel*. He quizzed me after my presentation at the Computer History Museum on Aug. 11, 2022, and I thank him for that.

161:*In the 1950s*: Uncapher (1971), 4, 11–12, graphic information was written calligraphically on a vidicon tube, then scan converted line by line into raster mode.

There was a rumor at the first Siggraph conference (the annual computer graphics conference) that Evans & Sutherland had horizontal antialiasing in one of their hardware flight simulators in 1972, but they kept it secret at the time [Richard G. Shoup, email Jan. 2014]. Robert Schumacker, an engineer who built visual simulators for General Electric, then E&S, verified this rumor in an email Mar. 6, 2018: "The Watkin's processor (early 70's) did 'edge smoothing' based on edge slope and made an estimate of best representation for pixels along a scan line. This was one dimensional and didn't hold up for complex situations within a pixel. In the mid 70's we demonstrated improved results by averaging sub-scanlines, the resultant 'filtering' being different horizontally and vertically. Our first comprehensive anti-aliasing, implemented in a real time system, appeared in late 1970's CT5 [an E&S product in 1979]." [See the next annotation.]

James Kajiya, email Apr. 29, 2017, "I got to E&S in 1973. By that time they had realized horizontal filtering in hardware by doing box filtering over a pixel, viz. finding the fractional coverage of an edge over a square area. I think there was maybe an earlier system that did this . . . They didn't have full antialiasing."

162:*The first explicit and*: Shoup (1973); *The* SuperPaint *System (1973–1979)*, Internet Archive Wayback Machine,

http://web.archive.org/web/20020110013554/http://www.rgshoup.com:80/prof/SuperPaint/, accessed Apr. 4, 2020, is Dick Shoup's archived website, which claims that the system came online in Apr. 1973 and that he did the antialiasing before anything else. In Smith (2016) I incorrectly gave the date as 1972.

However, Robert Schumacker, a flight simulator engineer at General Electric, demonstrated two-dimensional antialiasing internally in Oct. 1970: "I first demonstrated anti-aliasing at GE in 1970. The image was computed at multiple sub-pixel sample points and the results averaged to form the displayed pixel. The demonstration (figure 4.29) was done for a range of sub-pixel samples from 2 by 2 to 16 by 16. The image was computed multiple times, each offset [to] one of the sub-pixel sample points. The 35 mm film did the integration via multiple exposures" [email Mar. 4, 2018]. He gave these further details in email, Mar. 5, 2018: "The adding together of the 16 colors in the case of 4 x 4 and dividing by 16 was accomplished as follows: Sixteen images were computed, each one with the sample point offset to one of the sixteen sub-pixel sample points. These images were computed sequentially and each one was unblanked for (say) one frame while the camera shutter remained open. Thus we had 16 frames, each one an image computed from one of the 16 sub-pixel sample locations and displayed at the same physical pixel location on the display. The total exposure of the film was 16 x 1/30 second, or about 1/2 second (for this example). The film therefore performed the function of adding the 16 sample point colors at each pixel (and dividing by 16). With different sub-pixel sampling numbers the number of unblank frames and/or f-stop was adjusted to keep the total exposure constant. The film was used in this way to avoid having to add the non-trivial hardware needed to accumulate RGB results on the GE non-realtime set up that stored color codes in its frame buffer—a quick and dirty way to do the averaging. The result is the equivalent of a rectangular filter over exactly one pixel. Figure 4.29 (left) shows 1 by 1 subsampling (that is, no subsampling) versus 4 by 4 subsampling (right).

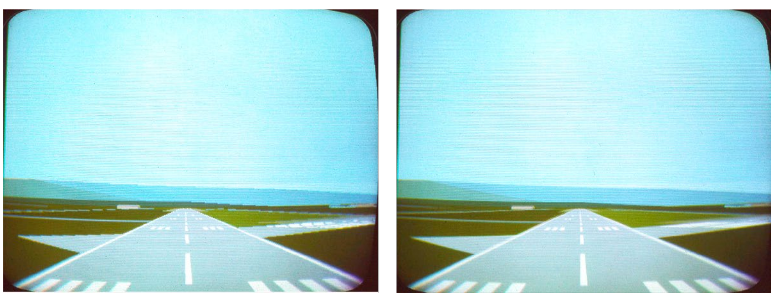

Figure 4.29

By the time we got to CT5 [in 1979] we implemented a much [more] sophisticated filter that extended over a 2 x 2 pixel area and did not use a regular array of sub-pixel sample points." Schumacker's technique uses the low-order box filter for reconstruction. I don't count this as the first antialiasing in Digital Light because the film averaging is an analog step. Nevertheless, this was a first.

And there was another example of subpixel averaging for antialiasing as early as perhaps 1971. According to Brand (1987), 171, Paula Mosaides, working with Nicholas Negroponte at the MIT Media Lab, introduced so-called Fuzzy Fonts which were fonts rendered as 1-bit pixels at one resolution and then averaged down to half-resolution, 4-bit pixels for display. That is, 2 by 2 subpixels were averaged to one pixel with a box filter. Negroponte is quoted, "I personally have exposed tens of thousands of people to Fuzzy Fonts since Paula Mosaides—I remember her name because she was Greek—got us started with this back in 1971." The idea of averaging 2 by 2 subpixels with a box filter applies generally. It's not restricted to fonts. Therefore this appears to be early antialiasing, perhaps the earliest. Unfortunately, the date of 1971 qualifies as hearsay so far. Negroponte (1977), 191–192, describes the technique but doesn't date it nor mention Mosaides.

162:*Shoup (sounds like*: Shoup (1973). Interestingly, Schumacker and the team at E&S also used a wagon wheel, denser than Shoup's, for a test image. "The spoke pattern was generated on CT-5 in 1979 with a very different system architecture that provided a comprehensive solution to aliasing . . . The spoke pattern consists of maximum white triangles on a black background, each one pixel wide with 4 pixel spacing at the periphery. . . . Mike Cosman was the genius behind the implementation details for convolving a 2 pixel diameter symmetric filter with pixel fragments in a way to virtually eliminate orientation bias and variations in average image intensity in regions toward the center, despite some mostly uncorrelated local anomalies as the triangle width shrinks to 1/8 pixel or less" [email, Mar. 4, 2018, from Schumacker].

162:*The first explicit use*: Catmull (1974); Crow (1977). Another Stockham student, Malcolm Blanchard, wrote an antialiased line drawing program (*smoline*) at the New York Institute of Technology about 1976 [email Jan. 29, 2014], which I used there then. It didn't explicitly use the Sampling Theorem, but a low-order (box filter) approximation to it. Catmull (1974) also used the box filter approximation.

165:*Leo Tolstoy, War*: Tolstoy (the 1992 Maude translation), first lines of Book Three, Part III, Chapter 1. A discussion of Zeno's paradox, then of the invention of calculus to solve the paradox, lead to Tolstoy's theory of history as a continuum, with error being introduced when only discrete samples of history are considered. It's a metaphor of sampling without his understanding Sampling.

165:*Tom Gunning, introduction*: Mannoni (2000), xix, introduction by Tom Gunning, Professor of Cinema and Media Studies, University of Chicago.

165:*There are several*: Strictly speaking, a soxel is an audio sample after it has been digitized (represented with bits). And similarly for a pixel. Samples (frames) in classic cinema are analog. We will digitize them into bits when we discuss digital movies and games in later chapters.

166:*He was Teddy*: Edward James Muggeridge, son of John and Susanna, was born Apr. 9, 1830, and baptized May 9, 1830, All Saints, Kingston upon Thames, Surrey, England. John was a corn dealer, and they resided in Kingston [*All London, England, Church of England Births and Baptisms, 1813–1917*, https://www.ancestry.co.uk/search/collections/1558/?name=Edward+James_Muggeridge&name_x=1_1, accessed Apr. 4, 2020]. "Muybridge Eadweard of 'Park View' Liverpool-road Kingston-upon-Thames died 8 May 1904 Probate London 30 September . . . Effects £2919 3s. 7d." [*England & Wales, National Probate Calendar (Index of Wills and Administrations), 1858–1995*, https://www.ancestry.com/search/collections/1904/?name=Eadweard_Muybridge&name_x=1_1,

accessed Apr. 4, 2020]. On Nov. 7, 1856, E. I. [*sic*] Muygridge declared his intention to become a US citizen in California [*US Naturalization Records Indexes, 1794–1995*, https://www.ancestry.com/search/collections/1192/?name=E.+I._Muygridge&name_x=1_1, accessed Apr. 4, 2020]. E. J. Muygridge is listed in an 1861 directory for San Francisco [*US City Directories, 1822–1995*, https://www.ancestry.com/search/collections/2469/?name=E.+J._Muygridge&name_x=1_1, accessed Apr. 4, 2020].

The complete set of aliases comes from the careful accounting of them in Ball (2013). Muybridge's gravestone spells his name Eadweard Maybridge, for one last, but mistaken, alias. However, one British patent from 1878 also gave his surname as Maybridge [Hopwood (1899), 238].

167:*His most colorful*: The first name of the son, Florado Helios Muybridge, honored the cheating mother Flora, and the middle name honored the (perhaps) cuckolded father. His gravestone states, "Son of the photographer Eadweard Muybridge." Muybridge was "Helios, (E. J. Muybridge) landscape photographer" in 1872–1874 San Francisco directories [*US City Directories, 1822–1995*, https://www.ancestry.com/search/collections/2469/?name=E+J_Muybridge&event=1873&event_x=1-0-0, accessed Apr. 4, 2020].

Muir first came to Yosemite in 1868. The earliest photos of Yosemite were probably those of Carleton Watkins in 1864–1866. Muybridge (as Helios) took his photos there during the period 1867–1872.

167:*It was his*: Hendricks (1975), 71; Solnit (2003), 139; Ball (2013), 30; Mannoni (2000), 307. Muybridge lived in San Francisco. The killing was in Calistoga, north of San Francisco, at the north end of Napa Valley, and the trial was held in the town of Napa in 1874.

167:*Muybridge affected the*: The ancient coronation stone was installed on its current base in 1850 when Muybridge was about 20, the year he departed for America (as Muggridge). The base is a 7-sided plinth with these face inscriptions in order (using approximations to the actual inscribed characters): “EADWEARD | DCCCC”, “AÐELSTAN | DCCCCXXV”, “EADMUND | DCCCCXL”, “EADRED | DCCCCXLVI,” “EADWIG | DCCCCLVI”, “EADWEARD | DCCCCLXXV”, “ÆÐELRED | DCCCCLXXIX”. The first Eadweard, crowned in 900, was son of Alfred the Great. Eadweard’s son Æthelstan (an alternative spelling) is considered to be the first king of England. Eadwig’s successor was Edgar, crowned 959, who isn’t listed on the base. The second Eadweard succeeded Edgar, and Æthelred (an alternative spelling) succeeded Eadweard. The Ð represents the sound “th”, hence the alternative spellings.

169:*Edward Muybridge, under*: Muybridge apparently made the first photograph of the horse leaving the ground in 1872 and improved the result in 1873, but none of these first photos have survived [Hendricks (1975), 46; Ball (2013), 123–125]. The naked man was often Muybridge himself.

169:*What he actually*: His first system had 12 cameras. The shutters were designed by John D. Isaacs, a young draftsman working in the Oakland shops of Leland Stanford’s railroad [Solnit (2003), 185–187].

169:*To show the*: Braun (2010), 161, “Muybridge’s zoopraxiscope combined a magic lantern, a lens and, between the two, a gearing mechanism that rotated two discs: a glass disc measuring sixteen inches (40.6 cm) in diameter and, turning in the opposite direction, a fenestrated metal-shutter disc. The glass disc bore figures around its circumference . . . the picture disc and slotted shutter disc rotated in opposite directions with an unsettling effect: the figures were distorted, appearing squeezed as well as unnaturally tall and thin.” (An LP record is 12 inches (30.5 cm) in diameter.)

The fact that there were in some instances 24 frames was a coincidence apparently and had no later influence on the frame rate of 24 frames per second that became standard for movies. The standard of 24 frames per second was derived by watching silent films, projected at a variable rate from say 15 to 30 frames per second, and selecting a rate that worked but wasn't unnecessarily fast, since the cost of film increased directly with increased projection speed.

169:*Muybridge showed this*: Ball (2012), 6 (date of first projection at Stanford's mansion), 12–13 (made shot in 1873 [1872 on p. 121] showing all four hooves off the ground, made first set of successive shots 1878 of horse in motion), 16 (first projection was of 12 images for 1.5 seconds), 18 ("he had hired an artist to paint the pictures on a glass disk, and he had shown this virtual world based in photographs to an audience"; also mentions that Zoëtropes were toys of the 1860s and 1870s and that there had already been versions that projected), 120 (Stanford hires Muybridge to settle the four hooves off the ground problem), 121 (May 1872, Sacramento, Muybridge makes first shot of Occident's hooves all off the ground, photographs have not survived), 122–123 (the famous bet probably not true), 307 ("instantaneous" photographs the rage; Muybridge buys much equipment for a horse shoot, 1876 or 1877, in Sacramento first), 307–308 (painting made from the photo of Occident with all hooves up, blur in photo was painted out, the driver's head was cut from a photo and pasted onto the painting, which was rephotographed to make the final image that became famous and widespread, people accept it as true), 312–315 (multi-camera facility set up on the Farm, first worked May 1878, first 12-camera shoot of a trotter June 11, 1878, submitted patent applications June 18, 1878), 316 ("Muybridge's camera [*sic*] was the first to capture time, and these are the photographs that launched moving pictures"), 318–319 (Marey mentioned, he encouraged Muybridge to animate his images).

Solnit (2003), 184–185 (first image, shown Aug. 3, 1877, photograph of a painting, with driver's face preserved, otherwise silhouette, one-thousandth second exposure). Ball (2012), 319 (Stanford okays 12 more cameras; his technique unknown), 320 (1879 Muybridge makes many 24-image pieces), 326 (1879, shutter, foreshortening, "Muybridge wanted the glory of motion, so he hired a painter named Erwin Faber, who worked with magic lantern slides, to paint facsimiles of the photographs on the glass disks. He told Faber to give the horses elongated legs and torsos, counteracting the optical distortion. Faber painted, in color, around the edges of the disk"), 328–329 (Stanford didn't pay, not much anyway), 334 (1881 Marey invites Muybridge to France), 336–337 (re Stillman's book; "He mentioned Muybridge's name once." This is not right, as Muybridge's name appears in the very first paragraph, the very last paragraph, and an entire appendix is attributed by name to him), 338–339 (1882 Royal Society, Muybridge submitted "On the attitudes of animals in motion"), 340 (he sues Stanford), 360–61 (he meets Edison), 362 etc. (Chapter 21, the Edison battle).

170:*And Muybridge wasn't*: Dickson's drawing is from the back cover of Dickson and Dickson (1895). There's a problem with it. The candle holder as shown is placed between a slit and the opposite picture (or else it floats somehow). It couldn't work as shown.

I constructed a careful geometric simulation of a Zoëtrope, assuming that the eye position and direction remain fixed. It revealed a slightly more complex, and surprising, story than that described here. The next still isn't suddenly revealed in its entirety—as the text implies—as its corresponding slit appears. What the eye actually sees is the next still revealed smoothly from the right then obscured smoothly from the right. It's wiped on and then wiped off. Only at one instant is the entire frame revealed—at the halfway point. (This description assumes the Zoëtrope is spinning clockwise as seen looking down on its top.) Recall that the drum is always in motion. So the next still is actually moving to the right as seen through the slit, and its slit is moving to the left. The total effect, however, is that the frame appears still on the eye, revealed as the left edge of its slit moves left, then obscured as the right edge of its slit moves left. Taking the total illumination to be directly related to the proportion of slit area to total area, this suggests that the frame spreader function is a tent shape: off at the left and right of the function, with straight-line increase to full on in the middle from both directions. It's a crude approximation to an ideal spreader, but better than a box shape. It fails as an ideal spreader, even an approximation, because it doesn't overlap timewise with the next or succeeding spreader. See Section 1 of Smith (2015a).

Henry Heyl, in 1870, demonstrated his Phasmatrope disk-based projection device. It featured a disk with a sequence of photographs mounted around its outer edge—of a dancing couple, for example. The sequence was not captured in real time, however. The couple was carefully positioned in each still so that at projection speed, their dance was animated [Musser (1994), 45–48].

The dimensions are not to be taken too literally. There's a Zoëtrope at the Cinémathèque française in Paris that is several feet across (a reproduction of one by Marey), and there are Zoëtropes at the Lawrence Hall of Science in Berkeley, CA, that are less than a foot across.

170:*The pictures in*: Rojas and Chow (2013), 5, "The fourth century CE historical text *Record of the Western Capital* . . . contains a description of how the Western Han craftsman Ding Huan . . . (active in the first century BCE) developed an optical device consisting of a circular band with images of birds and animals positioned around a lamp such that the heat from the lamp would create convection currents causing the band to rotate, thereby making the bird and animal images appear to 'move quite naturally' . . . Historian of science Joseph Needham has proposed that this device . . . may have been an early Zoëtrope—a technology that, when it was (re)invented in Europe in the 1830s, became an important predecessor for the development of film in the 1890s."

170:*Nor was Muybridge*: Illustration from Kircher (1671), 768. Musser (1994), 21, observed the misplaced lens. The oldest known actual magic lantern (but without evidence of sequences of projections) might be one built in 1720 in Leiden, the Netherlands, by Jan van Musschenbroek [https://www.luikerwaal.com/newframe_uk.htm?/oudste_uk.htm, accessed Apr. 4, 2020].

Kircher is the Leibniz of cinema, so to speak. We noted in an annotation of the Turing chapter that Leibniz contemplated a notion like Turing's in the 18th century, but Turing brought the idea home.

171:*Animators also famously*: I constructed a careful geometric simulation of a Zoöpraxiscope, assuming that the eye position and direction remain fixed. I simulated a 12-frame disc, using letters of the alphabet for images. The shutter was a disc of the same size but opaque except for 12 radial slits cut into its circumference (cf. photograph in Ball (2013), 367). The depth of each slit was sufficient to reveal the full height of each frame, but the slit width revealed only about one tenth the frame width at any one instant. At each step of the simulation the disc of images was rotated one degree clockwise, and the shutter disc was rotated one degree counterclockwise. The parts of the frame visible at each increment were accumulated as they were revealed. The accumulation would be accomplished by persistence of vision on the retina of a human viewer. The result of 15 steps, where the projected frame held the letter A, was a squeezed A. The height was correct but the width had been reduced substantially. An A of base width 1.375 in. was squeezed before projection to an A with base width 1 in.—a reduction in width to approximately 72.7 percent. To project an image of a horse, say, the inked version of the horse would have to be elongated by the inverse, or 137.5 percent. The simulated Zoöpraxiscope was simply my invention, bearing only an approximate resemblance to Muybridge's, but the principle is clear: The continuous rotating shutter mechanism causes obvious foreshortening of the frames on the disc. Furthermore, the letter A resulting from this simulation—the frame as projected—was a rather ragged approximation of the letter A in the actual frame on the disc. See Section 2 of Smith (2015a).

172:*Animators hold these*: The image appeared on a 1992 Christmas card from Pixar. Its caption is "Plate 1292. Child Lamp Hopping Eadweard Muybridge ca. 1889." The last page of the card carries this message: "Eadweard Muybridge's seminal work on the analysis of animals and human beings in motion began as an experiment to help Leland Stanford win a bet that all four hooves of a galloping horse could be off the ground at once. Muybridge proved Stanford right, and in the process invented what later became the basis for motion pictures. His hundreds of innovative photographs of human and animal locomotion have been a reference for students of the arts for over a century. | Until recently, his studies of the movement of small appliances were thought to have been lost in a 1922 Palo Alto fire. In 1991, during remodeling work in a former billiard hall, which is now a frozen yogurt shop in Menlo Park, trunks of glass plates were found in a room which had been sealed off for decades. Students of Muybridge have just started to tap the riches of the master's small appliance work. | The finest example unearthed to date is this series, *Child Lamp Hopping*, thought to date from ca. 1889. It is presented here as a tribute to the pioneering Eadweard Muybridge."

George Carwardine designed the classic Anglepoise task light in England, and patented the design in 1932. It was mass produced in England by Herbert Terry. Norwegian Jacob Jacobsen, a Norwegian lighting designer, bought the patent for the light in 1937 and designed his very successful Luxo 1001 Lamp based on it [https://design-technology.org/georgecarwardine.htm, accessed Apr. 4, 2020]. The Pixar lamp is based on a Luxo lamp and was granted permission (ex post facto) to use it in an early animation *Luxo Jr.* (1986), with credit: "'Luxo' is a trademark of Jac Jacobsen Industrier A.S." *Luxo Jr.* was added in 2014 to the US National Film Registry.

173:*But it wasn't*: Stillman (1882), first paragraph, first page of text, in the preface by Stanford, "I employed Mr. Muybridge, a very skillful photographer, to institute a series of experiments," and the appendix begins, "The following account of the methods by which the original photographs were produced that served as the basis of the analysis of the paces, the results of which are contained in this volume, was furnished by Mr. E. J. Muybridge, the photographer by whom they were executed," followed by a four page description of the technique. Its last paragraph again mentions "Mr. Muybridge."

The book consists of only 127 pages of text, featuring an additional 107 plates of illustrations (with a sheet of tissue protecting each). Of these, only five are photographs, and three of those are of the 24-camera apparatus Muybridge devised for the horse photographs. So only two plates in the book are the raster scan plates of 24 images of a horse in motion that we associate with Muybridge. There are many raster-scan plates derived, as silhouettes only, from Muybridge's photographs by artists using India ink.

In 1881 Muybridge assembled five copies of a handmade book called *The Attitudes of Animals in Motion*. It was based on the Stanford experiments, and he presented one copy to Stanford. Muybridge historians Solnit (2003) and Ball (2013) claim that Stanford took umbrage at how much more the Parisian public honored Muybridge than himself when they both visited at the same time. And that, in spite, Stanford omitted Muybridge's name from the title page of Stillman

(1882). Stanford paid Muybridge $2,000 for his copy, or about $50,000 in today's money ($2,000 in 1913 is $52,500 in 2019 dollars by the CPI (Consumer Price Index) which began in 1913).

A plaque on the Stanford campus, erected in 1929, credits four people, Leland Stanford (in the largest letters) for conception, direction, and patronage of the photographic experiment, Eadweard J. Muybridge for the photography, John D. Isaacs (who designed the electrical shutters for Muybridge's cameras [Ball (2013), 312]), and J.D.B. Stillman, for analyzing the photographs. The claim for Stanford is: "This extensive photographic experiment portraying the attitudes of men and animals in motion was conceived by and executed under the direction and patronage of Leland Stanford." Muybridge "showed that the photographs could be combined in projection to give the true appearance of motion"—which is not what he actually did. And the spelling Eadweard is anachronistic.

174:*By the time*: The Royal Society is often confused in Muybridge articles with the Royal Society of the Arts, or with the Royal Institution. But Muybridge made clear [Hendricks (1975), 141–142] that it was Mr. Spottiswoode, the president of the Royal Society, who invited him to write an article. Andrew Spottiswoode was president of the Royal Society from 1878 to 1883. So he would have been president in 1882 precisely when Muybridge was doing this work and when the Stillman book was published.

174:*And he lost*: Ball (2013), 306, cites "The Paces of the Horse," *Popular Science*, Dec. 4, 1874. The 1872 and 1873 photographs don't survive, so probably weren't very good. Stanford, inspired by the 1874 article, asked Muybridge to try again. On pp. 333–334, "In July 1881, by telegraph from France, Stanford told his lawyers to transfer patent interest in Muybridge's photographs and equipment to the photographer. The two had agreed on a price: one dollar, and the deal was done," citing the Muybridge papers at the Bancroft Library, University of California.

175:*Nevertheless, the wealthy*: Ball (2013), 323, "Stanford had spent some $42,000 for all the experiments, or about $950,000 in 2010 dollars." By the CPI (which began in 1913) $42,000 in 1913 had the same buying power as $925,086 does in 2010, or $1,003,753 in 2015. So it's safe to say Stanford spent the equivalent of a million dollars or more in today's money on the Muybridge experiments.

175:*But before heading*: *Groundhog Day* (1993) starts by making us believe the protagonist is in an infinite loop, but actually there is a way out of the loop. The movie was added in 2006 to the US National Film Registry. *Rashomon* (1950) is an Akira Kurosawa masterpiece that tells presumably the same story from four different contradictory points of view. It was given a special Academy Award in 1952.

176:*There's no single*: Spehr (2008), 650, makes the point that the movie machine really includes a fourth piece, the printer machine that develops the exposed film and converts it into positive print film suitable for projection. Since this part of the movie machine did not make it into Digital Light, I will not pursue it, but the point is a good one.

176:*It's not obvious*: Although reality presents smooth continuous visual flow to the eye, as it does to a movie camera, the eye is not a passive instrument like the camera lens. The eye is in constant motion—tiny jerking movements called *saccades* [French for *jerks*]. The astonishing thing is that we perceive a smooth continuous flow despite this erratic motion of our eyes.

178:*Figure 5.7*: Note added 22 Jan. 2021 (after the book was in production): I revisited figure 5.7 and realized that it isn't as clear, or as simple, as it could be. A two-dimensional Fourier wave (a corrugation) is a one-dimensional wave (a classic sine wave) extruded through space in the direction orthogonal to the dimension carrying the sine wave. By analogy, a three-dimensional spacetime Fourier wave is a two-dimensional wave (a corrugation) extruded through time, the dimension orthogonal to the space occupied by the corrugation. I'll just call this an extruded corrugation.

My simplified presentation of Fourier's great idea was this:

In one dimension of space or time we can add together waves of various frequencies and amplitudes to get a one-dimensional function in the real world. I don't ignore phase, but I only mention it in passing as another adjustment that has to be taken into account to fully implement Fourier. The elemental addend is a wave along the horizontal axis, shown with no phase offset.

In two dimensions of space we can add together corrugations of various frequencies and amplitudes to get a two-dimension function in the real world. I don't ignore phase and angle, but they are mentioned in passing as other adjustments necessary for full adherence to Fourier's theory. The elemental addend is a corrugation, shown with no phase offset and with the furrows aligned along the other spatial dimension (let's call it the vertical dimension). It has a frequency only in the horizontal dimension, but when it is rotated, in its plane, through an angle, then it is seen to have a horizontal and a vertical frequency. That is, if you slice the rotated corrugation with a plane through the vertical axis (and orthogonal to the plane of the corrugation), the bleeding edge is a wave. And similarly if you slice it with a plane through the horizontal axis.

In three dimensions of spacetime, by analogy, we can add together extruded corrugations of various frequencies and amplitudes to get a three-dimensional function in the real world. Of course, there are those other adjustments, of phase and of angle (in three-dimensional space), that have to be used to get full Fourier capability. So what figure 5.7 should be is an extruded corrugation, shown with no phase offset and with the furrows aligned along the vertical spatial dimension, and with the temporal extrusion aligned along the time dimension. That is, it has a frequency only in the horizontal dimension. It's rotation of this element into three-dimensions that induces frequencies in the vertical dimension and in the temporal dimension.

Consider figure 5.7 as drawn. It shows a corrugation that has a frequency in the horizontal dimension and in the temporal dimension. To be consistent with the other two presentations, it should have shown a frequency in the horizontal dimension only—a "pure" extrusion of a corrugation into the time dimension. Each slice through the extruded corrugation is simply the corrugation. Figure 5.21 is a modification of figure 5.7 to a simpler picture, consistent with the lower-dimensional presentations:

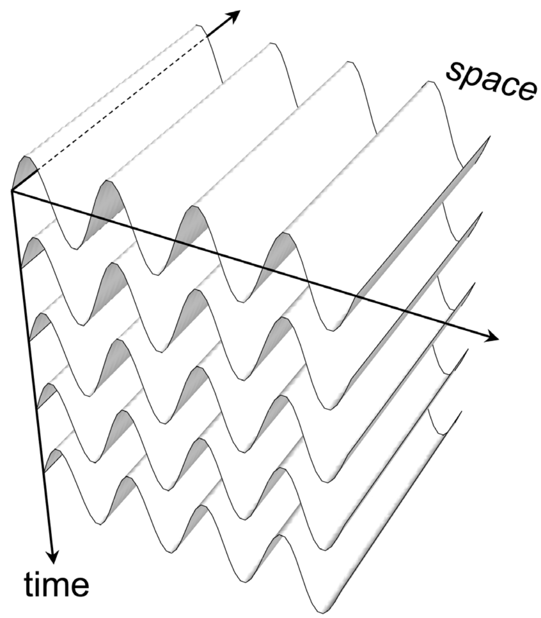

Figure 5.21

Alternatively, I could have rotated the spatial plane of figure 5.7 about the time axis to get a representation of the element with frequencies in all three dimensions, instead of just in the two shown in that figure. See Pearson (1975), 4–5, for mathematical details.

179:*In summary, a*: Even more imagination is needed here to be complete: The corrugation extends forever in space, and its pulsing continues forever in time.

179:*The Sampling Theorem*: Whether the standardization at 24 fps (frames per second) happened quickly depends on your point of view. For historians, it took a long time, from 1895 to the advent of sound films as standard fare in the 1920s. Sound films had to standardize so that the sound worked correctly, and did so at 24 fps, but silent films were often at 20 fps or lower, if they were at a constant speed at all. Early on, in an 1891 patent application, Edison specified "at least as high as" 46 fps, but only actually claimed 30 fps. 46 fps is an interesting number because it approaches the 50 fps refresh rate that the eye nominally needs. But that speed was probably never attained [Hendricks (1961), 106–108].

180:*But even this*: In Digital Light we can accommodate negative lobes, but in the case of the analog frames of classic cinema, there is no such thing. The spreader with no negative lobes chosen here is a classic Gaussian curve.

181:*As you might*: To implement this spreader would require that five frames in a row be available to the projection lens at any one time. That's because of the overlap of spread samples during reconstruction. Contributions from the frames preceding and following the current frame would be illuminated and then added to the illuminated current frame. This could be accomplished using mirrors to combine the frames together into one. And shuttering would have to be eliminated. It can be done, as known for a long time, with lensing that maintains a frame optically stationary [e.g., Hopwood (1899), 151, 187, a Casler patent of 1897]. We won't pursue this further because it's not practiced and probably never will be in the analog world.

182:*Here's the surprise*: A digital implementation could use a spreader with negative lobes, and wouldn't need the mirrors or fancy lensing (see previous note).

There were several projectors proposed near the dawn of projection (1895) that did spread the frames. See, for example, Hopwood (1899), 88–91, for a description of Gray's projector, patent filed Mar. 9, 1895, "Also, in a certain position, portions of both beams of light [illuminating two successive frames] will reach the projection lens; that is to say, one beam of light will be vignetted into the other and there will be no interruption of illumination." These can be construed to have been crude outside-the-pupil projectors.

Paul Pottash, email Oct. 18, 2015, collector of early cameras and projectors, reminded me that there were, and are, systems that pulse the light source rather than shutter a constant one. For example, Ottomar Anschütz's Electric Tachyscope of 1887 used a flashing Geissler tube to illuminate each frame; Dickson carried on experiments in 1889 at the Edison labs of a related device [Spehr (2008), 106, 133].

182:*What did the*: Early inventors intuitively understood that instantaneous frames were desirable. There was a spate of interest in "instantaneous" photography then, but this just meant exposure times of short duration, not zero duration.

182:*Second, they made*: American collector Paul Pottash recalls that flicker was reduced by going to double-bladed, or even triple-bladed, shutters—and hence double projection, or triple projection of each frame—and that most projectors by the time of World War I had double-bladed shutters [emails Aug. 25, 27, 2015]. French historian Laurent Mannoni found evidence in an early French technical history [Ducom (1911), 139, 142] of a double-bladed Gaumont projector and a triple-bladed Pathé projector. Ducom (1911), 299, suggests that the reduced flickering might have been a pleasant side affect of balancing a shutter disk. A rotating disk shutter with just one blade (hence one opening) *must* be physically unbalanced, all the weight is in the single opaque blade. To smooth the mechanics—and hence decrease wear and vibration—early inventors balanced the weight by placing multiple blades symmetrically about the shutter disk center. But Pottash points out that use of a counterweight on an otherwise unbalanced disk was a well-known technique, and was used on an early (ca. 1908) Edison projector shutter in his collection. So it appears that reduction of flicker was probably the main intent of double (or multiple) projection of each frame. For whatever reason the early inventors had naïvely approached the eye's nominal need of 50 refreshes per second (or more) without knowing about that need. And the technique is an old one, dating to the early part of last century.

182:*The third thing*: It's worth a reminder that the retina is not a stationary, passive receiving device. The eye, hence the retina, is in constant jerking, or saccadic, motion.

183:*We've just described*: Actually it's possible to get optically stationary frames from continuous movement using a lens. This was done in some early machines and patents, as mentioned in a previous note, but wasn't adopted by the industry. Some of the early projectors with intermittent movements didn't shutter at first. For example, the original Jenkins and Armat Phantascope that led to the "Edison" Vitascope added shutters only later, in 1898 [Paul Pottash, email Oct. 18, 2015]).

At the end of the film era, an intermittent movement was a device that you could hold in your hand. Colleague David DiFrancesco knew all about them. It was one of his secrets of success in getting the laser film reader/writer at Lucasfilm/Pixar to work. It was perhaps the most highly refined mechanical device in film Hollywood. David, email Feb. 14, 2017: "The movement I used in the 6 Laser scan/recorders I designed and built from 1979 to 2011, are generally referred to as 'pin registered animation shuttle mechanisms' and mine were built by George Randle Co. Hollywood Ca. They were not the normal (small) animation shuttle mechanisms seen in standard animation camera stands at Disney or Fleischer and other studios. Mine were 3 times larger to accommodate both 35 mm and 70 mm, 8 perf VistaVision 3 pin format as well as 35 mm 4 perf 2 pin and the one and only 3 pin 5 perf 70 mm registration format."

184:*Persistence of vision*: The retina is difficult to model, and the various models that do exist are difficult to explain in a book such as this. Nevertheless, one of the well-known models, by Silveira and de Mello (1998), models the temporal response of cells in the eye (the ganglion cells, a few layers removed from the rods and cones) with a spreader that is high in the center and diminishes rapidly away from the center with a negative lobe. That shape resembles the pixel spreader described in the chapter on Sampling. But this inside-the-pupil spreading is not done visually, with light intensities. It's done electrochemically with the responses of the cells, the kind of signal that the brain actually uses. Light goes in, but pulse trains emerge and go to the brain. The puzzle is, why should the eye/brain do a reconstruction at all, if that's indeed what it's doing?

186:*Consider the front*: A photograph online of an extant Butterfield stagecoach shows large rear wheels with 14 spokes, and smaller front wheels of 12 spokes. The stagecoach used by the Wells Fargo Bank as their corporate image also has back wheels with 14 spokes and front wheels with 12.

"The next spoke revolves exactly into the place of the previous one" isn't quite true because the stage—and hence the wheel—moves one foot forward during the rotation. But the point is that there's a pattern that repeats 12 times per wheel revolution.

186:*If a horse*: The strange artifacts wouldn't appear if the too-high frequencies were removed from the visual flow before sampling into frames, as required by the Sampling Theorem. But there is no intentional prefiltering of reality as it flows into a camera.

186:*If a spoke*: The eye can, in fact, see backward-spinning wheels in real life, probably because of the tiny rapid eye movements, the saccades. In effect, the eye itself perhaps samples reality. See Purves, Paydarfar, and Andrews (1996).

187:*Since sampling is*: There have been attempts to change the frame rate of movies. *The Hobbit* series of movies (2012 onwards) was shot at 48 fps, for example. Doug Trumbull unsuccessfully championed a cinematic system called Showscan in the 1980s with 60 fps (building on work of master Hollywood camera builders Cunningham and George Randle). Video already commonly uses 60 fps. Higher frame rates occasionally mentioned are 72, 120, and even 240 fps.

Here, as usual, we state that sampling occurs at twice the highest frequency, but recall that the Sampling Theorem actually states the rate as just greater than twice the highest frequency. In the case of film, 24 frames per second can accurately represent visual flow with highest Fourier frequency of *slightly less than* 12 cycles per second.

Note added Aug. 15, 2021, just after publication: I have been alerted by friends Garrett Smith and George Joblove that there are professional efforts afoot to alleviate the "wheels going backward" and other time-aliasing problems. Two companies mentioned that have partial solutions are described at https://tessive.com and https://www.reald.com/truemotion, both accessed Aug. 15, 2021.

187:*Henry Hopwood, Living*: Hopwood (1899), 226. This is also the epigraph of Mannoni (1997). Note that 1899 was just four years after the birth of cinema.

187:*A major simplification*: I rely on three excellent cinema historians for much of the American history in this chart and chapter: Gordon Hendricks, Charles Musser, and Paul Spehr—these three books in particular: Hendricks (1961), *The Edison Motion Picture Myth*; Musser (1994), *The Emergence of Cinema*, and Spehr (2008), *The Man Who Made Movies: W.K.L. Dickson*. For French history I rely on Laurent Mannoni (2000), *The Great Art of Light and Shadow: Archaeology of the Cinema*, and the collected letters of the Lumières [Rittaud-Hutinet (1995)]. For the history of animated movies, later in this chapter, I rely on another historian Donald Crafton, principally his book Crafton (1993), *Before Mickey: The Animated Film, 1898–1928*.

Another excellent source is Hopwood (1899) written just after the invention in 1895 of movie projectors, by a British patent inspector who was only interested in the hardware and captured in great detail the very beginnings of the cinema. Its largest lacuna is the inventions he attributes to

Edison, while complaining about how hard descriptions of them were to obtain, saying even that they were long-concealed: "a patent concealed from public view for six years!" [Hopwood (1899), 79]. He wasn't aware that the Edison machine was essentially Dickson's, whose name never appears. He does catch that the machine of Armat and Jenkins looks suspiciously like the Edison Vitascope (which actually was designed by Jenkins and Armat) [Hopwood (1899), 74, 241].

The Demenÿ-Gaumont line on the Franks side of the chart is highly abbreviated, omitting details ultimately irrelevant to Digital Light. Here's what actually happened [condensed from Mannoni (2000), 439–450]: Demenÿ designed the Chronophotographe camera (beater-cam, 60mm, no perforations, patented 1893) and Phonoscope (a disk-based "projector," patented 1892). Gaumont agreed to sell these products in an 1895 contract. He changed the names to Biographe and Bioscope, respectively (trademarked 1895). This was not a full cinema system, so I don't portray it in the chart. Demenÿ (with Léopold Decaux) modified the Biographe into a "reversible" camera/projector machine (beater-cam, perforations, 1896). Gaumont abandoned the Phonoscope (aka Bioscope) in 1896. Joly sued Gaumont in 1896. Joly had Demenÿ's cameras on the Gaumont premises seized in 1896. Gaumont (unjustly it seems) ended his association with Demenÿ in 1896. Demenÿ converted the reversible Biographe to 35 mm in 1897. In 1901 Gaumont bought Demenÿ's patents for a ridiculously small amount and proceeded to sell the 35 mm version of the Biographe (also called a Chrono).

A name that shows up several times in the early history of movies is Edward Hill Amet and his Magniscope projector (ca. 1896). Paul Pottash [email Oct. 18, 2015] reports having seen a demonstration of his projector, that its images were imperfect, but it worked. Amet's work figured in early patent battles [Spehr (2008), 468, 630].

187:*And again, as*: A non-exhaustive list of omissions: Max Skladanowsky of Germany had a public showing of his Bioskop projector in Berlin in Nov. 1895; Robert Paul showed his Theatrograph projector in England in Feb. 1896 [Musser (1994), 91]. Birt Acres, British, beat out the Lumières to a British projector patent in 1895, but apparently didn't give a public demonstration until 1896 [Hopwood (1899), 98, 240]. William Friese-Green and M. Evans of England had a patent issued in 1889 that caused Edison and Dickson serious patent problems later, but apparently the Brits never accomplished much with it [Spehr (2008), 106–111; Hopwood (1899), 65, 238].

Figure 5.22 is a continuation of the flow chart of cinema (figure 5.12), showing the Brits team.

A recent book, Brown and Anthony (2017), gives detailed history of the Kinetoscope in England, with much new information about Birt Acres in particular. Charles Musser, in his introduction to the book, mentions the Edison-Dickson partnership and the Armat-Jenkins partnership, then (p. ix): "In England, this pattern had its counterpart in the Birt Acres-R. W. Paul partnership. Moreover, very much like Edison-Dickson and Armat-Jenkins, their partnership soured soon after they achieved notable successes. Each partner subsequently claimed that he was the one who deserved the lion's share of the credit for the relevant invention. Each has also had his scholarly supporters. In this study Brown and Anthony provide considerable evidence to support their advocacy of Birt Acres, but it will be interesting to see how Ian Christie, who is working on an extensive biography of R. W. Paul, will assess similar evidence." So there's more to come.

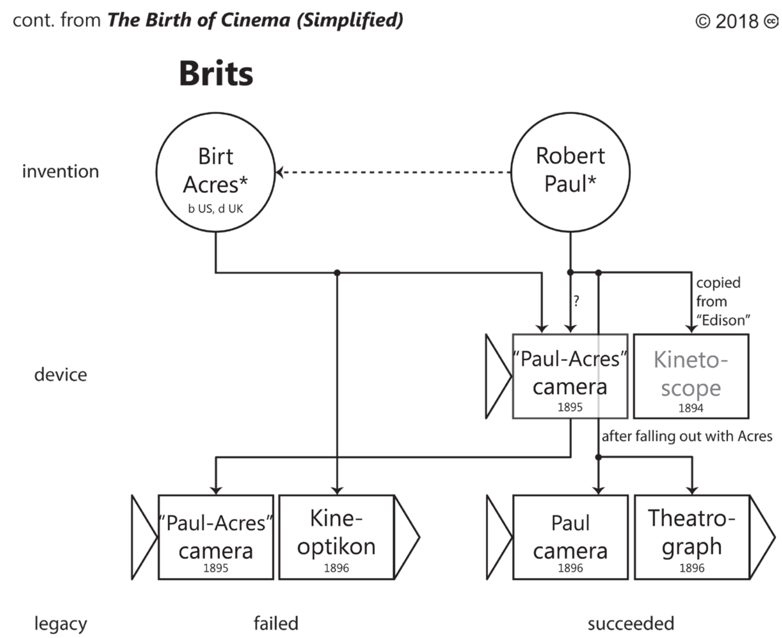

Figure 5.22

There are many names missing from the pre-cinema era or early cinema era. Some of the prominent missing ones are Ottomar Anchütz and his Tachyscope, Wordsworth Donnisthorpe and his Kinesigraph, Joseph Plateau and his Phenakistoscope, Simon von Stampfer and his Stroboscope, Henry Heyl and his Phasmatrope, Émile Reynaud and his Praxinoscope, and many more. Some of the surprising names in pre-cinema are Michael Faraday who analyzed some phenomena of motion from stills, James Clerk Maxwell who improved the Zoëtrope, and Charles Babbage who discussed the Thaumatrope [see Annotated Bibliography in Hopwood (1899), 255, 258, 257, respectively].

190:*Perhaps the most*: Spehr (2008), 111–117; Howells (2006); Scott (1931); Scott (1923); David Nicholas Wilkinson, *The First Film* (2016), online at https://vimeo.com/ondemand/thefirstfilm/181293064, accessed Apr. 4, 2020; see a digital reconstruction of a Le Prince film, photographed Oct. 14, 1888, Leeds, Yorkshire, at https://www.youtube.com/watch?v=nR2r__ZgO5g, accessed Apr. 4, 2020.

Le Prince filmed his first movies made with a single-lens camera and paper-based film in late 1888. The camera was his own design and featured a pressure-style intermittent movement (that is, with unperforated film). The camera doubled as a projector, by swapping the back for one with a lamp [Howells (2006), 187]. Subsequently he substituted celluloid film for the problematic paper film. He was ready to project a movie in 1890 in New York, and had rented a venue in upper Manhattan for that purpose. But his Sept. 1890 disappearance intervened. There is an affidavit, signed in 1898, by an individual claiming to have seen one of the 1888 films projected in 1888 or 1889 [Howells (2006), 195]. Various other affidavits appear in Scott (1931), signed much later but by workmen who collaborated with Le Prince on the mechanisms. Two of the cameras survive, including the one-lens version used for the 1888 movies. The Wilkinson film shows the intermittent movement of the camera in action. Le Prince's 1888 patent was used to officially deny primacy to Edison's later patent. The claim of Le Prince's primacy to a complete movie system appears well grounded.

190:*Charles Musser, The*: Musser (1994), 115–116, continues, "Participating in a press screening at his laboratory on 3 April, he [Edison] stole the show; if Armat [an inventor, with Jenkins, of the Vitascope] was present, he stayed discreetly in the background." The next day the *New York Journal* reported, "For the first time since Edison had been working on his new invention, the vitascope, persons other than his trusted employs and assistants were allowed last night to see the workings of the wonderful machine." Edison had obtained rights to the machine by buying its patent, with a business deal that required that it carry his name only.

190:*I was raised*: Spehr (2008), 115, "Because many—no, most film historians—have accepted that Edison was one of the darkest figures in film's early years, it deserves some clarification." Spehr is the retired [now deceased] former Assistant Chief of the Motion Picture, Broadcasting and Recorded Sound Division, Library of Congress, Washington, DC.

191:*As a case*: Isaacson (2011), 347, quotes Ive: “I pay maniacal attention to where an idea comes from, and I even keep notebooks filled with my ideas. So it hurts when he [Jobs] takes credit for one of my designs.” Ive had a team of 18 working on these designs.

192:*The two men met*: Paul Spehr, email June 15, 2015: “Muybridge appeared twice in Orange in early 1888. This was just after the lab in Orange was finished and while it was being staffed and equipped. . . . the public announcement that they’d met (initiated by Muybridge) came after the second meeting.”

192:*Edison quickly deduced*: A caveat’s purpose was to prevent rivals from patenting the same invention. This practice ceased in 1909. Edison submitted four famous early caveats about movie devices [Hendricks (1961), Appendix B]. The first showed the cylindrical recording format, and the second showed reel-to-reel perforated film [Musser (1994), 63, 67 (with Edison’s sketches reproduced)].

192:*Dickson had to*: Paul Spehr, email June 15, 2015: “I wouldn't say Dickson despised Edison. He was very conflicted. Yes, he desperately wanted recognition, but like almost all of the staff, he liked Edison and being cast out was traumatic. Though Edison continued to call him a XXer [double crosser], after 1912 he wrote some cordial letters and started paying Dickson a pension.”

193:*Thomas Edison, ca. 1894*: Dickson and Dickson (1895), 54–55, from “the June number of *The Century*,” quoting Edison, also on p. 4 in Edison’s handwriting. In the actual quote Edison misspelled Marey as Marié.

193:*W.K.L. and [sister]*: Dickson and Dickson (1894), preface. The often purple prose of this biography might be mostly due to W.K.L.'s sister Antonia.

193:*He often used*: The "Right Honorable" designation was by Samuel Insull [Spehr (2008), 9]. I've inspected hundreds of Dickson records, and only one of them misspelled the name Dixon. It wasn't a common error in WKLD's case, so Edison's use was surely deliberate.

194:*Historians—even those*: Hendricks (1961), 163–168, Appendix C: Fifty Representative Dickson Errors, "The following errors show the extent to which Dickson himself, in his many statements, wandered far afield from the truth."

194:*William Kennedy-Laurie*: Dickson and Dickson (1895), 54, possibly written by his sister (and second author) Antonia. Two surnames that often appear side by side in a lineage are sometimes joined with a hyphen to indicate the constant pairing. And sometimes the paired names are treated as a single name. Since this use of hyphens is inconsistent, I use them in names only in direct quotations. Many of these aristocratic families tend to pass down surnames in their lineages as first names of descendants.

194:*What he consistently*: Smith (2019) is a scholarly documentation of W.K.L. Dickson's descent. Much of it proceeds from the Dickson, Waite, Ricketts, and Barrett families of Jamaica. A Waite ancestor was Thomas Waite, one of the regicides of Charles I. Although Dickson did descend from a Hogarth family contemporaneous with the famous Hogarth's, I was unable to establish a connection. The famous Hogarth had no children, so the connection, if it existed at all, was indirect. The Robertson and Laurie families are established as stated, including the connection to the Royal Stuarts.

An unsolved problem in Dickson's biography is: Why did Dickson's mother choose to move her family from Europe to near Richmond, VA, a few months before her death? No satisfactory reason for that particular choice, such as a relative, has been found.

194:*Dickson, being an*: Nor does Edison's ancestry bear close scrutiny either, so far as being an all-American hero. His great-grandfather John Edison, an early resident of NJ, then a New York City banker, was a Loyalist during the American Revolution and immigrated to Canada just after. Thomas's father, Samuel Edison Jr., was born in Canada and immigrated to Michigan about 1838 and then to Ohio, where Thomas was born.

194:*Dickson was the*: Paul Spehr, email June 15, 2015: "John Ott was the head of Edison's 'Precision' machine shop and the lead machinist. In the early stages of the cylinder experiments (1889), John and [Edison] made the first drawings and in the summer of 1892 it was John who did much of the design work on the final version of the Kinetoscope."

The IMDb online movie database, https://www.imdb.com/name/nm0005690/, accessed Apr. 4, 2020, lists 326 movies for William K. L. Dickson, from *Monkeyshines* in 1890 to *Pope Leo XIII* in 1903.

195:*Another Edison caveat*: Hendricks (1966), 58–59, mentions the "plaster bust of Edison painted to look like bronze," which, to be fair, Edison asked to be removed a few weeks after the opening. "He thought its display undignified." The electric dragon with green eyes was an Edison symbol supplied to parlor operators. The potted palms were probably just a marketing touch, as were the many ladies. Another drawing of about a year later shows no palms, ladies, bust, or dragons.

Paul Spehr, email June 15, 2015: "Edison had stayed away from the marketing of the Kinetoscope. It was the Holland Brothers' parlor . . . Edison just wanted to sell the films to the marketers, he paid little attention to how they showed them. But Edison's name—and bust—was marketable."

A peep show was sometimes called a nickelodeon because it cost 5¢ per show. Although it's presented as a failure-to-project in this chapter, it's interesting to note that a peep show shares single-person viewing with the most modern virtual reality (VR) goggles.

196:*Edison's business partners*: Although Jenkins's name remained on the patent for the Phantascope, all business dealings were with Armat who had bought him out. Email from Paul Spehr, June 15, 2015, "Armat had bought out Jenkins, but it was the Armat-Jenkins patent. Raff & Gammon [Edison's business concessionaires] set-up the relationship. Edison modified Armat's projector and patented it later as modified. But Edison never had a dominant patent on a projector, not one he could use in his many lawsuits." Paul Spehr, email Aug. 17, 2015: "Armat retained his patent, later sued Biograph for infringement but they worked a deal and Biograph took over rights to Armat's patents."

196:*Importantly, and missing*: Paul Spehr, email June 10, 2015: "[Film] is the key to what went on in the early years. Eastman's celluloid made Edison's camera possible—Dickson was in Rochester in a flash to get some. The troubles Eastman had producing satisfactory film in 1893–1894 had a crucial effect on what happened in 1894–5 and into 1896. Eastman turned the market over to Blair, the source of Edison's film into 1895. The early film was not cut to camera/projector size, but by 1896 Blair and European Blair (now semi-independent) were precutting film to 35 mm, but unperforated. Though Lumiere set-up their own film mfg. company, when they started they purchased from European Blair—35 mm unperforated. So the Cinematograph used 35 mm, but different perfs. Similarly, Paul and Acres could buy unperforated 35 mm from European Blair and they did. Sometime in 1895–6 European Blair began perforating—I've found no record to verify this, but the widespread use of 35 mm in European cameras and projectors confirms it. Eastman had to be persuaded to go seriously into 'cine' film. His European manager talked him into it in June, 1896 at a time that Eastman was going to Europe for an extended business-pleasure trip. While he was gone. Kodak's president, [Henry A.} Strong, managed things in Rochester and pushed the cine film business with notable success. There was no patent on the 35 mm format so its ready availability led to the rapid spread of the format and to international standardization. The factor that ultimately made the large formats (Biograph, Eidoloscope and Demeny's and Lumiere's) obsolete."

196:*Dickson consulted with*: Spehr (2008), 618, Dickson letter of Jan. 19, 1926.

197:*The first extracurricular*: The Lathams were the father Woodville Latham and his two sons Otway and Gray. Lauste is another name missing from Hopwood (1899), but the Lathams and the Eidoloscope do appear briefly on p. 261. Email from Paul Spehr, June 15, 2015, "The Lathams had a press screening of the Eidoloscope on April 21, 1895 (then called Pantoptikon), the commercial showings started May 20, 1895." It's an unsettled conflict whether Lauste created the Latham's projector [email from Spehr, Aug. 17, 2015].

197:*That year,* 1895: So Skladanowsky's Bioskop projection in Berlin, Nov. 1, 1895, was the first public commercial projection in Europe, barely edging out the Lumières [Mannoni (2000), 457]. Raff and Gammon were primary promoters of Edison machines and films. The patent on the Phantascope was in the names of both Armat and Jenkins, but the deal with Raff and Gammon was executed by Armat alone. Armat and Jenkins had fought, and Armat had bought out Jenkins by that time.

197:*And so was*: Letter written Mar. 31, 1932, by Dickson (born Aug. 3, 1860) from Jersey, Channel Islands, to his relative, Raynes W. S. Dickson, in Melbourne, Australia [Smith (2019), Fig. 12, from the University of Melbourne Archives]. Eastman was George Eastman who had a lot to do with early celluloid film manufacture and processing. He has been idolized, like Edison, although there were other players, like John Carbutt and Thomas Henry Blair, who were crucial to the mastery of celluloid film.

In fairness, Edison did reward Dickson—and his coworker William Heise—financially for the invention. Musser (1995), 20, "Edison also paid generous royalties to Dickson and Heise for their key roles in the inventive process." Spehr email, Sept. 14, 2015, "Yes, he [WKLD] made out pretty well in 1894. At least 5 percent and perhaps 10 percent—I've not seen it spelled out. Might have doubled or tripled his salary."

197:*Dickson formally parted*: Dickson and Marvin began meeting annually at a spa in upstate in New York in 1887. Casler began to join them there a few years later. Dickson and Casler created the tiny Photoret camera probably in 1892 and announced it in Dec. 1893, with backing from Marvin. An important distributor was Koopman's Magic Introduction Co. in New York City [Spehr (2008), 290–294]. Spehr email, Sept. 14, 2015, "Casler and Marvin were natives [of upstate NY]."

197:*Casler, with Dickson's*: Casler and Dickson also built a peep-show competitor—not a projector—called the Mutoscope.

The company was first known as the American Mutoscope Company, then the American Mutoscope and Biograph Company, and finally just the Biograph Company [Musser (1994), 145]. Casler obtained a patent on the Mutoscope in Nov. 1894 [Spehr (2008), 352]. Casler had contributed to pre-cinema with a card-flipping device, also called a Mutoscope; the Lumière brothers continued to pursue card-flipping in 1898 with a device they called the Kinora [Hopwood (1899), 36–39]. Biograph patented the Mutoscope in France before the Lumières patented the Kinora, so they did business together in the UK (and Gaumont made some of the parts) [email from Paul Spehr, Aug. 17, 2015, who added "Competition was less competitive at the end of the 19th Century"].

198:*Marey knew that*: Alternatively, *chronophotography* can be thought of as so generic that it includes both pre-cinema and cinema.

198:*Marey knew about*: Mannoni (2000), 325, "Marey showed [ca. 1873] that the galloping horse was, at a given moment, suspended above the ground, and that then its left hind leg touched ground." So at about the same time that Muybridge showed all four hooves off the ground in a fast trot, Marey demonstrated it in a gallop.

198:*Muybridge, Marey, and*: Ball (2013), 318–319, "Marey got in touch with Muybridge directly, writing him in December 1878 . . . Marey told Muybridge that he should 'animate' his photos and 'create a revolution'." Mannoni (2000), 331, "During his visit to Paris in September 1881, Muybridge brought Marey the first sequential photographs of a bird in flight," but Marey was disappointed in the quality of them. Ball (2013), 334, "In August [1881] Muybridge set off for France . . . His trip would not be a buying tour, but something closer to a victory lap. . . . On September 26, Marey gave a reception for the inventor."

Later Edison was added to the circle. He famously met Muybridge in 1888, inspiring Edison to do movies right. Musser (1994), 66, "During his visit to Paris [1889], Edison had met Etienne-Jules Marey and become acquainted with the Frenchman's methods of photographing continuous series of images on a film strip that was moved along intermittently in front of a single camera lens." Spehr (2008), 142–147, "Edison was received in Paris as a celebrity among celebrities. . . . It is the dinner celebrating the fiftieth anniversary of photography that holds particular interest." Edison was the guest of honor at this dinner, attended by Marey, the Lumière brothers, and many other notables. "Marey and Edison both confirm that they met at the Exposition [p. 145]."

198:*One of the*: Spehr (2008), 138–140, "If Dickson, Brown, Edison and Fred Ott [brother of John Ott] can be believed . . . a version of the Kineto using strips of film was started, probably just before Edison left for the Paris Exposition." Here and on pp. 142–147 Spehr presents his supporting arguments in this contested claim. Specifically, the dominant film format of the last century was 35 mm film with four rectangular perforations, on each side of the film strip, per frame. (The original Kinetograph film format was close to 16 mm; Dickson redesigned in 1891–1892 to 35 mm [email from Paul Spehr, Aug. 17, 2015].)

199:*Laurent Mannoni, The*: Mannoni (2000), 436.

200:*Laurent Mannoni, The*: Mannoni (2000), 422.

200:*Mannoni's epigraph puts*: *Reversible* does *not* mean that the film can run backward.

201:*But drop that*: A main source for the Lumières is their collected letters [Rittaud-Hutinet (1995)]. The letter [pp. 16–17] from Davanne to Louis Lumière, Mar. 22, 1895, mentions "your success at the Société d'Encouragement . . . with your projection of moving images . . . which your audience in Paris found equally fascinating." The Cinématographe was shown again on July 11, 1895, in Paris before 150 people [pp. 21–22]. In the letter of June 30, 1920, from Louis Lumière [pp. 195–200], "the lecture I gave at the Society for the Advancement of National industry (22 March 1895) during which I projected, before an audience of several hundred people, a long series of cinematographic images." Both Leon Gaumont and Jules Carpentier attended that first showing.

201:*There's no doubt*: Spehr (2008), 111–117; Mannoni (2000), 346–350. As opposed to the Lumière device, Bouly's device didn't have sprocket holes, using pressure instead for frame registration. Bouly's device was not also a film printer as was the Lumières'. The Dickson et al. Biograph used a pressure system, which they might have borrowed from Bouly. It's not clear that the Lumière machine was actually used as a printer, however. Paul Spehr, email Sept. 5, 2015: "When the Lumiere cameraman, Promio came to the US in 1896 he filmed in NY, Niagara Falls and Chicago but the film was delayed because it was sent to Lyon for processing and printing."

201:*Unfortunately, the Lumières's*: The Lumière film format was 35 mm but with one circular perforation per frame, so incompatible with the Edison perforation system of four rectangular perforations per frame [Musser (1994), 135]. Musser (1994), 177, "the cinématographe ceased to be a powerful force in America cinema during the spring of 1897."

201:*The name Georges*: Mannoni (1997); Mannoni (2000); and Lefebvre, Malthête, and Mannoni (2000).

201:*Étienne-Jules Marey*: Marey's relationship with Demenÿ is derived principally from Mannoni (2000), 333–363. The father-son aspect is most clear in the many letters between the two, transcribed in Lefebvre, Malthête, and Mannoni (2000).

259:*As mentioned earlier*: Hopwood (1899), 83, "M. Demeny incorporated a new and important modification into his German and English patents applied for only two months later—that is to say, in December, 1893. This development was not added to his French patent until July, 1894 . . .

The film, after passing in front of the aperture, where it is steadied by friction rollers, is periodically struck by an eccentric rod or dog-motion, which draws down sufficient film to change the picture." The relevant US patent was Demenÿ's no. 544,480, dated Aug. 13, 1895, claim 14.

Another important mechanism that appears in several different projectors is the so-called "Latham loop."

202:*In later years*: Mannoni (2000), 362, transcribes Marey's complaint this way: "I learned that he [Demenÿ] had found it necessary to modify, in order to make it patentable, and to exploit in his own name one of my instruments whose description I had already given and which was, as a result, in the public domain. While legally permissible, this type of action is not among those which, in the scientific world, can be considered acceptable."

202:*In 1895 Demenÿ*: Mannoni (2000), 417–421, 442–450, covers the complicated Gaumont-Demenÿ relationship. I have omitted all mention of Demenÿ's Phonoscope (renamed Bioscope by Gaumont), since it was disk-based, not strip-based. Demenÿ dealt with Marey, de Bedts, the Lumières, and Gaumont re the Phonoscope. Léopold René Decaux assisted Demenÿ and Gaumont in converting the Biographe to a reversible machine. A solid line connects Gaumont to the Biographe because he was an engineer as well as a businessman. As a young man he worked for Jules Carpentier, who later famously helped the Lumières perfect their Cinématographe.

203:*Joly had the*: Mannoni (2000), 449, "He [Demenÿ] had never ceased to claim, with equal measures of tactlessness and truth, his part in the invention of the cinema. Rejected by the friends of Marey and by Gaumont, he is viewed with a certain contempt by the 'Lumièristes' of yesterday and today." Mannoni (2000), 446–449, covers the Demenÿ-Gaumont split.

203:*Joly noticed that*: Mannoni (2000), 434–439, p. 437: "By 3 May 1896 he [Pathé] was in a position to offer his fairground clientele a film projector—whether this was a Joly machine or a copy of the Cinématographe Lumière is a complete mystery." Joly went into business next with Eugene Normandin, who had bought all the early patent rights to his machine. In a financial squeeze, Charles Pathé went into business with his brother Émile, hence the full company name Pathé Frères.

204:*Demenÿ's third defeat*: Mannoni (1997), 78–83, includes photos of the drawings. The Louis Lumière letter of June 30, 1920 [Rittaud-Hutner (1995), 195–200], denounces Demenÿ's claims. In it (p. 198) Lumière mentioned his visit to Demenÿ's sometime after Nov. 1 and before Dec. 28, 1894: "I did not see any device while there." But he failed to mention the drawings he had been shown there in December. The fact that the mechanism shown Lumière was crude comes from an email from Laurent Mannoni, Aug. 18, 2015.

204:*Demenÿ also appears*: Mannoni (2000), 430, "The two Americans [Jenkins and Armat] had no hesitation in taking up this excellent drive mechanism [Demenÿ's beater] for their projector. Demenÿ had no chance: misunderstood in his own country, and pirated by the Americans."

Paul Spehr [email Dec. 9, 2015]: "This is Armat's application for a patent for a Vitascope, that became U. S. 673,992, May 14, 1901. The application was filed February 19, 1896, Serial no. 579,901. The letter of rejection was dated March 26, 1896, from patent examiner Oscar Woodward. He rejected claims 1, 2 & 3 on patents Le Prince no. 376,247, Jan. 10, 1888, and Demeny, no. 544,480, Aug. 13, 1895. He rejected claim no. 14 on Demeny 544,480. . . Armat's claim [14] read: 'In combination with a picture-carrying film or strip and means for moving the same so as to exhibit successively the pictures thereon, a rotating element adapted to intermittently engage and move the film a predetermined distance once during each revolution thereof; the engaging part of said element being provided with a covering of soft but smooth material adapted to protect the surface of the film and prevent the same from wearing away, substantially as described.'"

204:*By 1907 the*: Eastman was an unenthusiastic member of the trust. Spehr email, Sept. 5, 2015, "Independents had no problem buying film stock through Jules Brulaor who supposedly was selling European film but was rumored to sneak some Edison stock in his shipments."

205:*A claim that*: Nordisk Film was founded in Denmark in 1906. The order is Gaumont, Pathé, Nordisk, Universal, and Paramount.

Not too much should be made of the separation of Hollywood physically from the East Coast because the large studios had branches, or even their main offices, in the East. Universal, in particular, had corporate offices in New York City, and still does.

Paramount was originally known as Famous Players-Lasky.

205:*The remote Hollywood*: *Motion Picture Patents Co. v. Universal Film Mfg. Co.*, 1917, the Supreme Court found unenforceable the MPPC claim that a user of a patented film projector must use it only for projecting films authorized by the patentee.

206:*Donald Crafton, Before*: Crafton (1993), 12. The full title is *Before Mickey: The Animated Film, 1898–1928*. This is my primary source for the history of early animation.

206:*Ashton Stephens, a*: Crafton (1993), 110, citing the Chicago *Examiner*, Feb. 9, 1914.

206:*Defining them is*: An exception is an animated film where the frames are created nonphotographically by painting directly on the celluloid base of the film. One of the earliest animated films is of this variety, made in Germany in 1897 and in the collection of the Cinémathèque française, Paris. Canadian Norman McClaren created several such films in the 1940s.

206:*These films illustrate*: The clay-based Wallace and Gromit movies are other good examples—for example, Nick Park's *The Wrong Trousers* (1993). The Harryhausen example—of skeletons composited over live action—shows that animation can be mixed with ordinary live-action cinema.

There were many other early animators than those listed here. See Crafton (1993).

207:*Early cinema was*: This is a *match cut*, where the pictures before and after the cut match in size, shape, and position (a symmetric position in this case)—and direction of movement, in this case. To evoke the scene I've omitted some of what actually happens in the transition. The bone flies upward, reaches apogee, and starts to tumble downward. Then the cut occurs to a cylindrical satellite also moving downframe, bringing the Earth's surface into view. Several other cylindrical satellites, but not this original one, glide above the Earth. The slow dance of satellites culminates in the grand approach to Space Station V revolving slowly to the majestic music of Johann Strauss's *An der schönen blauen Donau* (The Blue Danube Waltz, 1866). *2001: A Space Odyssey* (1968) is listed in the prestigious National Film Registry of the US Library of Congress.

208:*Hence the world*: Crafton (1993), 232–235. Fischinger's *Motion Paint No. 1* (1947) is listed in the National Film Registry. Larry Cuba, a computer graphics pioneer, helped to run iotaCenter devoted to such films in Los Angeles, CA [http://iotacenter.org/, accessed Apr. 7, 2020].

209:*Donald Crafton, Before*: Crafton (1993), 61.

209:*Succeeding the trickfilms*: Crafton (1993), 112–116. Re mixing live action with animation: (p. 113): "McCay lightning sketches the prehistoric landscape on a large pad and calls the dinosaur out of her cave by name; then the animation begins." Originally he was onstage in a vaudeville act. He would interact with a projected movie showing the drawings. In filmed versions, the live action of McCay himself is intercut with the animated action of Gertie.

209:*Émile Cohl is:* Crafton (1993), 58–89, for Cohl (especially pp. 60, 64, 81–85, and 89); also Crafton (1990), a book devoted to Cohl. His real name was Émile Eugène Jean Louis Courtet, but he affected the Cohl alias for nearly all his career. Cohl came to New Jersey and worked with the Éclair Co. there, but all of his films were lost to fire. Cohl's *Fantasmagorie* (1908) can be viewed online at https://publicdomainreview.org/collection/emile-cohl-s-fantasmagorie-1908, accessed Apr. 4, 2020. He died in France, where he's not completely forgotten. For example, there's a Square Émile Cohl in Paris not far from the Cinémathèque française, and a Place Émile Cohl in Nantes that intersects Rue Georges Méliès.

210:*Donald Crafton, Before*: Crafton (1993), 113, re Winsor McCay's *Gertie the Dinosaur* (1914), a film he describes (p. 110) as "the enduring masterpiece of pre-Disney animation."

210:*The magical soul*: Cf. *to inspire*, from Latin *inspirare* 'breathe or blow into,' from *in-* 'into' + *spira-re* 'breathe.' The word was originally used of a divine or supernatural being, in the sense 'impart a truth or idea to someone' [from Google].

210:*It wasn't obvious*: See discussion of actors and animators in the Finale chapter.

210:*As a child*: Disneyland 2.11, *The Story of the Animated Drawing,* available in four parts [https://www.youtube.com/watch?v=UXDwn2OELMU&t=6s, accessed Apr. 4, 2020] is a particu-larly interesting program because Walt gives a history of animated cartoons. He mentions or shows a nice mixture of Yanks and Franks: Lascaux, Altamira, Egyptian mural art, Leonardo da Vinci, Paul Roget, Joseph Plateau, Émile Reynaud, Winsor McCay, J. Stuart Blackton, J. R. Bray, Raoul Barré, Earl O. Hurd, Pat Sullivan, Otto Messmer, and Max Fleischer, before arriving at his own company's films. He doesn't mention Muybridge, Marey, Cohl, or his partner Iwerks.

Animator Steve Smith in the San Francisco area taught me basic animation skills in the early 1970s. I also was self-taught at about the same time from a famous book, *Animation*, by Disney animator Preston Blair, a version of which I bought for $1.50. We learned the details of large-scale cel animation from a team of old timers at New York Institute of Technology on Long Island in the late 1970s. We begin implementing cel animation digitally for the Disney company as the Graphics Project at Lucasfilm, completing the effort at Pixar in the 1980s. It was known as CAPS (Computer Animation Production System), a system I proposed and negotiated with Disney. It was implemented by a team headed by Tom Hahn. See further details later in this chapter and in the Millennium chapter.

211:*In the early*: Crafton (1993), 77.

211:*In another technique*: Crafton (1993), 192–200, for Raoul Barré. Crafton describes slash and tear as the inverse (p. 194) of Cohl's decoupage system.

211:*A strong reason*: Crafton (1993), 137–150.

211:*Into that patent*: Crafton (1993), 150–157. It wasn't Bray who dropped the patent hammer on competitors. It was his formidable wife, Margaret Bray.

212:*Wicked Witch, Snow*: Hodges (1983), 149.

212:*Since cel animation*: Crafton (1993), 244–246, gives German Lotte Reininger credit for the first feature-length animated film, *Die Abenteuer des Prinzen Achmed* (*Adventures of Prince Achmed*) (1926).

She used two-dimensional shadow puppets against color-tinted backgrounds. *Snow White* was in full color and had sound. There are also reports that Argentinian Quirino Cristiani made two animated films even earlier, but they were lost to fire.

212:*The cel animation*: If a movie is 90 minutes long, then at 24 frames per second there are 90×60×24 = 129,600 frames to fill. Animated movies were often shot on 2s in the early days, so 12 new frames per second, where each frame was recorded twice. This practice halved the effort to about 65,000 new frames per movie. These numbers don't include the titles and end credits, which add another 30,000 or so frames to a feature-length film.

212:*To create each*: This omits some of the animation hierarchy in a large animation studio. There a *head animator* draws the *keyframes* of an animated character and imparts timing information for the frames that will occur between the keyframes. Then an *assistant animator* cleans up the head animator's more casually expressed keyframes—ensuring, for example, that areas to be colored are completely enclosed with lines. Then *inbetweeners* generate the missing frames between the keyframes, using the timing specified by the head animator. All these steps are in pencil on paper. Then the inkers take over, transferring the penciled lines on paper to ink on celluloid.

215:*Frank and Ollie*: Frank and Ollie were ennobled in the Disney company by being made Disney Legends in 1989. That same year Ub Iwerks was also made a Disney Legend, as were the other seven of the Nine Old Men: Les Clark, Marc Davis, Milt Kahl, Ward Kimball, Eric Larson, John Lounsberry, and Wolfgang Reitherman.

216:*They distorted reality*: Thomas and Johnston (1981), 51. Since there are 12 drawings between two successive high points, this bounce was probably intended to be shot on 2s for a one-second bounce. One-half second—that is, if it were shot on 1s—seems to be too fast.

217:*When I played*: I told this story at Trinity College, Cambridge, several years ago. There were lords and ladies in the audience seated on a special couch at the front of the room, directly before me. At the end of my talk, I was delighted to spot Lady Huxley, wife of Nobelist Sir Andrew Huxley, looking up at me with a twinkle in her eyes and a mischievous smile as she clapped the big, fat, sloppy way I had described. She and I had a grand time at the party afterwards, and with Lord Huxley who co-formulated the famous Hodgkin-Huxley model of how a neuron works.

218:*Laurent Mannoni, of*: On a visit July 10, 2015. See also Mannoni and Campagnoni (2009), 182–183, 249.

218:*But the US*: Crafton (1993), 169–173. The releasing company was formally Goldwyn-Bray Pictograph (p. 172). Max Fleischer applied for a patent on rotoscoping in 1915 and it was granted in 1917 (U.S. patent 1242674 (A), Method of Producing Moving-Picture Cartoons) [see Crafton (1993), 171].

219:*Dave Fleischer played*: IMDb, https://www.imdb.com/name/nm0313101/, accessed Apr. 4, 2020, John Gentilella (1914–1997), animator at Terrytoons on five films, 1938–1944, began work with Famous Studios in 1944. Famous Studios was the first animation division of Paramount, after Paramount took control of Fleischer Studios, ousted Max and Dave, and changed its name. In particular, Gent was an (uncredited) animator in *Spinach Packin' Popeye* (1944), directed by Izzy Sparber and (uncredited) Dave Fleischer.

219:*Ed and I*: Our most direct interface to the cel animation team at NYIT wasn't Gent, but a young animator named James A. "Jamie" Davis. Two others were Dante and Victor Barbetta. The background artist we interacted with was Paul Xander.

219:*Russell Merritt, quoted*: Iwerks and Kenworthy (2001), 24, probably from the Leslie Iwerks interview with Russell Merritt in 1998 (p. 236). Co-author Leslie Iwerks is Ub's granddaughter, and Don's daughter. As a film producer, she created and directed the documentaries *The Hand Behind the Mouse: The Ub Iwerks Story* (1996) and *The Pixar Story* (2007).

219:*Leslie Iwerks and*: Iwerks and Kenworthy (2001), 15.

219:*It's time to*: Iwerks and Kenworthy (2001), 1–14, for the early history of the pair. I usually use surnames for the people in this book whom I don't know personally, but since there are several Disneys I will refer to Walt Disney as Walt. Not only does this distinguish the three persons here by that surname (Walt, Roy O., and Roy E.), but it dissociates the man Walt from his company Disney. And since I use Walt's first name, I also use Ub's. See also Gabler (2006), 46–50.

220:*He was so*: Iwerks and Kenworthy (2001), 15–24.

221:*It was in*: Iwerks and Kenworthy (2001), 54, Walt urged the name Mortimer Mouse, for an actual pet mouse he'd had, but his wife Lillian called it too sissy a name. Walt did succeed in naming Minnie Mouse, however, for an early financial supporter's wife. Gabler (2006), 112–116, however, calls this naming legend into question. Silvester (2015), 7, also calls it a legend. But all sources agree that Iwerks drew Mickey Mouse.

The Walt Disney Company position is that Walt and Ub co-created Mickey, which doesn't appear to fit the evidence. Their disapproval of my treatment took the form of denying me permission to use several illustrative pictures from that era for this book. Most of them appear in Iwerks and Kenworthy (2001), a Disney publication which serves as the principal source for my version.

Mitenbuler (2020), an excellent new book on classic animation, appeared while I was proofing this book. Reid Mitenbuler reached much the same conclusion as I re the Disney version of the

Mickey creation myth, including these remarks [pp. 90–91]: "The exact origins of Mickey Mouse are murky—Disney knew that a good creation myth works best when left a little slippery. He was a performer first, never letting dry facts or details get in the way of a good story. . . Ub Iwerks, Disney's chief collaborator, typically laughed off these stories as 'highly exaggerated publicity material.'"

221:*Perhaps the proverbial*: Gabler (2006), 143–144; Iwerks and Kenworthy (2001), 78–84. The Walt Disney Company similarly disapproved of my treatment of the split between Walt and Ub, but it is supported by Iwerks and Kenworthy (2001), a Disney publication. Walt is to be praised for all that he accomplished—which was large—but not for what he did not. I have no trouble separating Walt, the man who inspired much of my life and career, from the too-good-to-be-true marketing legend. In fact, the distressing tendency toward all-perfect heroes is much of what this book argues against. On the positive side this book is, in a large sense, about the immensity of what Disney actually accomplished and how it actually happened.

222:*In February 1930*: Iwerks and Kenworthy (2001), 87.

222:*Sadly, the Walt*: Iwerks and Kenworthy (2001), vi, in the Introduction by film critic Leonard Maltin, "I thought I knew all there was to know about their notorious split, when the Disney brothers felt abandoned by a trusted colleague, but this book told me much more about the story—as seen from both sides."

223:*By the time*: My handwritten notes for trip to Disney, Jan. 3, 1977 [Smith (1977)]: "[Dave Snyder] was very in favor of our stuff but figured his higher ups wouldn't back its development (but should!) 'Ub would have'" and "[Dave Snyder] used to work directly under Ub Iwerks whom he openly admired." Also, "We re-presented the demo (in the old Mickey Mouse Club offices) to

Frank Thomas, Ollie Johnston, Art Hansen, and Ken Stevens." So this was when we first met Frank and Ollie, who were to be our friends and supporters until their deaths in 2004 and 2008, respectively. One of my treasures is a copy of Thomas and Johnston (1981), inscribed "to Alvy—a real leader in your own field—best wishes—Ollie Johnston Frank Thomas." N.B., David Snyder was a manager of complex technical processes at Disney, starting there in 1968. He then proceeded to a long career as an executive at Disney, Disney affiliates, and other entertainment companies.

Roy E., Walt's nephew, engineered the replacement of top management by Michael Eisner and Frank Wells. Wells was responsible for the CAPS deal with Lucasfilm (then with Pixar). I received the first check, for $1 million dollars, from Wells for CAPS and proudly received it again for a photographer from a group including Roy E. under a tapestry of Mickey Mouse in 1986. Unfortunately Wells was killed in a helicopter accident in 1994. Later Roy E. again used his influence to encourage a top replacement, of Eisner this time, by Robert Iger, who was the man finally responsible for Disney's purchase of Pixar in 2006.

224:*Otto Messmer, foreword*: Crafton (1993), xv, Foreword.

224:*Otto Messmer, epigraph*: Crafton (1993), 301.

225:*Donald Crafton celebrates*: Crafton (1993), chapter 9, particularly 300–321. Some Australians still claim primacy for Sullivan, who was born in Sydney, but nearly all animation historians now agree it was Messmer.

225:*Sullivan's name was*: It might only be coincidence that Walt and Ub's relationship was starting to fray about this time.

225:*I haven't really*: Our understanding of the brain changes by the moment. My wife's nephew Adrian Bondy sent me his 2017 paper on research showing that the lowest level of the visual cortex (in Macaque monkeys) affects what signals get sent from the retina to the brain, presumably altering what the mind perceives. The higher levels of the cortex are surely involved too, but it's a fresh insight that the brain is modifying what the retina "sees" from the very beginning of its processing.

226:*The story of*: Ed Catmull was in on this great hire too. See details in the Millennium chapter.

231:*Philip J. Davis*: Full reference: "Philip J. Davis, Symposium on Approximation of Functions at General Motors, 1964" as given by Schoenberg (1973), v, in its use of the quotation as an epigraph for its preface.

231:*A pleasure of*: Tom Porter recalled [email Aug. 4, 2016] that he implemented spline paint probably in late 1981, perhaps in 1982. Ravi Shankar recorded a live album in San Francisco in 1982, with Ali Akbar Khan and Alla Rakha: "Concert recorded at the Palace of Fine Arts at a benefit for the Ali Akbar College of Music, San Rafael, California, USA," https://www.discogs.com/Ustad-Ali-Akbar-Khan-Pandit-Ravi-Shankar-With-Ustad-Alla-Rakha-At-San-Francisco/release/2804789, accessed Apr. 5, 2020. The album issued under the EMI label as an LP in 1983. The Computer Graphics Research Group at Lucasfilm was located in San Rafael in 1982.

231:*By happenstance there*: The artist was Maureen Jones, whom I never heard from again. I used the flower in 1982 as an element in a cover design for a Japanese magazine, *Nikkei Computer*, that published Feb. 21, 1983, http://alvyray.com/Art/Equilibrium.htm, accessed Apr. 5, 2020. Other elements of this design were copper vessels by another of the Pixar geniuses, Rob Cook, who had mastered the look of metallic surfaces, and additionally some of my graftal plants with many blossoms.

232:*Henry David Thoreau*:Henry David Thoreau, *Walden, or Life in the Woods*, Boston: 1864, 232–233 of 248.

232:*The spline of*: Typically, French curves come in sets, offering a higher probability of finding the curve parts needed.

233:*Serious draftsmen need*: French curves aren't just for children or amateurs. Car body designers have been known to use very large versions, called *sweeps*, several feet long [Robin Forrest, conversation June 12, 2017].

233:*The geometrical spline*: We don't use the term *whale* in computer graphics, but we do sometimes use the alternative *knot*. A mathematical spline is made piecewise too, as with the French curve, each piece being known mathematically as a polynomial curve. The polynomials used are typically cubic.

While assembling picture credits for this book, I learned that the painted ducks are no longer available from Pete Peterson, the person who made the ones in figure 6.2: "I stopped making them in 2013. I made them for personal use, but boatbuilding friends saw them and it became a hobby."

234:*Alan Kay, Xerox*: Alan Kay, July 20, 1982, at a seminar called "Creative Think," organized by Roger van Oech, author of a book on creativity called *A Whack on the Side of the Head*, published in 1983 (implying that the seminar was prepublication). Recorded by Andy Hertzfeld of the original Apple Macintosh team who attended. Andy's notes are filled with Alan Kayisms and may be found at *Creative Think* (1982). Alan, email July 3, 2016, re his sayings, "A few were done at PARC [Xerox

Palo Alto Research Center, pronounced "park"], but I think the bulk of them were coined in the 80s and 90s while I was at Apple." The following argues for PARC:

This is Alan's own explanation: "At PARC we had a slogan: 'Point of view is worth 80 IQ points.' It was based on a few things from the past like how smart you had to be in Roman times to multiply two numbers together; only geniuses did it. We haven't gotten any smarter, we've just changed our representation system. We think better generally by inventing better representations; that's something that we as computer scientists recognize as one of the main things that we try to do." [Quoted on http://billkerr2.blogspot.com/2006/12/point-of-view-is-worth-80-iq-points.html, accessed Apr. 5, 2020.]

Alan helped to hire me at Xerox PARC in 1974. Alan, email of July 3, 2016, "I left PARC on a Xerox Sabbatical in 1980."

234:*We met Sir*: Whittaker's math students at Trinity included G. H. Hardy and John Littlewood who achieved public notice in the recent movie *The Man Who Knew Infinity* (2015) as the sponsors of Indian savant Srinivasa Ramanujan.

234:*The Theory of*: Whittaker and Robinson (1923), 2. Also this, from the preface (p. v): "A knowledge of the Theory of Interpolation is required by all who make inferences from the results of observation, especially by astronomers, physicists, statisticians, and actuaries."

235:*Whittaker's point of*: Robin Forrest, in conversation on June 12, 2017, in Norwich, made the point that Whittaker was never actually interested in creating an entire continuous curve between two given data points. He was only ever interested in generating one or a few data items between the two.

235:*Kotelnikov's Sampling Theorem*: It's worth a reminder here that I often omit the qualifier "slightly greater than" when I state the Sampling Theorem. This is just to make the wording less clumsy for the lay reader. The theorem actually requires that sampling be done at *slightly greater than* twice the highest frequency in the Fourier representation. I'll be happy if the casual reader intuitively remembers only that it's twice, or about that.

235:*Despite the two*: The bandpass version of the Sampling Theorem is for smooth curves that have both a highest and a lowest Fourier frequency component. Sampling in that case occurs at twice the *difference* of those two frequencies. In the simpler version (the so-called *lowpass* version) of the Sampling Theorem, the lowest frequency is assumed to be 0, so the difference between the highest frequency and the lowest is just the highest frequency, so we sample at twice the highest frequency. See the Turing chapter about how bandpass sampling was used in his Delilah vocoder.

Whittaker had a philosophical and religious bent, as indicated by the title of his 1946 *Space and Spirit: Theories of the Universe and the Arguments for the Existence of God*. And he thought Henri Poincaré discovered special relativity, not Albert Einstein—a view now rejected by a majority of scholars [argued in Torretti (1983), 83–87].

[Math] Mathematicians talk about one statement *implying* another. Thus if p *implies* q, then p is true implies that q is true, but q is true doesn't necessarily imply that p is true. The statement q implies p is the *converse* of p implies q. If both a statement and its converse are true, then they are said to be *equivalent*. Thus, if p implies q and q implies p then p is equivalent to q. And p is equivalent to q is exactly the same as saying q is equivalent to p. So p and q are completely interchangeable. Kotelnikov first proved this: (curve c is represented by a sum of Fourier waves of highest frequency F) implies (curve c is represented by samples of c taken at a frequency greater than 2F).

Then he proved the inverse: (curve c is represented by samples of c taken at the frequency greater than 2F) implies (curve c is represented by a sum of Fourier waves of highest frequency F). Thus the two representations are exactly equivalent. Whittaker proceeded in the other order but got to the same result, the equivalence of the two representations. But Kotelnikov also proved the more general "bandpass" case that (curve c is represented by a sum of Fourier waves of highest frequency F and lowest frequency f) implies (curve c is represented by samples of c taken at a frequency greater than 2(F–f), and Whittaker didn't.

236:*Figure 6.3 (left)*: I don't really know the original data points of the Ravi Shankar demonstration, but I do remember the curve's general shape. Neither Tom Porter [email Mar. 17, 2017] nor I can remember whether the spline was interpolating or approximating (see note 272:*Bézier's (or de)*). I've assumed interpolating for this presentation—that is, the spline passes through, not near, the ducks.

237:*Next we repeat*: Figure 6.41 (left) is the original tablet data again, positioned on its side so that horizontal position is (awkwardly) measured vertically. Figure 6.41 (right) is a plot of the horizontal positions of each point, at equal time steps. It's just the points at the left spread out horizontally in equal steps.

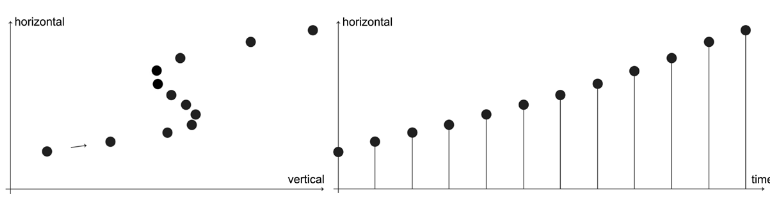

Figure 6.41

We do the same kind of construction again: Spread each sample with a good spreader, and add up the results (figure 6.42). The smooth curve passes through—interpolates—the "sampled" horizontal positions, located at the spreader peaks again. This curve looks almost like a straight line, but it isn't and doesn't have to be.

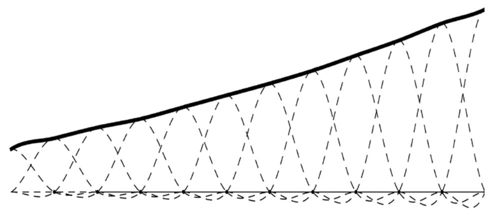

Figure 6.42

238:*Let's go through*: You might argue that there *is* a real curve being sampled by the tablet points, the curve that the stylus tip passes through during the gesture. But we don't reconstruct that physical thing. We construct a geometric model, or representation, of it. Notice also that a spline uses two one-dimensional spreader applications to create a two-dimensional thing.

240:*The spline that*: Catmull (1974), Appendix A; Catmull and Rom (1974). See also Smith (1983). I first learned this spline from a textbook (unpublished, but issued as a Stanford tech report [Clark (1981)]) on computer graphics by Jim Clark (my colleague at NYIT, subsequently cofounder of Silicon Graphics and Netscape). Clark called it a Cardinal spline, with Catmull-Rom being a special case.

240:*The two different*: [Math] A common name for the spreader in interpolation context is *basis function*, but I find *spreader* much more intuitive. The spreader for the Catmull-Rom (or Cardinal) spline can be divided into four parts, the two negative lobes and the two halves of the positive lobe (the hump). Each of these can be described as a piece of a cubic equation (of the form $\mathrm{a}t^3 + \mathrm{b}t^2 + \mathrm{c}t + \mathrm{d} = 0$, where t can be thought of as time in the Ravi Shankar example). Since the horizontal positions of a spline come from a simple sum of spreaders, then those positions must be cubic too. And similarly for its vertical positions. Such splines are sometimes described as piecewise cubic curves.

We could call a spline, with positions generated with the ideal spreader, a Whittaker spline, making it one of the earliest (1915). But nobody actually uses, or has ever used to my knowledge, pure Whittaker splines for curves in computer graphics. (For one thing, the ideal spreader, called *sinc*, is infinite in extent, a serious problem in the real world.) Whittaker was about data points, not curves.

241:*The picture in*: Forrest (1979) is an earlyish paper that discusses different renderings of a model into a display. It also contains this interesting sentence, p. 254: "model-making machines [machines that cut foam, say] are regarded as graphical devices." The models referred to here are the actual objects, made of foam say, and are not to be confused with the internal geometrical models in the computer.

241:*On the other*: Although I use "geometry" as the basis of computer graphics models in this book, I really mean to include carefully defined mathematical objects as model components, not just classical geometric objects. An easy example already encountered in this chapter is the spline. A spline is a piecewise polynomial curve, which is not typically considered geometry. But it is a carefully defined mathematical object that shares with geometry the notions of zero width and precise location in space. It's succinctly represented in memory and invisible until rendered to a display.

Other examples of this extended notion of "geometry" are the functions plotted on Whirlwind in the Dawn chapter (4). Wolfram Research Mathematica, which I use in many figures for this book, is an app in which the internal models are often from this extended notion of "geometry." I certainly consider it to be a computer graphics app.

241:*Computer graphics is*: In the modern world, there is much crosstalk between the two types of synthetic programs. In the next chapters, we investigate the large role of pixel-based procedures in computer graphics. And pixel-based programs such as Photoshop often use geometric shapes as input. For example, Photoshop allows the creation of a solid rectangle as part of a picture. But this geometry is immediately rendered to pixels and preserved that way.

A crossover case in point: The Ravi Shankar spline demonstration was done using Tom Porter's paint program at Lucasfilm. In general, a paint program is pixel-based, but in this case the program's spline paint operation was implemented via classic computer graphics, a rendering from a geometrical model which also included appearance attributes (width, color, transparency).

241:*The Adobe and*: The fact that we still have the Adobe product pair of Photoshop and Illustrator is an artifact from the calligraphic versus raster past. There is no reason any longer to separate the two design products, except for the market reality that millions of users would be quite unhappy to have their known Creative Space product change to accommodate the other Creative Space. The user interface to Photoshop differs markedly from Illustrator's.

A surprising example of a design product that incorporates both types of input under one user interface is Microsoft PowerPoint, but it's not considered a high-level creative tool in the same league with Photoshop and Illustrator. It does show how both geometry and pixels can be mixed seamlessly in one creative product.

242:*A major goal*: Stereo display is often called 3D (three-dimensional). The notions of Creative and Display Spaces make it easy to draw the distinctions we want. Three-dimensional computer graphics is three-dimensional in Creative Space but generally two-dimensional in Display Space. VR is three-dimensional in both Creative and Display Spaces. So-called 3D movies are three-dimensional in Display Space. I tend to use *stereo* to mean 3D display, because that's often how it's accomplished. And thus three-dimensional, or 3D, is reserved for describing Creative Space.

242:*A spline is*: To get a two-dimensional spline, we created a smooth curve through the vertical locations, then a smooth curve through the horizontal locations. We stepped along those two curves reading off at each step the vertical and horizontal locations of the next point on a two-dimensional spline. To get a three-dimensional spline, use the same trick again for the third dimension, call it depth, of each point. Create a smooth curve through the depth positions. Now, as we step along the three curves, we can read off the vertical, horizontal, and depth locations of the next point on a three-dimensional spline.

Three-dimensional splines can be spatial curves, as just described, or they can be paths in spacetime. To create the latter, construct a smooth curve through time instances in the same manner as we just did for depth locations.

242:*What exactly is*: Welchons and Krickenberger (1949), 7, 57. This textbook lasted for almost 50 years before being supplanted. My geometry teacher, Mr. W. C. Robinson, challenged me on the first day of class by saying that nobody had ever proved every theorem in the book. So, of course, I did, and that led pretty much to Pixar.

More carefully, a broken line has each line segment sharing an endpoint with only one other line segment, and with the very first endpoint (of the first line segment) and very last endpoint (of the last line segment) not shared. Some would count a broken line as a polygon too, an *open* one. I'll use the definition that a polygon is assumed closed here, with no dangling endpoints.

243:*But we'll immediately*: [Math] To simplify the presentation here, we assume only planar polygons. A triangle has to lie in the plane that its three vertices lie in. It's intrinsically a two-dimensional concept. A triangle can reside in a three-dimensional space but it itself is fundamentally two-dimensional. A polygon, however, doesn't have to lie in a plane. The leftmost vertex of the polygon in the figure might lie one inch closer to you than the other three. Nonplanar polygons have to be dealt with carefully. We simply assume that they aren't a problem, because they aren't allowed in this simplified presentation. Practicing computer graphicists cannot ignore them.

Similarly, we assume only convex polygons here. The four-sided polygon shown is convex, which means that every vertex falls outside the triangle defined by the other three. A nonconvex polygon can be divided into triangles too, but greater care must be taken to create triangles that lie inside the original polygon.

And we don't consider self-intersecting polygons, where the edges of a single polygon intersect. For example, if A, B, C, and D are four points in counterclockwise order on a plane, then the polygon ABCD is a valid polygon, but ABDC is not.

And, finally, we here ignore degenerate triangles—triangles of zero area. For example, if one vertex lies on the line joining the other two, the triangle has zero area.

Robin Forrest stated much of the problem succinctly in conversation, June 12, 2017, "non-planar polygons may be convex, non-convex or self-intersecting when projected onto 2D." To be clear, all the problems mentioned above must be dealt with in actual computer graphics practice.

243:*Because of this*: The filled-in squares of the checkers gameboard could have been modeled with triangles, but weren't.

243:*But consider Pixar's*: I mean that the geometry of the model can be specified with triangles exclusively. There are usually many other things in a model than just geometry—color, transparency, light sources, textures. The next chapters address these.

A common generic term for Pixar-like movies is CGI, for *computer-generated imagery*, but that is a larger category that includes special effects in addition to character animation. Pixar-like movies are not actually modeled with triangles, *but they could be*. Most other ways to create surface models can be converted into meshes of triangles. For example, a succinct way to model a ball would be with a sphere, specified simply by a center location and a radius. But a sphere can be divided horizontally and vertically along lines of longitude and latitude into quadrilaterals (except at the poles), each of which can be converted to two triangles. The sphere's polar regions are already divided into triangles by this technique. Using a sphere rather than triangles is modeling at a "higher order" of representation. The point is, however, that the sphere *could be* modeled with triangles.

Modern modelers don't tend to think in terms of triangles, but they are often satisfied with models built from polygons—sort of one step up from triangles. In the early 1980s at Lucasfilm, the brilliant Loren Carpenter wrote a rendering program called *Reyes* that reduced every scene to millions of tiny polygons that he called "micropolygons." Each micropolygon could have been modeled from two or more triangles, as explained, but that's not what the Computer Graphics Project at Lucasfilm actually did. *But we could have*.

244:*For decades computer*: Newell (1975), figures 28 and 29. Thanks to Jim Blinn, email June 21, 2017, for the information about Newell's full tea set, and to Ivan Sutherland, email Jan. 24, 2018, for a Boston Tea Party connection: The original home of the Computer History Museum in Boston (now in Mountain View, California) was at, or very near, that historic location.

244:*Figure 6.11 shows*: Note that the bottom and backsides of the left teapot are missing. We say that the hidden lines have been removed.

These mesh wireframe teapots are more squat than the original ceramic one. This shortening happened as the model was passed around from lab to lab, so most teapot renderings one finds in the world (there are many) are squat. Jim Blinn, email June 21, 2017, offers this convincing explanation: "I decided that the scaled version looked nicer than the original so that was the one I used for my experiments. Some erroneous articles have said that the scaling was due to the non-square pixels of the E&S frame buffer, but that is incorrect." N.B., "non-square pixels" means that the horizontal spacing between pixel locations differs from the vertical spacing. This was a problem in early computer graphics.

Another detail that we don't treat further here are the lines at the teapot's silhouette. These have to come from somewhere because they don't usually happen to fall on edges of the polygons in a given mesh.

245:*I also noted*: I estimated the number of polygons in the right teapot model at 8,500. Dividing each into two triangles yields 17,000 triangles. Storing three coordinates for each triangle vertex leads to 51,000 memory locations in the teapot list. But each vertex doesn't have to be stored. Computer graphicists have spent years devising clever ways to efficiently organize location data for a model, to make rendering efficient in time and memory usage. Here, for example, most triangle vertices are shared with other triangles. A little cleverness lets us halve the number of memory locations required. I rounded up to 26,000 since it's only a very rough estimate.

246:*A model made*: I'm assuming here that the four-sided polygons in one of the teapots have all been divided into two triangles.

247:*Although displaying triangles*: Some plumbing ignored here: 1. The coordinate system used for storing a three-dimensional model is not the same coordinate system used by the display screen.

The transformation from one coordinate system to the other is done by the program. We discuss later the projection of three dimensions into two, in perspective. 2. The old calligraphic displays had to be redrawn every, say, fifth or tenth of a second because their phosphors would decay. The refresh of the picture had to be managed by the program. 3. Often the two-dimensional view chosen of a three-dimensional scene doesn't encompass the full scene or object, thus causing some triangles to be "clipped" off at the edges of the display. Of course, this clipping problem must be taken into account. 4. The wireframe teapot on the left in a previous illustration differs from the one on the right in an important way: It appears to be opaque because the triangles on the backside of the teapot body aren't shown. Getting rid of "hidden lines" required much expertise of early computer graphicists. Since our goal is fully colored and shaded objects, we do not spend time here on the old problem of hidden line removal [see Roberts (1963), Freeman and Loutrel (1967), Loutrel (1970).]

247:*The first rendering*: Bresenham (1965) was the first formal publication of the algorithm. It's actually about drawing very short line segments, not lighting up pixels, but is readily adapted (and often is) to lighting up pixels too. It cites the original publication as "An Incremental Algorithm for Digital Plotting, ACM National Conference, Aug. 30, 1963, Denver, CO, the proceedings of which were never published.

Bresenham's Algorithm, https://xlinux.nist.gov/dads/HTML/bresenham.html, accessed Apr. 5, 2020, has this interesting quotation from Jack Bresenham himself, Nov. 2001, which establishes the date of dissemination as 1962: "I was working in the computation lab at IBM's San Jose development lab. A Calcomp plotter had been attached to an IBM 1401 via the 1407 typewriter console. [The algorithm] was in production use by summer 1962, possibly a month or so earlier. Programs in those days were freely exchanged among corporations so Calcomp (Jim Newland and Calvin Hefte) had copies. When I returned to Stanford in Fall 1962, I put a copy in the Stanford comp center library. | A description of the line drawing routine was accepted for presentation at the 1963 ACM national convention in Denver, Colorado. It was a year in which no proceedings were published, only the agenda of speakers and topics in an issue of Communications of the ACM. A person from the IBM Systems Journal asked me after I made my presentation if they could publish the paper. I happily agreed, and they printed it in 1965."

247:*Here's a line segment*: Bresenham's algorithm featured use of integer arithmetic instead of real arithmetic, a serious speed consideration at the time.

248:*What first attracted*: We had both attended Stanford University for our PhDs too, something I also didn't know. Jack got his in 1964 and I completed mine in 1969 (awarded in 1970).

Foley and van Dam (1982) was that important textbook. Jim Foley and Andries "Andy" van Dam are major players in computer graphics.

Bresenham's slightly different version of the story, email from Jack Bresenham, June 14, 2017: "On home leave while on assignment to Hursley [IBM, UK], probably in late 1983 or early 1984, I visited my parents Mary & Floyd in Clovis (1101 N. Prince St.). Jim Foley's graphics book had just been published and I'd sent a copy to my parents. My parents and your parents were good friends. Mother told me your mother was visiting our house when your mother noticed Dr. Foley's book on the coffee table. She remarked her son was mentioned in the book and had several illustrations in it as well. Mother then made comparable mention that I, too, was included in the book. They had a good smile when they realized we each worked in computer graphics. Later when I met you (at Siggraph, as best I recall) . . ."

Bresenham had been with IBM San Jose, CA, from 1960–1967. He was with branches of IBM in Italy, NY, and NC in the 1970s. And with IBM in Hursley, UK, from Mar. 1981–Aug. 1984 when he interacted with Robin Forrest several times. He retired from IBM in 1987, then taught at Winthrop University in SC from 1987 to 2003. He retired to Rio Rancho, NM, near Albuquerque in 2011. Jack was born in Clovis, Oct. 1937. His brother Dick was born in 1943.

248:*Let's now turn*: There are actually three connections of this chart to the earlier one in the Dawn chapter (4): (1) that of MIT and Whirlwind as shown; (2) Maurice Wilkes who cofounded the computer-aided design group to which Robin Forrest belonged at Cambridge, UK; and (3) IBM which partnered with MIT to build the Sage computer and with GM to build DAC-1 equipment.

249:*Everything I said*: Some (but not all) of the players who did not fit on this two-page figure are (in no particular order): (1) Don Greenberg in architecture at Cornell who started computer graphics there in 1968 (but see the next chapter); (2) Rod Rougelot, a real-time graphics expert at GE in 1972 who became fundamental to E&S and who enabled Greenberg in 1972 to make the "Cornell movie" (but see the next chapter); (3) Andy van Dam and Ted Nelson who, inspired by Engelbart, wrote Hypertext Editing System in 1967; (4) Nicholas Negroponte, who studied with Coons at MIT in 1962, became an important leader at MIT (Architecture Machine, Media Lab), and was a member of the MIT Department of Architecture with Tim Johnson; (5) Rich Riesenfeld and Elaine Cohen who are mentioned in another annotation; (6) Ed Fredkin who founded Information International Inc. ("Triple I") in 1962, and Marvin Minsky of MIT who served on its board; (8) Doug Ross of MIT who mentored Sutherland and cofounded with Coons the Computer-Aided Design Project at MIT in 1959; (9) Maurice Wilkes, Donald Welbourn, and Charles Lang (who had worked with Coons) who formed, with Robin Forrest, the Cambridge UK Computer-

Aided Design Group in 1965; (10) Dan Alpert and Don Bitzer and the Plato system development at the University of Illinois [Dear (2017)]; and (11) Glen Culler and Robert Huff (see next). Some of these will be mentioned further in the next chapters. Some others are sprinkled throughout the text and appear in other annotations.

Culler and Huff (1962), 129, "To make possible an operation of this sort requires a fairly sophisticated computer with suitable interrupt capability and a form of input-output equipment which provides for rapid, sophisticated displays of graphical or numerical information from the computer, and offers convenient means for controlling the computer's activities by easily and accurately feeding back information to the computer in graphical or numerical form. | A system of this type can be realized in many ways. At the present time a satisfactory version of the requisite input-output equipment exists in the form of a Display and Analysis Console (DAC) developed at Ramo-Woolridge. For output, this console has two 17" scopes (with resolution 103 lines in each direction) which permit the display of line segments as well as points. Input of information to the computer is accomplished by means of a crosshair, whose position changes in response to a control lever, and whose coordinates are, on push button command, transmitted to the computer, leaving a small cross displayed on the scope; a light gun (photocell) which can be used to select, with complete accuracy, any desired luminous point of a display; a series of push buttons, . . ."

249:*Computer graphics by*: I considered using computer-generated imagery (CGI) for the non-CAD part of computer graphics. This was nicely symmetric with CAD and used the word "imagery" in the picture-focused part. I decided against it for a variety of reasons: 1. CGI has taken on the connotation of 3D computer graphics, usually animated or interactive. Using CGI for the non-CAD part of computer graphics implies that the interface to Windows or MacOS, or any two-dimensional app, would be called CGI. 2. I personally find CGI a harsh term that has to be explained to lay persons whereas computer graphics is comfortable and doesn't have to be explained. 3. "Computer-generated" seems to imply that the computer did it, not the human creators. 4. My natural disinclination to use uppercase acronyms.

252:*But in the*: In the current world (2020) the claim, that non-CAD computer graphics models are seldom used to create objects in the real world, is becoming less true. They might nowadays be used to drive 3D printers to produce maquettes for approvals, reference, and sanity checks, and possibly as toys for marketing as mentioned. Yet the principal purpose of such a model remains to make pictures.

In modern CAD, pictures of the models are often generated too—accurate floor plans of a proposed building, say—but they are not usually the principal goal. And in the latest context, called the Maker Movement, computer-aided design models are actually rendered in physical materials deposited drop by drop in real three-dimensional space, a layer at a time—a technique often called "3D printing." An object is the display, in a sense, with the display elements being blobs of chemical substances deposited in regular locations on a three-dimensional raster.

Confusingly, practitioners creating objects and those creating pictures both use pictures and models during their process. The distinction is between *picture-as-interface* to the design of an internal model (in both computer-aided design and computer graphics) versus *picture-as-output* (in computer graphics). CAD designers interact with an internal model of say, a building or a machine part, via a display of the object. The designers change the stored internal model as they work on the design. Character designers in an animated movie production work in much the same way, interactively positioning the arms, legs, fingers, lips, eyes, and so forth, of a character while viewing a displayed (often simplified) picture of it. [Thanks to Robin Forrest for suggesting the phrase "picture as interface," conversation May 3, 2017.]

253:*MIT was heavily*: In 1940 the Servomechanism Lab and the Radiation Lab were established. In 1946 the Radiation Lab became the Research lab for Electronics (RLE) Lab. In 1951 the Whirlwind computer project was separated from the Servomechanism Lab into the Digital Computer Lab. The RLE was renamed Project Lincoln in 1951, and the Digital Computer Lab (with Whirlwind) was folded into it. In 1952 Project Lincoln was renamed Lincoln Lab. The Servomechanism Lab became the Electronic Systems Lab in 1959. The MIT Computer-Aided Design Project was formed in 1959 in the Electronic Systems Lab.

254:*Consider a future*: Bush (1945), 16.

254:*He got a*: Bush (1945), 19–20. He didn't know Moore's Law, of course, so predicted poorly (p. 10), "The advanced arithmetical machines of the future will be electrical in nature, and they will perform at 100 times present speeds, or more." He misattributed: "The abacus . . . led the Arabs to positional numeration and the concept of zero." But these were Indian inventions. However, the number of things he got right is surprising.

254:*Bush (no relation*: Bush was chairman of the Office of Scientific Research and Development, which made him effectively the first Presidential Science Adviser.

254:*Then came the*: Sputnik went up in Oct. 1957. ARPA was created in Feb. 1958. NASA began operations in Oct. 1958. ARPA became DARPA for the first time in 1972, for Defense Advanced Research Projects Agency. It was ARPA during the years of interest here. Licklider was hired by

Jack Ruina, the third director of ARPA. Its fourth director was Robert Lamb Sproull, father of Bob Sproull, coauthor of the famous computer graphics textbook, Newman and Sproull (1973).

255:*It seems reasonable*: Licklider (1960), 7.

255:*Lick didn't get*: Ivan Sutherland, email Jan. 24, 2018, emphasized that early computer designer Wesley Clark was not of the time-shared school. "He foresaw that computing would fall rapidly in cost, and so he devoted as much computing power to a single person as possible to see what would happen. That's why his TX-0 and TX-2 featured in so much early development . . . Funding for Lincoln came from the Air Force rather than from ARPA. There's a distinct bifurcation in the lines of development started by Lick and by Wes Clark."

255:*This is an*: Engelbart (1962), ii, the abstract.

256:*Bob Lenox*: This epigraph is an epigraph in Paul Ryan, *Cybernetics of the Sacred*, Anchor Press, 1974. Bob Lenox was a 1970s rock musician.

256:*The Cold War*: Sage stood for the forgettable and forgotten Semi-Automatic Ground Environment. The true name of a Sage computer was the hideous AN/FSQ-7, abbreviated Q7.

256:*Among the remaining*: Note added June 24, 2022: a BBC TV production aired about 1982, called *Painting By Numbers*, is archived at https://ia600408.us.archive.org/11/items/paintingbynumbers/paintingbynumbersreel1.mp4. Its temporal locations 6:27–8:52/37:08 are devoted to Sage. A roomful of humans interacting with Sage can be seen at locations 7:26–7:30, 7:38–7:45, and 8:11–8:16, but none using the "soldering gun" device.

257:*The normal business*: The story of the pinup, with pictures, is from Edwards (2013). Lawrence A. Tipton snapped a Polaroid of the anonymous work, traced from a contemporary *Esquire* magazine picture. Notice that this suggests that an internal model was created as the "artist" traced the girlie onto the screen. This is not to celebrate the sexism of the early male-dominated computer world, especially the Sage world, but rather to show that no matter what the machine, once understood to be a picture maker, it was used that way.

258:*Stewart Brand, Rolling*: Brand (1972).

258:*A new breed*: TX stood for "Transistorized eXperimental." There's a silent, undated video of the TX-0 computer on YouTube, *TX-0 Computer, MIT, 1956–1960*, https://www.youtube.com/watch?v=ieuV0A01--c, accessed Apr. 5, 2020, that shows interactive raster graphics starting at about 1:40 min.

258:*Those original hackers*: Brand (1972).

259:*At least one*: Levy (1984), 157, followed Peter Deutsch from MIT to PARC: "The systems software was set up by a Xerox PARC (Palo Alto Research Center) hacker . . . He was a long-haired, bearded Peter Deutsch, the same Peter Deutsch who at age twelve had peered over the console of the TX-0 twelve years before. A Berkeley graduate, he had managed to blend the whole-earth California life-style with intense hacking at PARC."

259:*In 1984 journalist*: Levy (1984), Part 1, Chapter 3. There actually was a TX-1 project, but it bogged down and was never completed. Parts of it became the TX-2 project."

259:*In the Dawn*: *Wikipedia* article on Thomas Stockham, accessed June 8, 2017: "While at MIT, he noticed several of the students using an MIT Lincoln Laboratory TX-0 mainframe computer installed at the campus to record their voices digitally into the computer's memory, using a microphone and a loudspeaker connected to an A/D-D/A [analog to digital, digital to analog] converter attached to the TX-0. This expensive tape recorder led Stockham to his own digital audio experiments on this same computer in 1962."

Graetz (1981), 58, "many of the programs developed on TX-0, such as . . . Thomas Stockham's FLIT debugging program, were the first of their kind." Unfortunately, Levy (1984), 18–19, refers to him everywhere as Tom Stockman—for example, "The other program that [Jack] Dennis worked on with Stockman was something even newer—a debugger."

Stockham gained additional fame when he was called on to analyze the infamous 18.5-minute "tape gap" in tape recordings made by President Richard Nixon after the Watergate break-in. Stockham and team proved that there had not been an accidental erasure, as claimed by Nixon's team, but a series of five to nine erasures, and therefore definitely intentional.

259:*But the most*: Levy (1984), 45: "There had been several attempts to do this kind of thing on the TX-0. One of them was a hack called *Mouse in the Maze*—the user first constructed a maze with the light pen, and a blip on the screen representing a mouse would tentatively poke its way through the maze in search of another set of blips in the shape of cheese wedges. There was also a 'VIP version' of the game, in which the mouse would seek martini glasses."

One of the first PDP-1 graphics hacks was done by Marvin Minsky of AI (artificial intelligence) fame [Levy (1984), 46]: "One of Minsky's contributions to the growing canon of interesting hacks was a display program on the PDP-1 called the Circle Algorithm . . . Hacking further, Minsky used the Circle Algorithm as a stepping-off point for a more elaborate display in which three particles influenced each other and made fascinating, swirling patterns on the screen, self-generating roses with varying numbers of leaves . . . Minsky called the hack a 'Tri-Pos: Three-Position Display' program, but the hackers affectionately renamed it the Minskytron."

Levy carefully dates the development of *Spacewar* in his chapter 3 (of Part 1). Steve "Slug" Russell began it in late 1961 and brought the first version to fruition in Feb. 1962. He and several other hackers improved it throughout that year, adding star fields, gravity, and hyperspace.

Sam Fulcomer sent me the following pointer to a YouTube video of a restored PDP-1 with a running *Spacewar* program and other early graphics on it (accessed 20 May 2021): https://www.youtube.com/watch?app=desktop&v=1EWQYAfuMYw (*Spacewar* at about 13:23). A narrator mistakenly states that "it's really the first interactive graphics game on a digital computer ever." This is not true by about a decade, as established in this book, but it was nevertheless a big step forward in popularizing the notion of an electronic game.

Note added June 24, 2022: a BBC TV production aired about 1982, called *Painting By Numbers*, is archived at https://ia600408.us.archive.org/11/items/paintingbynumbers/paintingbynumbersreel1.mp4. Its temporal locations 10:50–11:43/37:08 are devoted to *Spacewar*, including Steve Russell instructing a young gamer on how to use it.

260:*In videogames, an*: Actually, however, some videogames slow down to 10 or 15 frames per second, and users still buy it as real time. And some videogames offer a quality versus gameplay control. A user can elect to have more responsive "play" with less image quality, or vice versa.

And at the other end, heavy duty gamers insist now on 100 frames per second or faster.

260:*Videogames are the*: "3D" or three-dimensional is an ambiguous term here. See discussion in note 242:*A major goal*. In the case of VR or "3D" movies, it's Display Space that is, apparently, three-dimensional. But actually, it's two two-dimensional pictures displayed to the two separate eyes. So the Display Space is actually two-dimensional. It's the brain that extracts a third dimension from the two two-dimensional displays. We always use "stereo" here for this case, not "3D." It's an analog of audio stereo, namely two different audio experiences given separately to the two ears from which the brain extracts a sense of space. There are actual three-dimensional displays, but so far they haven't reached serious market penetration [see *Wikipedia*, Volumetric display, accessed Apr. 5, 2020].

261:*The easy narrative*: Freeman (2009), 17–22, from his autobiography. One of Einstein's letters (written from the Institute for Advanced Studies, the Princetitute, July 1937) and a translation of it appear on 112–115. Freeman reported (pp. 40–41) that the families of an aunt and an uncle were exterminated in the Holocaust, except for three children who were saved via the Kindertransport program in 1939.

Phone call with Herb Freeman, Jan. 14, 2018, and email Jan. 24, 2018, "My Dad, who had come to the US a while earlier had enlisted the help of the National Coordinating Committee for Aid to Refugees and Emigrants coming from Germany. Their Executive Director took a special interest in the case and rounded up an impressive list of distinguished people to lobby in my behalf. Einstein was one such person who lobbyed on my behalf. The US Surgeon General was another, as were the director of of the New York City department of Health, the Executive Director of the New York Times, Mr. Max Frankel, Senator Robert Wagner (of the Wagner Labor Relations Act), and numerous others. It took two years but eventually it was successful. Clearly the immigration people had made a mistake and were unwilling to admit it. Well, soon it will be 80 years since that time!"

262:*About a year*: Freeman (2009), 39–51. Speedac was the SPerry [Corporation] Electronic Digital Automatic Computer. In 1968 the department name was Electrical Engineering and still had that name when I was hired. Freeman and I managed to get the name changed to Electrical Engineering and Computer Science (EECS) during my tenure.

There was an earlier journal for a subfield of Digital Light, computer-aided design, before *JCGIP*. It was the *Journal of Computer-Aided Design*, first published in 1968. The first issue of *Computer Graphics and Image Processing* was published Apr. 1972 with editors Azriel Rosenfeld, Herbert Freeman, Thomas S. Huang, and Andries van Dam. It's now known as *Computer Vision, Graphics, and Image Processing*.

262:*Herb hired me*: Freeman introduced me directly to Forrest and Baecker themselves, and indirectly to Wein via his work. Only Forrest of these three had association with the Utah school, as a visiting professor. Freeman also introduced me directly to Azriel Rosenfeld, an image processing expert, and a cofounder with Freeman of the *Computer Graphics and Image Processing* journal. Forrest validated the earlier journal *JCAD* from his extensive records. He published in the slightly later journal's first volume [Forrest, "On Coons and Other Methods for the Representation of Curved Surfaces," *JCGIP* 1(4)(1972): 341–359].

262:*Robin, my favorite*: The meeting with Forrest in Bloomsbury was in September 2016.

262:(*Computer graphics colleagues*: The British Quantel Corporation sued several small British computer paint program companies for infringement of five patents. The companies all failed as businesses, either from inability to afford to fight the cases in court, or to win if able to proceed to court. The British court case had no jury. Then Quantel sued Adobe in the US, claiming that Photoshop infringed. In US court, with a jury, all five patents were found invalid. The jury also found Quantel guilty of fraud, but the judge threw out that finding.

262:*Jack Bresenham was*: Email from Robin Forrest, Apr. 5, 2017, "Clovis and Stanford seem to be a potent brew. Yes, I did introduce you to Jack at SIGGRAPH, having just found out that you came from the same town. I think I mentioned this to Jack and he said he'd like to meet you. He thought his mother and your mother had heard of the connection somehow."

263:*I couldn't have*: Email from Robin Forrest, Mar. 22, 2017, "Incidentally, spline is an East Anglian dialect word for a thin lath of wood used in shipbuilding to create smooth curves by bending the lath round selected pins or ducks." I spent a term at Cambridge's Kings College (my wife's sabbatical) in the summer of 2017 and got to visit with Robin several times, as Norwich is not far away.

Email from Robin Forrest, Mar. 20, 2017, captures the extent of his early involvement in the community with many of its players: "In the spring of 1969 I toured the US, visiting companies and universities engaged in CAD research. This was arranged partly by Rolls-Royce for whom I was consulting and who were part of a collaborative project between IBM and the automotive and aerospace industries called Project Demand. I had been in touch with most of the companies as part of my PhD. Research—tech reports rather than papers were the main source of information, before the days of appropriate journals. The trip included giving a paper at the Pertinent Concepts in Computer Graphics conference at the University of Illinois, Urbana-Champaign. This was the second such conference and I came across the attendee list last week. I started my tour at M.I.T. with Steve Coons then went to Ann Arbor to give a talk for Bert Herzog. He switched the talk to the U of M[ichigan] campus at Willow Run so that people from the automotive industry could attend.

Bert marched me up to the front of the auditorium and I faced an audience in the hundreds for my first ever lecture. In Detroit I visited Ford and GM. My host at GM was Ed Jacks. I also met George Dodd who may still be around. One demo I was given was on a 2250 showing 'the crazy way Renault (pronounced Wren-Alt) design curves'. An unconnected set of point was placed on the screen and a curve appeared with no obvious relation to the points. I was given a copy of a 1969 paper by Bézier. Sometime later, I rearranged the rather ugly mathematics because Bézier's formulation was in terms of the initial point and then the successive polygon side vectors. Lo and behold, out popped the Bernstein basis. I worked up a CAD Group Report in 1970 and it appeared in the Computer Journal in 1971. The Tech Report got back to GM before the published paper. Bill Gordon realised that as it was known that B-splines were the spline generalisation of Bernstein polynomials, and would have the crucial variation diminishing property, this would be a suitable project for Rich Riesenfeld's PhD thesis at Syracuse where Bill had a semester as a Visiting Prof working with Steve Coons. I followed Bill as VP at Syracuse and supervised Rich. I have never fathomed the relationship between Renault, Citroen, Bézier and De Casteljau. Citroen used the Bernstein form but they had published nothing when I worked things out. In general, Citroen tended to be secretive. Their system was designed to approximate model data interactively, starting from clay or plaster models whereas Bézier always intended his system to be used for ab initio design. I translated Bézier's book on NC etc. and he gave me a copy of the French version with the dedication 'For Robin Forrest To whom I owe more than he perhaps thinks.' I've not unraveled that enigma.

"After Illinois I went to McDonnell in St Louis, Boeing in Seattle, Lockheed California in Burbank, TRW Systems Redondo Beach, Douglas at Long Beach and North American at Downey before calling in at the University of Utah where Ivan was working with David Evans, John Warnock and William Newman. The final visit was to Lockheed Georgia at Marietta."

As regards the "ugly mathematics" of Bézier, Rich Riesenfeld offered this counter [email Sept. 22, 2017]: "My view is distinctly different on this. Bézier gave a rather elegant algorithmic construction for defining his curves . . . He explained to me that it was motivated by the way one sketches. First, the incipient shape is suggested by longer, coarser strokes succeeded by refined shorter, more localized ones. He thought of his method as loosely emulating the sketching process. This helped me to get some insight into how this construction came about."

263:*Timothy Johnson, creator*: Daniel Cardoso Llach's *Builders of the Vision* (2015) is a principal source, told from the computer-aided design point of view and emphasizing design. The original quotation in Cardoso Llach (2015), 56, appears this way: "[Coons] turned me on, he turned Ivan [Sutherland] on, and . . . and he was worth several full professors," citing an interview by Cardoso Llach of Tim Johnson and Guy Weinzapfel on July 7, 2014.

264:*Steven Anson Coons*: David DiFrancesco and I visited the University of Utah as we departed Xerox PARC in 1974. We were urged by our Utah colleagues not to miss "Coons's last lecture." This was the only time that I ever saw Coons. In his lecture he taught us how to strike a match across the abrasive strip of a matchbook cover rather than along it.

Computer graphics pioneer, Jim Blinn said in an email Apr. 18, 2017, "Coons was a real character and an engaging teacher who I really enjoyed listening to." Blinn was awarded the Coons Award in 1999.

264:*The story goes*: Cardoso Llach (2015), 54, cites an interview with Rich Riesenfeld by Cardoso Llach, July 4, 2014. Riesenfeld was one of Coons's students and one of his closest collaborators.

He studied at Syracuse University, with Coons as PhD adviser, then joined the University of Utah. He was also a collaborator with Robin Forrest at Cambridge and Syracuse. Riesenfeld married Elaine Cohen, the earliest woman in computer-aided design.

265:*Coon's career had*: Cardoso Llach (2015), 54–56, cites Bertram Herzog's unpublished eulogy of Coons for the "under adverse conditions" comment, found in MC 510 S2, Box 2, Design (Correspondence), MIT Archives. Cardoso Llach further quotes, 56, a Coons colleague, according to Johnson in the Johnson-Weinzapfel interview: "why are you ignoring Coons [for promotion]? You know? He's better than all of us!"

265:*Robin Forrest's career*: This story is also found in Cardoso Llach (2016), 3, in an interview with Forrest.

266:*In the generality*: There were early systems that had a more restricted notion of a patch. North American Aviation had a system, called Autoloft, that used conic sections to interpolate between wing contours. The important point is that these surfaces could be defined mathematically [Cardoso Llach (2016), 3].

The problem of interpolating one written word into another is basically the same problem as interpolating between a two-dimensional animated character in one frame and the same character in a changed position in a subsequent frame. This turns out to be difficult with two-dimensional drawings.

267:*We owe both*: From a *2002 Outstanding Service Award: Bertram Herzog*, https://www.siggraph.org/about/awards/2002-service-award/, accessed Apr. 5, 2020, "His conversion to Computer Graphics occurred in 1963 when he met Coons and others at an MIT meeting." Herzog was, also like Freeman, not of the Utah school.

The first Siggraph conference was held in 1974 in Boulder, Colorado. The underlying organization itself was founded in 1969 [https://www.siggraph.org/about/history/, accessed Apr. 5, 2020].

267:*Pierre Bézier, about*: Both quotations are from Michel Landry, L'anticonformisme au profit de la création!, *L Tech Solutions,* https://www.ltechsolution.com/lanticonformisme-au-profit-de-la-creation/, accessed Apr. 5, 2020. The translations are from the French, respectively: "*On le décrit comme une personne joviale doté d'un esprit libertin. Un anticonformiste raisonné. Dans le milieu on le décrit simplement comme 'un Génie'.*" And "*Je suis demeuré depuis irrémédiablement classé comme un illuminé dangereux, et que l'on avait que trop longtemps laissé en liberté.*" The first translation is mine. I had trouble with the second so asked for help from several people, Susanna Forrest (Robin's daughter), Alison Gopnik (my wife, formerly of Montreal), and finally a friend and French speaker and translator, Pascale Torracinta, whose version is the one used here (except I changed her "that" to "who"). A Google translated version of Landry's page had this clumsy translation: "*I have since remained irremediably classified as a dangerous illuminant, and that we had left too much for too long."*

267:*Pierre Étienne Bézier*: Rich Riesenfeld, email Sept. 22, 2017, "[Bézier] had a keen and sophisticated sense of humor that he invariably directed toward me (and the superiority of Elaine's French compared to mine! [Elaine Cohen, Riesenfeld's accomplished wife]), but all in good fun, at the close of each letter. (Reflecting his cultural exposure, Bézier nearly always wrote to me in challenging, rather flowery, literary French, although his English was perfectly fine and suitable to any occasion." Riesenfeld and Cohen were awarded the Bézier Award in 2009.

268:*This all sounds*: Obituary for Bézier, in a special issue devoted to Bézier techniques of the journal *Computer Aided Design* 22, 9 (Nov. 1990). Bézier had been an Advisery Editor of the journal.

4CV History, https://www.conceptcarz.com/z20833/Renault-4CV.aspx, accessed Apr. 5, 2020, in an article by Daniel Vaughan: "Pioneered by Pierre Bézier, the 4CV featured innovative methodologies that made it an impressive car for the time. Bézier began his career as a Renault tool setter before gradually moving up to tool designer and eventually head of the Tool Design Office. In 1949 he designed the transfer lines (or transfer machines) as Director of Production Engineering and produced much of the mechanical pieces for the 4CV. The transfer machines were high-performance work tools that were designed to machine engine blocks. Bézier was imprisoned during WWII and while there he created and improved on the automatic machine principle which was introduced before the war by General Motors. Before robots, the new transfer stations with numerous workstations and electromagnetic heads help execute various operations on a single part to be consecutively performed by transferring the part from one station to another."

The mystery of Bézier's imprisonment was partially resolved as a result of an email exchange with Christian Boyer, Apr. 11–13, 2020. He sent me source De Andréa (2005), 52: "Cette innovation est le fruit de ses réflexions croquis à l'appui, transcrites sur des petits cahiers pendant sa 'villégiature' dans l'Oflag XIA entre 1939 et 1941." With the help of Google Translate: "This innovation is the fruit of his reflections, corroborated by sketches, transcribed in small notebooks during his 'vacation' in Oflag XIA between 1939 and 1941." A graphic novel of the "birth of the 4CV" depicts this event, captioned "dans l'Oflag: Pierre Bézier . . .," in a misearable rain against a barracks with his notebook [Dugomier, Bazile, and Magne (2017), 14].

Christian Boyer, email Apr. 17, 2020, "Success: phone call this morning to Pierre Bézier's daughter! . . . searching to her archives during the phone call, she found a letter of her father, 3 October 1940, with Osterode-am-Harz written on it! So finally SURE that Pierre Bézier was at XI-

A." We know from Gayle (2015), 127, that Oflag XI-A was located at Osterode am Harz (in Germany), that it was organized early (1939), and was closed June 22, 1941. Its prisoners, possibly including Bézier, were then sent to Oflag IV-D, in Elsterhorst at Hoyerswerda. See note: 269:*Bézier became seriously* for more on Christian Boyer.

Christian Boyer, email Apr. 20, 2020, speech by Pierre Bézier (in French) when he was 86, June 25, 1996: https://sites.google.com/site/histoiregrouperenault/un-peu-d-histoire/histoire-de-la-fabrication-chez-Renault/fabrication-moteurs-et-boites/discours-de-pierre-bezier-a-l-ecole-des-arts-et-metiers-1996, accessed Apr. 20, 2020. "Also an interesting speech by Michel Neuve-Eglise, AM Li.61 [Arts et Métiers, Lille campus, entered 1961], former CEO of Matra Datavision (later bought by IBM). Neuve-Eglise said that Pierre Bézier was a prisoner from June 1940 to mid 1941 = for one year. Probably right, because said in the presence of Pierre Bézier."

268:*Bézier was responsible*: 4CV stood for *quatre cheval-vapeur*, or four horsepower, which was what it had. Bézier (1971) described the development and production of a design (213, Figs. 7 and 8) that closely resembles the Renault 10, but he never states that it's so. There are a few minor discrepancies between the car in this photo and the model Bézier shows in the paper. In particular, the headlight recesses appear to come to a point in the model but are rounded on the actual automobile. And there is no indication on the model of the roof ridges on the auto.

269:*Bézier was vice-president*: See Cardoso Llach (2016), 13, for both quotations. From a conversation with Robin Forrest, May 3, 2017: Another computer-aided design pioneer who accompanied Forrest on the visit to Bézier was Charles Lang. Doug Ross cofounded the Computer-Aided Design Project at MIT with Steven Coons in 1959. Lang left the MIT group to join Forrest in the Cambridge University Computer-Aided Design Group, cofounded in about late 1965 by Maurice

Wilkes (of Edsac fame in the Dawn of Digital Light chapter) and Donald Welbourn after seeing Sketchpad at MIT. Welbourn was Forrest's supervisor at Cambridge [Cardoso Llach (2016), 2].

Robin Forrest, conversation May 3, 2017, informed me that the wooden sculpture in the photo (figure 6.21) isn't the same as the one in the anecdote.

269:*Bézier became seriously*: A turn in Bézier's life generally unknown in America is chronicled on the website of Christian Boyer: *Tell us, Pierre Bézier: why "Pierre de Jumièges"?* [Google translation from French] http://www.christianboyer.com/jumieges/index.htm, accessed Apr. 12, 2020. Pierre de Jumièges was an alias assumed by Pierre Bézier for a math column he wrote in 1978 and 1979, so beginning when he was 68. He also used it, probably in 1981, at the creation of the Cercle Pierre de Jumièges, while he was its president. It is thought that Bézier himself presented a paper on fractals at the Oct. 12, 1983, meeting of the Cercle [N.B., Mandelbrot (1982) had just appeared]. Page 6 of this site features photos of Bézier with Jacques Chirac, then mayor of Paris.

The logo of the Cercle was drawn by Bézier as a sort of signature. It's read as "the integral from minus infinity to plus infinity of PdJ," where the integrand stands of course for Pierre de Jumièges [see p. 6 of Christian Boyer's site]. Boyer is a past president (2011–2018) of Cercle Pierre de Jumièges. See also note: 268:*This all sounds*.

Another story worth recording illustrates the ongoing tower versus stinks battle. This came from Christian Boyer, email Apr. 13, 2020: "In the first years of his [Bézier's] functions/curves, he first named them 'Onésime Durand functions'. He said that they were invented by a French mathematician/professor named Onésime Durand, a common last name, but with a fun, unusual and obsolete first name. A good sense of humour and hoaxes! He was afraid, including inside Renault, that his math discovery was not seriously considered because coming from a mechanical engineer." See also Rabut (2002), 497, 501.

Bézier was honored in France as Chevalier de la Légion d'Honneur (an honor created by Napoleon) and with the Croix de Guerre 1939–1945. He had two diplomas from French *grandes écoles*: (1) Arts et Métiers (Pa. 27) [meaning Paris campus, beginning in 1927]; and (2) École Supérieure d'Electricité (ESE 31), also known as Supélec, entering 1931. [Email from Christian Boyer, Apr. 15, 2020.]

269:*Siggraph—the annual*: Bézier took his PhD at the University of Paris VI, also known as Pierre and Marie Curie University, or Université Pierre-et-Marie-Curie in French. The Bézier Award is given by the Solid Modeling Association. It has been awarded annually since 2007. Solid modeling is a branch of computer-aided design which represents not only the surfaces of objects but the interiors of them.

Bézier trained at the *grand école* for engineering known as Arts et Métiers ParisTech, founded in 1780 [see preceding note]. Graduates and alumni call themselves "gadzarts" [meaning *gars des Arts*, or Arts' guys] and have their own slang [*Wikipedia*, Gadzarts, accessed Apr. 13, 2020; email from Christian Boyer, Apr. 15, 2020]. Bézier was president of the Société des ingénieurs Arts et Métiers from 1977 to 1980.

270:*Paul de Casteljau*: De Casteljau (1999), 583–586.

270:*Paul de Faget*: Bieri and Prautzsch (1999), 579–581. There's a well-known algorithm associated with Bézier curves called de Casteljau's Algorithm, one way that de Casteljau is memorialized. The algorithm doesn't further concern us here.

Bézier said of de Casteljau: "There is no doubt that Citroën was the first company in France that paid attention to computer-aided design, as early as 1958. Paul de Casteljau, a highly gifted mathematician, devised a system based on the use of Bernstein polynomials . . . the system devised by de Casteljau was oriented towards translating already existing shapes into patches, defined in terms of numerical data . . . Due to Citroën's policy, the results obtained by de Casteljau were not published until 1974, and this excellent mathematician was deprived of part of the well deserved fame that his discoveries and inventions should have earned him." This is quoted on de Casteljau's *Wikipedia* page which cites Pierre E. Bézier, The first years of CAD/CAM and the Unisurf CAD System, *Fundamental Developments of Computer-Aided Geometric Modeling*, ed. Les Piegl, Academic Press, 1993, 13–26. [CAM is Computer-Aided Manufacturing.]

Robin Forrest email, Apr. 9, 2017, "The crucial point is that Citroen used de Casteljau to fit curves and surfaces to clay or plaster models whereas Bézier used the curves and surfaces to design shapes ab initio."

During the last stages of editing the manuscript of this book (May 11, 2020), I finally managed to make contact with Paul de Casteljau in Versailles, via his daughter, and pay him my respect. I had sent a physical letter several months earlier to the last address I had discovered for him, an address now over 20 years old. So, frankly, I expected no response. So this late response was a delight. The daughter informed me that the mail had taken so long because of covid19 problems. I have never received further word.

272:*Bézier's (or de*: A basis function is another name for a spreader. But interpolating splines use a basis too, so the B doesn't tell us anything informative. The spreader shown here is the B-spline spreader.

There are two general classes of splines, those that interpolate their ducks and those that approximate them. The former pass through their ducks; the latter pass near them. The Catmull-Rom spline discussed earlier in this chapter is a popular interpolating spline. The B-spline is a popular approximating spline. Closely related to the splines above are the so-called *nurbs*, for non-uniform rational B-splines, often used in three-dimensional computer graphics object design and description.

In the case of approximating splines, some practitioners reserve the term *knot* for points on the actual spline where the pieces join, using *control points* for the points that are only approximated by the curve. I use *ducks*, or *knots*, for the control points for ease of nomenclature when going back and forth between spline types. That is, ducks are the given points, regardless of whether interpolating or approximating them.

272:*The two splines*: Computer graphicists say that a B-spline curve is more graceful than a Catmull-Rom spline given the same set of ducks.

272:*In all cases*: Adobe's pen tool interface allows you to design a Bézier curve by moving the tangent lines. Each tangent line pivots on the point on the curve to adjust its angle, and its length is controlled by moving the off-curve point in or out.

275:*Robin Forrest translated*: Robin Forrest email, Mar. 22, 2017, "What I did was to take Bézier's published definition in terms of the start point and successive polygon sides and re-work the mathematics to reveal that the basis which works for polygon vertices is the Bernstein basis." Later Forrest would work with Rich Riesenfeld at Syracuse University. Riesenfeld's specialty was Bernstein techniques applied to computer-aided design and computer graphics. He would become part of the

University of Utah juggernaut. The book dedication story is from Robin Forrest email, Mar. 20, 2017.

Bernstein was born in Odessa in 1880 and died in Moscow in 1968. He spent his entire life in Russia except for his university education. He took his doctorate at the University of Paris, the Sorbonne, in 1904. Recall in the Turing chapter that we introduced the great David Hilbert. In 1900 Hilbert famously posed a numbered list of difficult mathematical problems to be solved. Then in 1926 he posed another problem of the same stature called the *Entsheidungsproblem*—or eProblem as we called it. Alan Turing solved the eProblem with his great idea of computation. Bernstein studied under Hilbert, and he partially solved Hilbert's 19th in 1904 and Hilbert's 20th in 1908.

Bernstein, Bézier, and de Casteljau were all in France at some time in their lives, but Bernstein had come to Paris and returned to Russia before the latter two were born. It appears to be coincidence that Bézier and de Casteljau derived their similar mathematics almost simultaneously, and that their math was essentially Bernstein's, but one wonders if there might not have been more of a connection.

MacTutor History of Mathematics, Sergei Bernstein, online at http://mathshistory.st-andrews.ac.uk/Biographies/Bernstein_Sergi.html, accessed Apr. 5, 2020: "After one year studying mathematics at the Sorbonne, Bernstein decided that he would rather become an engineer and entered the École d'Electrotechnique Supérieure [an error—it should be the ESE that Bézier would later attend (Bernstein in 1901 and Bézier in 1931)]. However, he continued to be interested in mathematics and spent three terms at Göttingen, beginning in the autumn of 1902, where his studies were supervised by David Hilbert. | Bernstein returned to Paris and submitted his doctoral dissertation *Sur la nature analytique des solutions des équations aux dérivées partielles du second ordre* to the Sorbonne in the spring of 1904. . . . The thesis was a fine piece of work solving Hilbert's Nineteenth Problem. . . . He moved to Kharkov in 1908 where he submitted a thesis . . . for yet another Master's degree. As well as describing his approach to solving Hilbert's 19th Problem, it also solved Hilbert's 20th Problem."

The *Wikipedia* page devoted to Hilbert's famous problems (accessed Sept. 20, 2017) does not list Bernstein for the solutions of 19 and 20, but since so many references do so, I assume that Bernstein must have made substantial contributions to the solutions of 19 and 20 but did not solve them completely himself. For example, the *Wikipedia* status given for 20 is "Resolved. A significant topic of research throughout the 20th century, culminating in solutions for the non-linear case."

Supportive of this is Martin Davis, email Sept. 25, 2017, "Part of the issue with those two (related) problems is that they sketch vast fields of study so that it is unclear what would constitute a solution. The AMS [American Mathematical Society] had a symposium in 1976 on developments arising from the Hilbert problems. It led to a volume of essays published in the AMS series Proc. Symposia Pure Math (vol. 28). (I have copy at hand because I'm co-author of one of the essays.) You will want to read in it: James Serrin's article 'The Solvability of Boundary Value Problems,' pp. 507–524, which has an extensive discussion of Bernstein's contribution. Also Bombieri's article which follows it (pp. 525–536)."

275:*Ivan Edward Sutherland*: Sutherland (1963), his PhD thesis. His thesis adviser was Claude Shannon, and Marvin Minsky was on his committee, but he highly credits Steven Coons and Doug Ross of the computer-aided design group at MIT. He also thanks Larry Roberts for help programming the TX-2, difference equations, and matrix manipulations. He thanks Wesley A. Clark and Jack L. Mitchell for making TX-2 available. And he gives special thanks to Leonard M. Hantman for "his additions to Sketchpad." In a Skype conversation, Jan. 23, 2018, Ivan told me that his thesis committee was Shannon, Minsky, and Coons, which is not clear from the thesis itself. On p. 138 of his thesis, Sutherland mentions as "future work," the Sketchpad III effort underway by Johnson "of the Mechanical Engineering Department," and Roberts's effort to extract three-dimensional models from photographs.

Leonard Hantman obit., *Boston Globe*, Feb. 17, 2003, C8, "He moved to Boston after his military career and worked for Massachusetts Institute of Technology's Lincoln Laboratories, where he designed 3-D display processes, among other things."

275:*It was Sutherland's*: Johnson (1963), his master's (of science) thesis. His thesis adviser was Steven Coons. He also thanks Ivan Sutherland and Larry Roberts for help programming the TX-2, and for sharing subroutines and programs that accelerated his development of Sketchpad III. Johnson, email Apr. 29, 2017, stated that he "rolled his own" three-dimensional display subroutines. He also thanks Wesley Clark and others for TX-2 access. See also Weisberg (2008), 3:18–22.

Calling the three men the Triumvirate and MIT classmates makes it seem that they were all of equal student stature, and perhaps even shared a common office at Lincoln Lab. But Sutherland and Roberts were PhD students and full employees of Lincoln Lab. They talked with one another frequently. Johnson was master of science student with comparatively infrequent contact with the other two and had only courtesy access to Lincoln Lab. I simplify somewhat by treating Lincoln Lab and MIT as synonymous, and students at MIT as classmates, regardless of stature and employment details. Treating Lincoln Lab and MIT as synonymous is like equating Sandia Lab with UC Berkeley, and JPL with Caltech. In each of these cases, the lab and the university have different functions and different locations, but they are formally attached at some level. And use of TX-2 required situation in the same place.

Re the photos of the Triumvirate: In Skype with Ivan Sutherland, May 9, 2017, he identified the strange object he holds in his photo as a robot that he designed as a student at Carnegie Institute of Technology (since 1967 known as Carnegie Mellon University). He mentioned that he and Roberts were officemates, not just classmates, and that a third was Leonard Kleinrock, who would become a founding force of the ARPAnet.

Tim Johnson is demonstrating Ivan's program Sketchpad in this photo, not Tim's program Sketchpad III.

277:*In the Dawn*: I don't believe there was ever a display built that worked as depicted on the left.

278:*Figure 6.30 (right)*: These pictures are symbolic. They are not photographs of actual displays.

278:*It must have*: Tim Johnson, email Apr. 20, 2017, in full: "The TX-2 sported a digital point display (no vectors were stroked there), as evidenced by the tracking cross that re entered itself by drawing points horizontally and vertically until they were no longer visible by the photo detector inside the focused light-pen. You can see the 'crawling ants' in the kinescopes of the display (on YouTube) showing lines that were out of sync with the TX-2 displayed frame rate (it never really flicked in real life). All lines were drawn by a subroutine that plotted out adjacent points."

Sutherland (1963), 67–68. Twinkling and interlace (the every eighth point trick) display could be toggled on or off. This apparently contradicts Johnson's claim (above) of never flickering, but he probably referred to a video interference flicker, not a display flicker.

Ivan Sutherland email of May 2, 2017, "The display described in my thesis was a point plotting display. Under program control it could illuminate a single pixel at the coordinates specified in the program. That's all it could do. It was, therefore, very slow."

In a Skype conversation with Sutherland on May 9, 2017, he told me that the randomness was true, generated by a Geiger-counter-like device, not due to a so-called pseudo-random-number generator typically used in software.

278:*Not surprisingly, when*: Sutherland (1963), Appendix E, Proposal for an Incremental Curve Drawing Display, 154–160, was not a proposal for a vector, or calligraphic, display like the LDS-1. Ivan Sutherland email, May 2, 2017, "LDS-1 was a line drawing display. In the early versions of LDS-1 we purchased the line-drawing analog device from elsewhere. Later on we (E&S) were able to build our own." The Picture System was first produced in 1974, registered trademark in 1975.

278:*Here's how to*: Descartes is perhaps a better reference than Euclid and the early Greeks because Descartes introduced coordinate systems to geometry. Hence Cartesian geometry would be the reference, not Euclidean. But we should also honor Apollonius of Perga for conic sections, and so forth. I'm rather loose with what I mean by "geometry" anyway, including analytic functions and other such succinct mathematical objects, as discussed in other places.

The word *viewport* has a troubled history in computer graphics, leading Jim Blinn, one of its most accomplished practitioners, to write a column in 1992 called "Grandpa, what does *viewport* mean?" [Blinn (1992)]. Early textbook Newman and Sproull (1973), 126–127, has a viewport being any windowed view on the display screen. In that sense, Sutherland transformed a view in two-dimensional model space to a two-dimensional viewport in Sketchpad. But I'm capturing here the moment when three dimensions first collapsed to two in perspective, Tim Johnson's contribution.

My use of *viewport* as an abbreviation of *perspective viewport* is unusual but reduces the verbiage and draws attention to the specialness of the (perspective) viewport.

281:*William Fetter, "The*: Fetter (1962), 36.

281:*Over a year*: Walter D. Bernhart and William A. Fetter, *Planar Illustration Method and Apparatus*, US Patent No. 3,519,997, issued July 7, 1970, filed Nov. 13, 1961. Although Bernhart is the first name on the patent, all subsequent publicity about it feature Fetter, who worked diligently to make it known. Several times Fetter claimed 1960 as the date for this patent [see also below], but I couldn't substantiate it: Fetter (1964a), 7, "The first perspective drawing produced by this system was plotted at Boeing in early 1960. (Figure 7)," where Figure 7 (on a later page) was the airplane drawing in the Nov. 1961 patent (issued 1970), reproduced here.

Fetter (1962), 36: "The first formal session on the subject occurred in June, 1960. . . . Fetter described the many areas of art, and directed attention to the one segment, perspective, that was predictable and controllable. It might, he felt, be successfully programmed by a computer. | He and Bernhardt [*sic*], convinced that it could be done, pursued the problem with every available moment . . . Fetter outlined a new concept of perspective, abandoning the accepted academic drawing methods. Bernhardt grasped the approach quickly and made the conversion to mathematics. This was turned over to the [unnamed] programmer who translated the math to computer language. To process a test of this, data from an aircraft drawing was supplied to a computer. Only two months after that first meeting [Aug. 1960], Boeing had successfully produced its first true perspective plot."

Email from Robin Oppenheimer, June 16, 2017, who obtained the following directly from Fetter: "[I] co-patented the first Computer Graphics patent, digital computer perspectives '60 [patent was filed Nov. 1961, with Bernhart]. | developed the first interdisciplinary Computer Graphics RD&A unit in industry '60 [plausible, Fetter (1962), 36, gives June 1960 as the date]. | produced the first perspective motion picture animation (Naval cockpit visibility) '60 [unsubstantiated, probably 1962]. | developed the 'First Man' an anthropometrically correct computer human figure '62. | produced the first full color Computer Graphics film (the Boeing TFX proposal) '63 [unsubstantiated, cf. <u>note</u> 282:*An interesting claim*] | wrote the first book in field, Computer Graphics in Communications, McGraw Hill '64 [Fetter (1965), but written in 1964 according to title page]." Perhaps Fetter dated by using the origin date of a project rather than its completion date.

281:*As evident from*: [Math] The Bernhart-Fetter perspective solution is accurate but not elegantly presented. I thank Jim Blinn (email June 18, 2017) for parsing Fetter's mathematics for me: Let $[V\ W\ D]$ represent a two-dimensional point on the picture plane in homogeneous coordinates. Then Bernhart-Fetter give this solution: $[V\ W\ D] = [x_i\ y_i\ z_i\ 1]\ E$, where E is a 4 by 3 matrix where each element is a function only of the eyepoint $p_e = [x_e\ y_e\ z_e]$. The point on an object that we wish to see in perspective is $p_i = [x_i\ y_i\ z_i]$. The picture plane is perpendicular to the line from the origin to p_e. The parameter k positions the picture plane along this line. This is the matrix E, row by row, where $\alpha_e = \sqrt{x_e^2 + y_e^2 + z_e^2}$, $\delta_e = \sqrt{x_e^2 + y_e^2}$, $k_e = k\alpha_e/\delta_e$, $K_e = k_e\alpha_e$:

$$\begin{matrix} -K_e y_e & -k_e x_e z_e & -x_e \\ K_e x_e & -k_e y_e z_e & -y_e \\ 0 & k_e \delta_e^2 & -z_e \\ 0 & 0 & \alpha_e^2 \end{matrix}$$

Divide through by the homogeneous coordinate to get the object point in perspective in the picture plane at $[v_i\ w_i] = [V/D\ W/D]$. For comparison to Zajac and Roberts, see <u>note</u> 284:*Zajac said, "The* and <u>note</u> 292:*The Roberts technique*, respectively.

281:*The mention of*: Fetter (1962), 36. Described in email from Robin Oppenheimer, June 21, 2017: "Gives a brief history of Fetter's work at Boeing with lots of illustrations. No mention of a film, but the drawings of a cockpit are the same found in the next documents [Fetter (1964a and b)]." Uses "computer graphics" several times. Mentions perspective and animation. Has figure with this caption (p. 36): "This is the first true perspective drawing by Boeing Computer Graphics." It's the figure of the plane from the Nov. 1961 patent filing. Fetter assigned the date 1960 to the coining of *computer graphics*, but I've found no evidence for it. Feb. 1962 is the earliest I've found the term in Fetter's writings. It isn't used in the 1961 patent (but see next paragraph).

The Bernhart-Fetter patent of Nov. 1961, issued 1970, assigns the patent to Computer Graphics, Inc., of Wichita, Kans. It's not clear however that this assignment—and use of "Computer Graphics"—occurred before the 1961 filing. It could have been made at any time prior to the 1970 issuance. It's a "mesne assignment" meaning intermediate in a chain of assignments, awaiting a final assignment. N.B. Bernhart is spelled Bernhardt in Fetter (1962), 36. At this time Fetter was giving himself and Bernhardt credit for "computer graphics."

Verne Lyle Hudson was born Oct. 27, 1915, KS, died Mar. 16, 2001, WA. [*US, Social Security Applications and Claims Index, 1936–2007*, https://www.ancestry.com/search/collections/60901/?name=Verne+Lyle_Hudson&name_x=1_1, accessed Apr. 5, 2020]. Boeing is careful to give Hudson credit for the term (cf. *Wikipedia*'s article on William Fetter, accessed Sept. 29, 2017).

282:*An interesting claim*: See note 281:*Over a year* for quotation from Robin Oppenheimer email of June 16, 2017. Furthermore, Fetter claimed that all but one of his early movies were in color, but I've been unable to verify it.

The films and videos are listed in Fetter (2001). It's a formal list of sixteen films and/or videos he made between (est.) 1962 to (est.) 1969. All but three were made at The Boeing Company. The oldest film listed is "[File No.] .862 [Est. Year] 1962 [Title of the Projection Program] *A4B–F4B, Carrier Landing*, [by] Fetter, W. A., 35mm [slides], 16mm [film], [video ¾" Umatic] .80d [video VHS Cass.] .8d [the preceding two items refer to other video projects which must include snippets from this one] [Source] Boeing [Color] Color [Sound] Sound [Minutes] 10 min." The second oldest film listed is "[File No.] Study [Est. Year] 1963: [Title of the Projection Program] *Dive Bombing, & Carrier Landing, CVA-19*, [by] Fetter, W. A., 16mm [film], b&w, silent." The third oldest is "[File No.] .864 [Est. Year] 1964: [Title of the Projection Program] *AMSA Cockpit Visibility*, [by] Fetter, W. A., 35mm [slides], 16mm [film],16mm [film], [Source] Boeing [Color] Color [Sound] Sound [Minutes] 10 min."

Since publishing the book, I have been made aware of what is perhaps the earliest 3-dimensional computer-graphics animated movie: *Rendering of a Planned Highway*, https://www.youtube.com/watch?v=ASq0Sm-iSaM, broadcast on Swedish television on Nov. 9, 1961. It is in perspective, and hence within the Central Dogma. Mark Wolf, in an email to me on Oct. 6, 2021, gave me the important details. It is part of a book on computer graphics on which Wolf is currently working. From Wolf's email I quote Ulf Sandqvist, a Swedish media scholar, about the piece:

It was done by the company Nordisk ADB. Nordisk ADB was one of the first private programming enterprises in Sweden. The company was specialized in computations for road and water engineering projects and worked for different government agencies. The short film was likely programmed and filmed in Dusseldorf, Germany on a computer called EDB-2. EDB was a copy of the Swedish BESK computer but was owned by the Swedish company Facit that had a business in Germany. Nordisk ADB also had a subsidiary in Dusseldorf together with Facit. The computers had a mounting mechanism to take photos of the oscilloscope. Programmers at Nordisk ADB realized they could make a movie by apparently using data from a road project in Stockholm (in Nacka).

The film was shown at an annual meeting of a large planning or road association in Germany by Carl-Olof Ternryd from Nordisk ADB. The film was a way to kind of "show the future" in road engineering. It was also shown in the evening news program on Swedish TV in 1961. Sweden had a state monopoly and only one TV channel at the time.

The more I think about this, the more amazed I get. They had to come up with a perspective solution. They had to master clipping of the 3D model against the 2D viewport. They had to build a hardware interface to an oscilloscope to take vector-drawing commands and display them, and also an interface to a camera. My first assumption is that they drew one frame at a time, filmed it, then the next frame, etc. It baffles me that, if they knew how to do all that, that we haven't heard more about them. Computers at that time were beasts. I suspect there is much more to this story. If not, then there was a loss of a giant opportunity by that Swedish group.

283:*At the famed*: Zajac (1964). A movie using Zajac's perspective solution, made in 1963 (date added later), can be seen at *AT&T Tech Channel*, https://techchannel.att.com/play-video.cfm/2012/7/18/AT&T-Archives-First-Computer-Generated-Graphics-Film, accessed Apr. 5, 2020, titled *Simulation of a Two-Gyro Gravity-Gradient Attitude Control System*, by Zajac at Bell Labs and narrated by him, one of the earliest computer-generated animations. Another interesting film of his, from 1967, made with Roger Shepard, titled *A Pair of Paradoxes*, can be seen at *AT&T Tech Channel*, https://techchannel.att.com/play-video.cfm/2011/10/10/AT&T-Archives-A-Pair-of-Paradoxes, accessed Apr. 5, 2020. It demonstrates Escher's (actually Penrose's) ever-ascending staircase and an audio analog, called Shepard's tone.

Care must be taken to distinguish Edward Zajac of this chapter, in the early 1960s at Bell Labs, from Edward Zajec who did computer graphics (only) slightly later. See http://edwardzajec.com/, accessed Apr. 5, 2020, for further information about the latter.

283:*The Zajac movie*: This picture appears to be calligraphic, but a closeup reveals it to be jagged, so rendered on a raster. It's not clear whether this picture comes from the microfilm plotter that Zajac used for making the film or from a printer of some sort.

284:*Zajac said, "The*: [Math] Zajac (1964), 170. Zajac used vector notation to state the perspective solution. I will put it in expanded form and use f for the camera's focal length for comparison to Roberts's solution (Zajac used L). Then Zajac's solution for a three-dimensional point (x, y, z) at focal distance f is the two-dimensional point in the picture plane $(fx/z, fy/z)$. Taking f as 1, as did Roberts, then the point in perspective is $(x/z\ , y/z)$. So if the given point is in the picture plane, $z = 1$, and the perspective point is just (x, y). If it's in the $z = 2$ plane, then in perspective it's $(x/2, y/2)$. At $z = 3$, it's $(x/3, y/3)$, and so forth, equivalent, within a scale factor, to Roberts's solution (see <u>note</u> 292:*The Roberts technique*) and exhibiting the foreshortening property. See also the Bernhart-Fetter solution in <u>note</u> 281:*As evident from*.

284:*Steven A. Coons*: Related to me by Ivan Sutherland in a Skype conversation on Jan. 23, 2018, in response to my asking whether I had correctly captured his (Ivan's) personality.

284:*Wesley A. Clark*: Related to me, proudly I think, by Ivan Sutherland in the Skype conversation of Jan. 23, 2018; Sutherland, email Jan. 21, 2018: "Wesley A Clark designed both TX-0 and TX-2 and arranged that they be used as personal computers. He later designed the LINC computer, the first machine designed with the intent that it provide interactive connection to laboratory instruments." Clark also worked on the Whirlwind team, joining the project in 1952, according to his *Wikipedia* page (accessed Jan. 24, 2018).

284:*He stored models*: MIT had many labs and facilities. To minimize confusion, I will often say that something happened "at MIT" if it occurred in any of the MIT sites, although they might be separated by several miles. Lincoln Labs, for example, was not separated from the main MIT campus by several miles, but it was a facility with high security.

285:*Steve Coons showed*: Tim Johnson email, Mar. 24, 2017, in which he also stated: "Ivan's signal Sketchpad contribution was his mind bending graphical constraints that locally minimized system energy (which also blew Steve Coons mind)." Minimization of system energy is a computer-aided design concern, as are strain or compression analysis.

Licklider (1966), 44, put it this way: "In 1962, at the Spring Joint Computer Conference in San Francisco, during the discussion period of a session on man-computer communication chaired by Douglas Engelbart, Ivan Sutherland mentioned his Sketchpad program and, at the end of the session, showed to a few lingering enthusiasts the most dramatic on-line graphical compositions that any of them had seen." Sutherland must have shown a movie.

285:*Constraints aside, the*: Krull (1994), 44–46; Weisberg (2008), 3:22–25.

285:*At first there*: Rich Riesenfeld, email of Sept. 23, 2017, pointed out a parallel between GM's DAC-1 and Citroën's de Casteljau curve: Because they both delayed or prevented publication, they both lost out in long-run contributions to the field.

Barrett Hargreaves, email Nov. 4, 2014: "We were a GM Research Laboratories group and our primary goal was to investigate ways that computers could help in the GM design and engineering processes. We were not so academically oriented that public announcements were a top priority. We made our 1964 SJCC presentations as other GM priorities would allow. In our DAC-1 group, engineers and designers from three or four GM divisions worked with us and we were obligated to keep their management updated. Most of our time was spent continuing DAC-1 development and keeping those GM operating divisions aware of the potential benefits . . . As we were developing the DAC-1 system and the DAC-1 hardware from IBM became available, we were all extremely impressed with the potential of the CRT and the light pen as a way to input data to a computer. Answering yes or no questions, entering design points and lines and modifying design surfaces was a giant leap compared to entering information and data on punched cards. Most of us had little understanding of what others were doing in these areas but we understood the enormous potential that eventually developed into the personal computer."

286:*Probably the most*: Barrett Hargreaves, email May 18, 2017. Also, in an email May 19, 2017, Hargreaves said, "In my remembrance, we did not use perspective as you noted. But, yes, it was common for a DAC-1 user to view a car part, modify that part and review his changes on the DAC-1 display consol[e]."

286:*According to Hargreaves*: Jacks (1964), 344, "Because of the nature of automobile design, it was necessary that the DAC-1 system be able to accept free form curves, i.e., curves which are constructed without consideration of particular mathematical representations. Furthermore, to provide compatibility with existing design procedures, precision input and output of such curves was needed. These requirements ruled against a 'sketchpad' type of operation. [A superscript here pointed to Sutherland's Sketchpad paper of the previous year]." This appears to mean that curves were more important at GM than line segments. DAC-1 also had a "position-indicating pencil" and a 17-inch display.

Hargreaves et al. (1964), 375, "the position-pencil control system can maintain the position of the beam under the pencil, making it appear that the pencil traces an image on the CRT screen." But, 379, "While the pencil or a light pen could be used for entering images consisting of connected straight lines, a highly sophisticated program would be required to track and accurately digitize drawings of curves which are connected to form an image." I take this to mean that although DAC-1 could have entered designs based on line segments as did Sketchpad, it did not because of the perception that models made of curves were more important.

Of further potential interest to future historians are these excerpts from another email from Barrett Hargreaves, Oct. 13, 2014: "We DAC-1 folks at the GM Research Computer Technology Department did have some coordination with MIT. We knew about Sketchpad. Through Dr. Bernie Galler, of the University of Michigan, we contacted MIT and became aware of their work on computer graphics. Specifically, a member of the MIT computer graphics group was contracted by GM Research to write a compiler for programming the DAC-1 hardware. We also consulted with a group of MIT people who had formed a company near Boston that had developed a 'light pen'. IBM incorporated that light pen design in the DAC-1 hardware. It was an early version of the computer mouse." Also, in an email of May 19, 2017, Hargreaves said, "I can remember seeing

Bert Herzog around the GM Research labs. Our most consistent University of Michigan consultant was Bernie Galler . . . who spent a lot of time with us."

Dr. Bernard Galler was a professor of mathematics at the University of Michigan and was a consultant with GM for 20 years [Dr Bermard Galler, Oral History by Atsushi Akera, Jan. 18–19, 2006, ACM Digital Library].

Sutherland (1966), 23, discusses the "voltage pencil" of the DAC-1 and compares it to the" light pen" at MIT.

286:*Walt Disney visited*: Barrett Hargreaves, email Oct. 13, 2014. Hargreaves spelled the name Hugh "Brose" in this email, but see next note.

286:*Again the dates*: Barrett Hargreaves, email May 18, 2017, "On the question of the Walt Disney visit, Hugh Brouse did not use DAC-1. He was a very early computer graphics programmer at GM Research. He used his own computer routines to create the animation. Hugh Brouse died a few years ago. All of us early GM computer graphics guys are in our 80s or older now."

Robin Forrest, email Mar. 20, 2017, "I think I exaggerated in saying that GM didn't get the credit for ALL of the techniques in Sketchpad, but I think they were early pioneers in interactive graphics. Interaction was the big breakthrough. Remember Siggraph stands for graphics *and interactive techniques* because of the advance from plotter graphics. I can't really remember seeing DAC-1 but IBM collaborated on the project and the IBM 2250 display was developed from DAC technology. At $250,000 it was not only expensive compared with the DEC 340 and CDC machines but it was a really poor machine. Pen tracking was crude compared to Sketchpad."

288:*Actually touching a*: See Dear (2017). On Oct. 13, 2017 in Raleigh, NC, I dined with Don Bitzer who informed me that the project, under a new name, had only ceased to exist the preceding year.

289:*And for computer-aided*: Sutherland created much of the terminology subsequently used for years in computer graphics and computer-aided design: instancing (define an object once, and reuse it several times in one model, make a change on the original and all copies, or instances, of it change automatically), display list (a quick access to the objects necessary for display, but not for further computation), and hierarchical models (a model made of submodels, each made of subsubmodels, etc.).

Skype conversation with Ivan Sutherland, May 9, 2017. I asked Ivan about the relationship between his and Bresenham's line-rendering algorithm. He replied that Bresenham's algorithm was aimed at requiring as little mathematical calculation as possible, but with TX-2, he Ivan had no such concerns. He had plenty of power to simply do the calculations.

289:*But most importantly*: Sketchpad, *by Dr. Ivan Sutherland with comments by Alan Kay*, https://www.youtube.com/watch?v=495nCzxM9PI, accessed Apr. 5, 2020. In his introduction Kay states that this is the earliest known film of Sketchpad, from the summer of 1962, and he dates it by mentioning a certain feature, visible constraints, that wouldn't be available until the Jan. 1963 version of Sketchpad. The demo features topological constraints (forcing of right angles and parallel lines, maintenance of symmetry, etc.), resizing, instancing, hierarchical objects, and making parts invisible, etc. It also "features" a blinking screen as the number of line segments and circular arcs increases.

Licklider (1966), 44: "If I had to pick out two milestones as the most significant in the development of man-computer interaction through graphics, I would pick the following two: In 1962, at the Spring Joint Computer Conference in San Francisco, during the discussion period of a session on man-computer communication chaired by Douglas Engelbart, Ivan Sutherland mentioned his Sketchpad program and, at the end of the session, showed to a few lingering enthusiasts the most dramatic on-line graphical compositions that any of them had seen." But TX-2 was immovable, of course. So it must have been the demo film that they saw in San Francisco in 1962. The second system mentioned by Licklider (1966), 44, was DAC-1: "In 1964, at the Fall Joint Computer Conference in San Francisco, Jacks, Foote, Krull, Allen, Hargreaves, Joyce, and Cole of General Motors Research described various aspects of their DAC-1 (Design Augmented by Computer) System, and Foss, Gray, Sharp, Sippel, Spellman, and Thorp of IBM described the equipment facility. DAC-1 was an experimental system used in a way that approached operational significance. The designer at the console created or modified the designs of parts of automobiles."

290:*Tim Johnson had*: Case in point, added June 22, 2022: an old BBC TV production aired about 1982, called *Painting By Numbers*, is archived at https://ia600408.us.archive.org/11/items/paintingbynumbers/paintingbynumbersreel1.mp4. Its temporal locations 9:24–10:40/37:08 are devoted to Sketchpad. The sequence starts with a still image of Ivan Sutherland, but the person shown in motion demonstrating the program is Tim Johnson, author of contemporaneous Sketchpad III, not Sutherland, author of Sketchpad (although the program Johnson is demonstrating is Sketchpad, not Sketchpad III). Johnson appears beginning at 9:39 and again at 10:02, with cutaways to the Sketchpad screen. Then at 10:08 an unidentified person appears (he's the interviewer for an earlier documentary at MIT) and the narration erroneously claims that Sketchpad did hidden line removal on 3-dimensional objects. It was a 2-dimensional program only so did not do hidden line removal. Sketchpad III was 3-dimensional, but did not implement hidden line removal. The third member of the Triumvirate, Larry Roberts, did do hidden line removal. So the demonstration in this video at time locations 10:10–10:40 was probably of Roberts's work, definitely not Sutherland's and probably not Johnson's.

Note added June 24, 2022: I ran an experiment on Apr. 30, 2021, and reported it in an email of that date to historical researcher Brian Berg. Here is a summary: I entered "Ivan Sutherland" in Google Chrome then clicked on "Images." I counted images of Ivan at the controls of Sketchpad and of Tim Johnson at the controls of Sketchpad III. I didn't count images of Tim Johnson at the controls of Sketchpad, nor displays of Sketchpad or Sketchpad III that did not show the human controller: Page 1 of images showed 5 of Tim and SP3, and 6 of Ivan and SP; p. 2 (after clicking on Show More Images) had 8 of Tim and SP3, and 2 of Ivan and SP; p. 3 had 4 of Tim and SP3, and 1 of Ivan and SP. So of 26 total images, 17 (over 65%) were misidentified as Ivan on Sketchpad.

Then I ran this second experiment: I entered "Ivan Sutherland Sketchpad." In this case, of the 63 total images, 40 were of Tim on SP3 and 23 of Ivan on SP. So images of Tim Johnson on Sketchpad III were misidentified as images of Ivan Sutherland on Sketchpad in over 63% of the cases. Tim was not identified even once.

290:*Johnson's Sketchpad III*: The four-window approach to engineering design was an old one. It was the layout I was taught to use in my early 1960s mechanical drawing class in high school, although we seldom if ever drew the fourth window in perspective. I've talked with old friends who've assured me that architecture students did draw that fourth window in perspective. Johnson simply adapted the approach to the CAD world.

290:*In figure 6.34*: Johnson (1963), his MIT thesis and the publication of it.

290:*The viewport was*: Tim Johnson email, Mar. 24, 2017, complete quotation with mathematical details included: “Ivan got the homogeneous thing going by pointing me in Larry Roberts’s direction. I quick[ly] appreciated how clean (and brilliant) his approach was—just boils down to Matrix math! A bonus was the Matrix subroutines had been optimized [presumably by Roberts] for the TX-2 assembler, so execution was blazing fast (for those days). So I added the 4×4 and 4×1 stuff to my Sketchpad III program.” The 4 by 4 matrix manipulation techniques introduced by Roberts are as important as his perspective solution, which depended on the matrix methods. All computer graphicists use his matrix techniques. The matrix math is quite clever but outside the scope of this book.

Johnson’s full remark regarding the viewport: “The perspective view port was my notion. I piled it on by using three of the four knobs (which had flywheels on them so you could flick them into continuous rotation—loved those flywheels!) below the TX-2 CRT to: | 1) change the focal length | 2) change the scale | 3) Spin about a user selected axis | Never did use the fourth knob since object translation was handled by the light pen. I used Ivan’s subroutines to clip lines at the fixed viewport perimeter.”

Note that Johnson actually uses the term perspective viewport for what I’ve termed the viewport in this chapter. By the broader meaning of the term, all four views in Sketchpad III are viewports. It’s the perspective viewport that is especially important to computer graphics.

Johnson also verified, in an email of Mar. 25, 2017, that the photo is indeed of him on Sketchpad III (not Sutherland on Sketchpad).

It was Tim Johnson who notified me, on Dec. 31, 2018, of the death of Larry Roberts on Dec. 26, 2018, Redwood City, CA. An obituary for him appeared in the *New York Times*, Dec. 30, 2018, p. A20 of the New York edition, and is also available at https://www.nytimes.com/2018/12/30/obituaries/lawrence-g-roberts-dies-at-81.html, accessed Apr. 5, 2020. It does not mention his fundamental contribution to computer graphics.

290:*I asked Johnson*: Johnson email, Mar. 30, 2017, additionally: "I was interpolating three (for X, Y, and Z) parametric cubics."

291:*And what had*: Tim Johnson email, Mar. 24, 2017, complete quotation: "My trajectory after Sketchpad III was to start a research project in the department of architecture based on Ivan['s] constraints idea to arrange activity blocks into architectural plans based on new constraints like visual access, sequence, adjacency, etc. That led to a MIT professorship for me, and I later had a craving to get my hands dirty again, so I built a demo solar building with phase change thermal storage in ceiling tiles on the MIT campus that demonstrated the first use of Low-E glass for passive solar heating (MIT Solar Building 5). Then I got tired of getting dirty hands and started a successful business doing stylized photo-realistic architectural renderings. Thereby ending up in your field after all."

292:*But his far*: Roberts (1963), his PhD thesis. His thesis adviser was Peter Elias, but he credits Claude Shannon, Murray Eden, and Thomas Stockham for advice and encouragement. And he gives special thanks to Leonard M. Hantman who "programmed the major part of the 3-D display process."

292:*The Roberts technique*: [Math] Here's roughly how Roberts's perspective works. Point (x, y, z, h) in space flattens to point $(x/h, y/h)$ in two-dimensional display coordinates. Roberts (1963), 16, taught us to use $h = 1 - zr$, with $r = S/f$, where f is the virtual camera's focal length (distance from its focal point to center of its focal plane) and S is half the film width. He suggests that r is often about $1/4$, so $h = 1 - z/4$. If $z = 0$ at the picture plane, then $h = 1$ there and the point projects simply to (x, y). At the $z = -4$ plane, in the direction away from the camera's focal point, $(x/h, y/h)$ becomes $(x/2, y/2)$. At the $z = -8$ plane, $(x/h, y/h)$ becomes $(x/3, y/3)$. At the $z = -12$ plane, $(x/h, y/h)$ becomes $(x/4, y/4)$. And so forth. This is the famous foreshortening of perspective. (I have reversed Roberts's use of x and z in this discussion.)

The z coordinate becomes z/h in perspective space. The argument above applied to the z coordinate show that it foreshortens in perspective too. This foreshortened depth is also used in computer graphics. I've omitted it from the discussion to simplify the presentation.

292:*But Roberts went*: [Math] Matrix algebra is beyond the scope of this book, but here's a brief hint at what a matrix is and why matrices are popular in computer graphics. A matrix is simply an array of numbers, in rows and columns. For example, here is a 2 by 2 (2 rows by 2 columns) matrix: $\begin{bmatrix} a & b \\ c & d \end{bmatrix}$, where $a, b, c,$ and d represent arbitrary numbers. Here is a matrix equation where the matrix on the left side of the equals sign is the product obtained by multiplying the two matrices on the right side: $\begin{bmatrix} i & j \\ k & l \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} e & f \\ g & h \end{bmatrix}$. Mathematicians like matrices because they are so succinct. This matrix equation exactly replaces the following tedious and difficult to read set of equations: $i = ae + bg, j = af + bh, k = ce + dg, l = cf + dh$. The brevity becomes even more obvious as the matrices get larger. Computer graphicists use 4 by 4 matrices, as inspired by Roberts.

In a matrix multiplication as above but with 4 by 4 matrices, the matrix version is easier to deal with than the corresponding set of sixteen equations with four terms each.

We use $[x\ y\ z\ h]$ as a representation of a point in perspective space. That's a 1 by 4 matrix, one row of four columns, called a row vector. If it's written in a vertical column, then it's a 4 by 1 matrix, called a column vector. Roberts showed how to use 4 by 4 matrices for scaling, rotation, translation, skew, and perspective of points stored as 1 by 4 row vectors.

The mathematics of homogeneous coordinates is attributed to August Ferdinand Möbius (1790–1868) and Julius Plücker (1801–1868), both German mathematicians.

293:*It turned out*: Retrospectives II (1989), 56–59, quotation from p. 59. Roberts used the *Playboy* image to determine how many bits per pixel he could throw away and still have a reasonable approximation of the original image. Despite Roberts's claim that he used German textbooks for perspective, he cites only the non-German textbook by Somerville (1959): "Although many books discuss this homogeneous system of coordinates, their presentations are either incomplete or are too involved for our purposes."

293:*Why isn't there*: To make Roberts's contribution memorable, I've simplified it a bit. As regards his internet contribution, a more careful statement is this: Roberts helped create ARPAnet, which became the internet.

294:*Licklider, Engelbart, and*: Lick, while at ARPA, funded a time-shared computer project called Project Genie at the University of California. Time-sharing doesn't concern us here, but the Project Genie principals do. One was Harry Huskey, whom we met in the Dawn of Digital Light chapter (4). Another was David Evans.

Sadly Harry Huskey died Apr. 7, 2017, at 101, as I was writing this chapter. I was lucky to have talked to him when I wrote the Dawn chapter.

294:*In 1970 Bob*: Sadly again, as I wrote this chapter, my wife informed me that Bob Taylor had also just died Apr. 13, 2017, the week after Harry Huskey's death.

See John Markoff's article, "Robert Taylor, Innovator Who Shaped Modern Computing, Dies at 85," *The New York Times*, Apr. 14, 2017. Some of my other colleagues at Xerox PARC were Bob Flegal, Larry Masinter, Dave Boggs, Jim Meyer, and many others. David DiFrancesco worked with me at nights there on Dick Shoup's SuperPaint program.

Bob Taylor, Harry Huskey, and Ed Catmull were inducted as Computer History Museum Fellows on the same night in 2013.

294:*As I wrote*: Roberts was inducted as a Fellow at the Computer History Museum on Apr. 23, 2017. His official induction, https://computerhistory.org/profile/larry-roberts/?alias=bio&person=larry-roberts, accessed Apr. 5, 2020, does not mention his important role in computer graphics.

For years, at Lucasfilm and Pixar, I wrote and maintained the libraries of subroutines that implemented the Roberts viewing transformations (where perspective is applied) and the Roberts object transformations (using 4 by 4 matrix algebra for object and camera translations, scalings, and rotations). I am intimately aware of his importance. Every frame of a Pixar movie goes through these basic Roberts transformations and is viewed in Roberts perspective.

295:*A second method*: Sutherland (1963), 132–133, Fig. 9.8. In a Skype conversation with Ivan Sutherland, May 9, 2017, I asked about the winking girl. Ivan claimed he'd never seen her wink, which implies that it was others who demonstrated the winking girl to amused visitors. Clearly this picture is from a calligraphic printer, not a dot array display. It's also the most obviously non-CAD example in the thesis.

I've read Sutherland's explanation of the two types of animation several times, to see if I misunderstood him. I interpreted his "appropriate application of constraints" to be the CAD meaning of that term—a physics-based constraint—which is what made Sketchpad so famous. But perhaps he meant to include an animator's movement along a drawn path as an "application of constraints." It's difficult to read it that artistic way, however.

296:*Jasia Reichardt, Cybernetic*: Reichardt (1968), 5, her full quotation begins: "The first is that no visitor to the exhibition . . ."

296:*Bell Labs was*: Knowlton (1964). The language is called only a "movie language" in this paper. It's apparently the same as Knowlton's language Beflix. A movie made with his system in 1964 (undated on the film itself, but mentioned in a footnote of the paper), *A Computer Technique for Producing Animated Movies*, can be seen at *AT&T Tech Channel*, https://techchannel.att.com/play-video.cfm/2012/9/10/AT&T-Archives-Computer-Technique-Production-Animated-Movies, accessed Apr. 5, 2020, author not given. A slightly later film, made 1964–1965 (date added later), at Bell Labs, *Programming of Computer Animation*, can be seen at *AT&T Tech Channel*, https://techchannel.att.com/play-video.cfm/2012/9/17/AT&T-Archives-Programming-of-Computer-Animation, accessed Apr. 5, 2020, by R. H. Hudgin (a student) and E. E. Zajac, using K. C. Knowlton's Beflix language.

296:*This was the*: Taylor (2014). The title says it all: *When the Machine Made Art: The Troubled History of Computer Art*.

297:*Although many people*: Email from Marceli Wein, July 3, 2017: Jasia Reichardt was a Polish Jew who escaped the Nazis in a manner similar to Wein's own escape. She was smuggled out of the Warsaw ghetto just before it was destroyed, taught to be Catholic, obtained new identity, fled from protector to protector, including an orphanage run by sympathetic nuns, and finally reunited with an aunt in London. See *Fifteen Journeys: Warsaw to London by Jasia Reichardt 2012*, http://compellingjewishstories.blogspot.com/2013/03/fifteen-journeys-warsaw-to-london-by.html, accessed Apr. 5, 2020.

297:*But Robin Forrest*: Cardoso Llach (2016), 17, "The image was . . . Well . . . We weren't really trying to design anything. We were just trying to see how flexible we could be. And she [Reichardt] said, 'I'll take this!' So she picked up a bunch of our polaroids and said, 'That's it! That's art!' And off she went with it. This was only 1968, at Cambridge, when I was writing my thesis or shortly after." So Reichardt got more excited as CAD receded.

297:*He also pointed*: Jasia Reichardt quoted on *Cybernetic Serendipity: The First Widely-Attended International Exhibition of Computer Art*, http://www.historyofinformation.com/detail.php?entryid=1089, accessed Apr. 5, 2020. She cites: "One of the journals dealing with the Computer and the Arts in the mid-sixties, was *Computers and the Humanities*. In September 1967, Leslie Mezei of the University of Toronto, opened his article on "Computers and the Visual Arts" in the September issue, as follows: . . . "

298:*People in this*: Reichardt (1968), 67–68, Knowlton, Zajac, and Vanderbeek; 86–87, more Knowlton; 88–90, Fetter's Boeing Man, but Fetter is unnamed; 92–93, Duane Palyka (see next chapter); 95, pictures from GM's DAC-1; 96, Robin Forrest. Also 66, Ron Resch (see next chapter). These are in addition to the creators listed in the quotation by Reichardt, and there are many others. *Cybernetic Serendipity* [Reichardt (1968)] is a collector's item today.

A fascinating "artist" in *Cybernetic Serendipity* was a group of five Japanese men who called themselves the Computer Technique Group from Japan (pp. 75–77). They were Koji Fujino, Masao Komura, Kunio Yamanaka, Haruki Tsuchiya, and Makoto Ohtake. Some of their classic pieces: (1) *Shot Kennedy No. 1*, JFK at the moment of bullet impact (idea and program by Tsuchiya); (2) *Return to Square (a)* and *(b)*, a human profile interpolates in steps to a square, two ways (idea by Komura, program by Yamanaka); and (3) *Running Cola is Africa*, a running man morphs to a Coke bottle which morphs to a map of Africa (idea by Komura, data by Ohtake, program by Fujiro).

I met curator Jasia Reichardt on Mar. 13, 2018, at a 50th anniversary of her *Cybernetic Serendipity* show, held at the National Academy in Washington, DC. In a followup email, Mar. 26, 2018, she told me that it was she who had had the translation made of the famous phrase "uncanny valley" from the original Japanese into English. Berkeley professor Ken Goldberg had told me of it.

298:*Ron Baecker, PhD*: Baecker (1969a), 6.

298:*Ronald Michael Baecker*: Ron Baecker is now Canadian, but he was born in the US and emigrated towards the end of the Vietnam War (in Aug. 1972, according to an email from Ron, Aug. 5, 2019).

299:*In late 1966*: Baecker (1969a), 4, acknowledgments, "Professor Ivan Sutherland, now at the University of Utah but then at Harvard, proposed use of waveforms to define changing picture parameters, and Tim Johnson of M.I.T. enlarged upon this suggestion." But neither Baecker nor Johnson remember the details [emails of May 2017]. This form of animation is of Sutherland's second type (per his 1963 thesis), by motion, rather than by substitution.

299:*Baecker generalized the*: Ron Baecker, Lynn Smith, and Eric Martin made a documentary movie of Genesys running on TX-2, titled Genesys: *An Interactive Computer-Mediated Animation System* [sent me by Martin, Sept. 28, 2015, but the film is undated.] Ron Baecker, email Aug. 5, 2019, sent this link to the movie: https://www.youtube.com/watch?v=GYIPKLxoTcQ, accessed Apr. 5, 2020.

Baecker (1969a); Baecker (1969b). Knowlton's animation system from the early 1960s at Bell Labs wasn't interactive. Another distinction was that Knowlton's system was a raster system, but Genesys was calligraphic—in that halfway form of calligraphic display peculiar to the TX-2 (with dots restricted to raster locations).

299:*In a recent*: For flow, I've slightly edited the email from Ephraim Cohen, May 25, 2017. Here's the original version: "I was introduced to Ron by a mutual friend, Lynn Smith . . . , then an animator at the Carpenter Center at Harvard, and since 1975 in Montreal at the CFB [Canadian Film Board]. Lynn and I were friends in High School. Ron was looking for people to use his animation system, which as I recall was all line drawings as p-curves (that is, time/parameter graphs). This was kind of confusing for most art persons at that time—I was a natural fit, so we were introduced. It was all done on the TX-2 in Lincoln Labs. Also, I killed an afternoon there playing space war (missiles, sun with gravity). | The animation I did was not much. I think it was all done in 2 days."

299:*Interpolation occurs when*: Baecker (1969b), 278. Baecker mentions another early animation system not discussed further here, *Café*, with geometric shapes driven by keyboard commands [J. Nolan and L. Yarbrough, An On-line Computer Drawing and Animation System, *Proceedings of the Conference of the International Federation for Information Processing* (IFIP), Aug. 1968].

Knowlton's Beflix system didn't inbetween, or interpolate, keyframes because there was no geometry in his system to interpolate.

We don't consider here hybrid systems which mixed analog curve generation with digital techniques. In the early days, David DiFrancesco, Dick Shoup, and I carefully checked out one such system, Scanimate, by Lee Harrison.

300:*In the spring*: *Schindler's List*, contains this entry: "[list no.] 2 [line no.] 5 [religion] Ju. [nationality] Po. [prisoner no.] 68825 [surname] Wein [forename] Wolf [born] 9.6.00 [occupation] Schneidermeister." There were two lists, list 1 had 297 names and list 2 had 801 names. A *schneidermeister* is a master tailor.

301:*Marceli studied at*: Marceli Wein, email of July 3, 2017, clarified that his PhD studies at McGill concerned the distribution of weather radar images.

301:*Burtnyk wrote the*: Wein (2015), 11–14, "Assistants then draw the fill in pictures that carry the image from one key picture to the next. | The work of the artist's assistant seemed like the ideal demonstration vehicle for computer animation. Within a year, Burtnyk had programmed a complete 'key frame animation' package that allowed the creation of animated sequences by providing only the key frames. The National Film Board in Montreal was contacted, and a project to allow artists to experiment with computer animation was started. | The first experimental film involving freehand drawings, called Metadata, was made by artist and animator Peter Foldes. This led to a more substantial collaboration on a 10-minute feature called Hunger/La Faim about world hunger and about rich and poor countries." "The script certainly brought memories," Marceli Wein told me.

La Faim (Hunger) (1974) was the first computer animation to be nominated for an Academy Award. It won a Prix du Jury at Cannes that same year. Peter Foldes of Paris was the animator and director. He would fly to Ottawa to work with Wein (and Burtnyk) and stay with Wein in his home while he did so, then fly back to Paris. Again and again. 1971–1974 seem to be the years of production. Support was the National Film Board of Canada, French section, and the National Research Council (of Canada).

301:*Burtnyk and Wein*: Jim Blinn, email June 21, 2016, "the film Hunger was shown at the film show of Siggraph #2 in Bowling Green. In fact, it was the only film in the show. And they showed it over and over at various times at the conference."

The *Ottawa Citizen*, Aug. 31, 2018, featured a photo with this caption: "In 1997, National Research Council scientists Marceli Wein, left, and Nestor Burtnyk were presented an Academy Aard for technical achievement, for the work they did in computer animation in the 1970s." [https://ottawacitizen.com/news/local-news/and-the-oscar-goes-to-ottawa-scientists-were-pioneers-in-animation-technology/, accessed Apr. 5, 2020.]

See also *Key Frame Animation*, https://www.youtube.com/watch?v=EPIE_h8jf6E, accessed Apr. 5, 2020, especially starting at about 3:06 min.

301:*Moore formulated his*: Intel (2005); Moore (1965).

302:*He also predicted*: Courtland (2016); Intel (2011).

304:*No, we have*: Famed computer architect, Gordon Bell, states a more nuanced "Law," called "Bell's Law," of course: "every decade a new, lower priced computer class forms based on a new programming platform, network, and interface resulting in new usage and the establishment of a new industry." Bell's Law can be considered a corollary to Moore's Law, which takes into account not only the explosion of bits but their organization—via parallelism, in particular. It's a way of beating the Moore's Law prediction. He established the Gordon Bell Prize for parallelism in 1987 to track such improvements. The speed of the winner in 1987 was .5 gigaflops. In 2022 it was 1.1 exaflops. That corresponds to about a factor of 10 every 4 years. (Gordon architected the famous VAX computer that we used—serial number 1—at the New York Institute of Technology in the late 1970s. He was an angel investor in my second startup company, Altamira.)

304:*Arthur C. Clarke*: Arthur C. Clarke, *The City and the Stars*, New York: Harcourt, 1956; republished New York: Signet Books, 1957. Blinn used the third printing of the Signet publication, 47–48. Blinn obtained his PhD from the University of Utah. His use of Clarke in his thesis is from an email he sent, Mar. 23, 2019.

304:*Ivan Sutherland, The*: Sutherland (1965), 508. This paper was written while Sutherland was at ARPA's IPTO. It has only two references, Knowlton (1964) and Sutherland (1963). The ability to 3D print a working handgun comes to mind when reading this excerpt.

305:*The Annotated Alice*: I more carefully distinguish VR and AR (and mixed reality) in the Finale chapter.

305:*Some consider Sutherland's*: Sutherland (1968), 759, "Half-silvered mirrors in the prisms through which the user looks allow him to see both the images from the cathode ray tubes and objects in the room simultaneously. Thus displayed material can be made either to hang disembodied in space or to coincide with maps, desk tops, walls, or the keys of a typewriter." The system could handle only very simple three-dimensional models, of just a dozen or so straight line segments, before bogging down [Sutherland and Sproull (1996)].

Lanier (2017), 43, by Jaron Lanier, an early leader in VR, lauds Sutherland's role.

Sutherland explicitly recognized the essential help of undergraduate student Bob Sproull on the head-mounted display project [Sutherland (1968), 764]. Steven Coons and Danny Cohen also contributed to the head-mounted display, according to Bob Sproull, email of July 21, 2019.

Robert Fletcher "Bob" Sproull is son of Robert Lamb Sproull, who was the fourth director of ARPA (and Ivan Sutherland's boss there). Bob Sproull (Jr.) proceeded to co-author the famous Newman and Sproull (1973) computer graphics textbook with William Newman, son of Max Newman who was Alan Turing's mentor and supporter.

Sutherland's head-mounted display was so heavy that it was suspended by an armature from above. (The photo shows only the optics, not the supporting armature.) Hence it was sometimes called the Sword of Damocles. That name comes from the story of a sword suspended by a single horsehair above a man (Damocles) thrown into a position of great power. It was meant to teach him that with great power comes great fear. But Sutherland's "sword" was to protect a user's head from damage whereas the anecdotal Sword was meant to threaten at every moment the imminent slicing open of Damocles's head.

The man wearing the optics system in the figure 6.40 was H. Quint Foster, according to email from Ivan Sutherland, Mar. 18, 2020.

305:*Sutherland's head-mounted display*: Sutherland (1968), 762, "Because the drawing data are represented in homogeneous coordinates, the single four-by-four matrix multiplication provides for both translation and rotation [with a superscript reference to Roberts (1963)]."

305:*Moore's Law enabled*: Sutherland and Sproull (1996).

305:*The best way*: Sutherland (1966); email from Jim Kajiya, Apr. 24, 2017. Kajiya prefaced this with, "The advice from Ivan that I remember is that the best way . . ." My longtime colleague, David DiFrancesco remembers Sutherland's claim, as I do, but neither of us is completely willing to trust our memories now. Kajiya has been a hardware designer at E&S, a computer graphics professor at Caltech, and a crack researcher at Microsoft Research. Sutherland's original list of 10 problems has spawned an entire cottage industry of computer graphics experts, each with his list of 10 unsolved problems. (There are not any her lists at this time to my knowledge.)

306:*Sutherland himself moved*: Sutherland has spent 20 years mastering asynchronous logic—that is, logic that is not clocked. He told me, on Jan. 23, 2018, that he now knows how to handle it.

306:*I started this*: Note added May 4, 2022: "1970s" in the first sentence here should be "1980s" (detected by Darcy Gerbarg listening to the audio version).

309:*First color pixels*: The caption of this picture in the brochure GE (1977) implies that the system was delivered in 1962. This is incorrect because the 1964 system [see GE–NASA (1964)] was incapable of three-dimensional objects such as the spacecraft. The Electronic Scene Generator system [NASA-2], delivered in 1967, did have this capability. The picture shown is not that of Mar. 31, 1967, the date of the first color pixels, but probably from later in 1967 when the system was delivered. The Mar. 31, 1967, date is justified in note 320:*The first color*.

311:*But how is*: The wording here is specifically for light-emitting display elements. Ink on paper uses display elements of the light-reflecting variety, but it amounts to the same thing.

312:*An 8-bit pixel*: [Math] Eight bits can hold $2^8 = 256$ values. 24 bits can hold $2^{24} = 16{,}777{,}216$ colors, with eight bits (256 values) each for the red, green, and blue color components. A 24-bit pixel memory at (old-fashioned) video resolution of 512 by 512 pixels requires 786,432 bytes, where a byte is eight bits. That's about 787 kilobytes to store 24-bit color directly.

An 8-bit pixel memory at the same resolution requires 262,144 bytes, or about 262 kilobytes. A colormap with 8 bits in, 24 bits out requires only 768 bytes, less than 1 kilobyte. So roughly 263 kilobytes, including the colormap, could support 24-bit colors indirectly, far cheaper than the 787 kilobytes for direct support. But, of course, only 256 colors can be used indirectly, although they can be selected from among over 16 million.

Another advantage of a colormap is that changing the table changes the color of all the pixels almost instantaneously. It was far faster, at the time, than actually rewriting the value stored at every pixel in the pixel memory.

The colormap was a detour—resembling the calligraphic detour—that lasted until Moore's Law provided sufficiently cheap memory to make it unnecessary a few years later.

313:*In this chapter*: [Math] "Kilo" and "mega" are commonly taken to mean 1,000 and 1,000,000. That's roughly true, but in the digital world they take on exactly the nearest power of 2. So "kilo" means 1,024 (the 10th power of 2), and "mega" mean 1,048,576 (the 20th power of 2). 16 megacolors means, exactly, 16,777,216 colors. "16 megacolors" is so much easier to say. It's the number of colors that 24 bits can specify (the 24th power of 2).

One particular such prefix is "peta" which means the 50th power of 2, or about 1 quadrillion (the 15th power of 10). I wanted to say in the Introduction that we are aswim in an "ocean of petapixels," a felicitous phrase I first heard from Ken Goldberg, professor at UC Berkeley. Ken asked me if it was an accurate measure. To make this computation simple, assume there are 10 billion people on earth (an overestimate currently). Then each of us would have on average 10 million pixels each, assuming there were 100 petapixels available in total. Again, making things simple, assume that each digital picture is 1 million pixels. Then each of us would have 10 pictures. So

100 petapixels is cutting it thin. An "ocean of zettapixels" is probably more accurate. That's one sextillion pixels, or 100 billion pixels each, giving us each 100,000 pictures on average. That's more comfortable and likely.

313:*Gene Youngblood, Expanded*: Youngblood (1970), 252. Youngblood, who isn't bashful about the large claim, completed the last sentence this way: "*City-Scape* is the first step toward that future time in which artists not only will be the acknowledged legislators of mankind but literally will determine the meaning of the word 'man.'"

313:*"The bit* requirements: Youngblood (1970), 205. Unfortunately, he was actually referring to display elements not pixels, but that confusion is ongoing. Here's the full statement: "The implications of the plasma crystal display system are vast. Since it is, in essence, a digital system composed of hundreds of thousands of discrete picture elements (PIXELS), it obviously is suitable as a computer graphics subsystem virtually without limitation if only sufficient computing capabilities existed. [Recall that this was 1970.] The bit requirements necessary for computer generation of real-time realistic images in motion are as yet far beyond the present state of the art."

314:*"This fantastic* system: Youngblood (1970), 205. Youngblood, email Mar. 12, 2019, "I contemplated the coming changes in a series of articles for the legendary underground newspaper, the *Los Angeles Free Press*, in 1969, and they became the Cybernetic Cinema chapter in *Expanded Cinema.* That will be clear anyway when my collected *Free Press* articles are published next year."

314:*"It has* been: Youngblood (1970), 252.

314:*There's a special*: Robert Nathan was apparently responsible for the design of a 480 by 512 pixel disk-based color framebuffer at JPL. Presumably the 200 by 200 framebuffer was the same technology. I tried unsuccessfully to contact him in Jan. 2018, with help from Jim Blinn (a friend, colleague, and former JPL employee). I did get this email message from Zareh Gorjian at JPL, Jan. 3, 2018, "Yes, I've heard of such a device. I believe it was the first digital frame buffer, designed by Dr. Robert Nathan, it was described in a talk he gave before he retired." I tried to reach Dr. Nathan, but unfortunately, he had died Sept. 29, 2017, at age 90, as Blinn informed me in email Feb. 9, 2018, an event reported in the Passings section of JPL publication *Universe* 48, no. 2 (Feb. 2018): 9.

315:*Mariner 4 sent*: It took 6 hours to transmit the stream of pictures back to earth (a little over 600 kilobytes). Each picture was digitized to six bits, so six bits each for the red and green images. The spread of the pixels was the shape of the pastel daub used in the hand-coloring process. An online video of the process gives the statistics as 240 kilobits (per picture), 8 hours and 35 minutes [cf. the 6 hours mentioned above] transmission time, and 40,000 "dots" in the picture [*Coloring the Mariner 4 Image Data*, https://mars.nasa.gov/resources/20284/coloring-the-mariner-4-image-data/, accessed Apr. 5, 2020]. A NASA archive abstract states: "On July 14, 1965, at 0018 UT, the picture recording sequence commenced. Vidicon output underwent analog-to-digital conversion and data were stored at 240,000 bits per picture (each picture was 200 lines by 200 pixels, 6 bits per pixel)" [*Mars TV Camera*, https://nssdc.gsfc.nasa.gov/nmc/experiment/display.action?id=1964-077A-01, accessed Apr. 5, 2020].

315:*Close inspection reveals*: Leighton et al. (1967), 59. Also, on p. xi, "An analysis of overlapping areas of 'red' and 'green' pictures for local variations in color (as distinct from brightness) shows only relatively small color variations on the parts of Mars photographed. The average color is distinctly reddish, and the light ('desert') areas are somewhat redder than the dark ('mare') areas."

Reports recently published in *Science* magazine show that Mars *does* have blue. Glaciers several hundred feet thick have been spotted just under a shallow covering of red Martian dust, with that peculiar deep blue of glacier ice seen on Earth. See, for example, *Ice Cliffs Spotted on Mars*, https://www.sciencemag.org/news/2018/01/ice-cliffs-spotted-mars, accessed Apr. 5, 2020: "A few years ago, something surprising popped out from the planet's sea of rust: a pale sliver of blue."

316:*The Mariner engineers*: Leighton et al. (1967), 29, "The intensity at each of the 200 × 200 elements of the TV picture was converted by the camera system into digital form for storage on magnetic tape and later transmitted to earth. Each such intensity was represented by an integer in the range 0–63, 0 representing the brightest intensity and 63 the darkest. This digital number (DN) was . . . ." So what I call "pixel value," they called DN.

The color key actually used can be seen at *PIA14033: First TV Image of Mars (Hand Colored)*, https://photojournal.jpl.nasa.gov/catalog/PIA14033, accessed Apr. 5, 2020. It assigns values 50–45 to "DARK" (a brown), 45–40 to a reddish brown, 40–35 to an orange, 35–30 to the color of the paper (a light beige), 30–25 to a slightly darker beige, and 25–20 to "LIGHT" (a yellow). There is no explanation of what color was used where these ranges overlap. Apparently pixel values less than 20 or greater than 45 did not occur.

316:*An August 1964*: The official name of the NASA-1 simulator was Electronic Scene Generator. GE-NASA (1964), the Final Report from GE in Ithaca, NY, to NASA in Houston, TX, was dated Aug. 1, 1964. Supporting email from Robert Schumacker, GE engineer on the project, Feb. 15, 2018: "NASA 1 was designed, built, and delivered from AEC Ithaca prior to shutdown and a partial move of facility to Syracuse in 1965. Rod [Rougelot], Ed [Wild], Lew [Lewis DeWitt], and I (and others [including Pete Doenges]) developed follow-on NASA systems in Syracuse until 1972."

AEC was the Advanced Electronics Center of GE. When it was shut down some of its people were merged into the Electronics Laboratory (E-Lab) at GE Syracuse [email from Robert Schumacker, Feb. 22, 2018].

316:*You can think*: GE–NASA (1964), 1, "The displayed environment is idealized. It consists of an unbounded plane surface . . . The ground plane is textured with cyclic orthogonal patterns. These patterns are variable (within certain constraints) by the user . . ." The system also displayed a star field that used repeating tiles, but I ignore such black-and-white graphics here.

GE–NASA (1964), 3, "To generate a perspective picture of a surface, the display raster pattern is first projected onto the surface . . . The pattern on the surface is given as input data and is stored in the computer. When the coordinates of the scanning spot image are determined, they are referred to these stored data (called the map table) to find the color of the surface at this point. The surface color then is used to specify the drive to the electron guns of the cathode ray tube on which the picture is being displayed."

Email from Robert Schumacker, Feb. 14, 2018: "Yes, the NASA Electronic Scene Generator was delivered and operational in 1964. The textured plane surfaces were generated with 8 x 8 maps. The main ground surface extended to infinity in both directions and consisted of four nested levels-of-detail—each higher LOD 8 x 8 map was contained in one cell of the next lower level-of-detail map. At any given slant range to the surface the image was a blend of two active maps appropriate to the slant range. Fading from one level of detail to the next occurred over an 8:1 slant range. This arrangement allowed emerging details in a given scene with large range ratios (eg low altitude view to horizon) as well as descents and transitions from high to low altitudes with useful velocity, attitude and altitude rate cues. In addition to the main ground texture maps there were other nested maps with fewer levels of detail for sky, and unique landing areas."

Email from Robert Schumacker, Feb. 16, 2018: "There are three levels of detail visible in the image. Starting at the bottom of the display, 'T's are nearly faded out and replaced by the yellowish LOD pattern which in turn is faded out about 85 percent of the way to the horizon in favor of the next level. The reddish pattern is a unique area that does not repeat."

317:*Another "almost first"*: A digital texture map has its colors stored as an array of pixels, not geometric subtiles with colors defined with potentiometers.

318:*Robert Schumacker ("Shoo*: Email from Robert Schumacker, Feb. 16, 2018, "Each level of detail map can select one of two colors assigned to that map. These colors are determined by analog controls, one set of RGB levels for each map. The potentiometers are set with desired colors for a given simulation."

Although Schumacker supplied me with the bulk of the technical details, our email thread was shared by other people familiar with the project: Rod Rougelot, Lew DeWitt, Pete Doenges, and Ron Panetta. Panetta kicked it off by sending me the photograph of the NASA-1 display reproduced here, and Donna Ruth responded when I first became aware of the *E-Lab* website (see bibliography). Nick England and Mary Whitton first introduced me to the *E-Lab* site.

318:*But then he*: GE–NASA (1964), 3, "Initially the raster lines were assumed to be parallel to the surface (i.e., roll is zero). To justify this assumption, the raster is actually rolled on the CRT to a horizontal position. The angle through which it must be rolled is computed on the basis of vehicle attitude inputs."

Email from Robert Schumacker, Feb. 14, 2018: “Due to computational limitations at the time we forced the TV raster scan lines to be parallel with the horizon by electronically generating a rolled raster scan (my contribution).”

318:*Youngblood dropped another*: Youngblood (1970), Computer Films section, beginning p. 207, starts with: “The foremost computer-filmmaker in the world today, John Whitney . . . .”

318:*John Whitney Sr.’s*: John Whitney Sr., *Permutations*, Pyramid Films, 1968, https://archive.org/details/permutations_201608, accessed Apr. 5, 2020.

Permutations was included in Jasia Reichardt’s famous 1968 exhibit in London, *Cybernetic Serendipity* [Reichardt (1968), 65], mentioned in the preceding chapter.

Youngblood (1970), 215–222. In 1966 John Whitney Sr. begun to use a program written for him by Jack Citron of IBM. It was called GRAF for Graphical Additions to Fortran, where Fortran was IBM’s popular general-purpose programming language at the time. Citron’s program could do one thing. It could plot a curve controlled by about sixty parameters. That provided such immense variation that Whitney never got tired of using it for new graphical creations during a three-year creative effort.

Whitney added color with an *optical printer*, one of the most important and most undersung tools of analog filmmaking. A projector projects an enlarged film frame onto a screen, but an optical printer projects it, unmagnified, onto an unexposed film frame in a camera. The unexposed frame is its screen, so to speak. Here’s one way to use an optical printer to make a black-and-white (grayscale) movie into a color movie. Project the grayscale film in the optical printer’s projector onto color film in the optical printer’s camera, through a red filter. Back up the film in the projector and in the camera. Now repeat the projection step but through a green filter. Then through a blue filter. The relative densities of the three filters determines the final color of the thrice-exposed film in the camera. Alternatively the optical printer might have three projectors with their outputs combined with optical devices before exposing the camera film. There are many tricks possible with an optical printer, cross-dissolves, blue-screen matting, and so forth.

318:*His brother James*: James Whitney's *Lapis* (1966) is wonderful, but not digital. See it at https://www.youtube.com/watch?v=kzniaKxMr2g&feature=youtu.be, accessed Apr. 5, 2020 , music by Ravi Shankar. Michael Whitney, *Binary Bit Patterns*, Pyramid Films, 1969, may be viewed at https://archive.org/details/binarybitpatterns, accessed Apr. 5, 2020, described there as "Shows a Persian-like pattern optically printed from digital computer-generated images." It's a color film.

Brother Mark Whitney specialized in live-action films.

Michael Whitney used as his graphical output device a machine manufactured by a Santa Monica, California, company that we'll hear more about—Information International Inc. (Triple-I).

319:*Whatever Kamnitzer's argument*: Youngblood (1970), 250–256. *City-Scape* was made (p. 251) at the Guidance and Control Division of NASA's Manned Spacecraft Center, Houston, Tex., 10 min., 16 mm, color. So architecture again enters the story. Recall Tim Johnson of the Triumvirate who joined MIT's architecture department, as did Nicholas Negroponte, a student of Steven Coons and founder of The Architecture Machine and the Media Lab at MIT.

Kamnitzer didn't consider his work art. Certainly Youngblood had trouble calling it that in *Expanded Cinema*: "Viewed merely as an animated film, *City-Scape* leaves much to be desired. Compared to *Yellow Submarine*, for example, it is like the earliest tintype compared to laser holography."

The simulator was limited to 240 edges. Although the early GE simulators for NASA were capable of 64 colors, it's not obvious that *City-Scape* used anywhere near that many.

320:*Youngblood marveled instead*: Youngblood (1970), 250.

320:*W. Jack Bouknight*: Bouknight (1969), iv. The quotation begins with: "The center of this production is of course, the computer graphics world, and in particular, the installation at CSL [Coordinated Science Laboratory, Univ. of Ill.] built by J. Stifle and his electronics technicians."

320:*The first grayscale*: GE-NASA (1966), a quarterly report on NASA-2 dated July 12, 1966, states on p. i, "the significant demonstration of a static tetrahedron, generated by prototype hardware, has occurred." And on p. 1: "Successful demonstration of a static tetrahedron, generated by the first prototype OGS [Object Generation Subsystem] hardware." This means that a three-dimensional object had been successfully rendered (presumably in grayscale since color is not mentioned). From p. 3, we know that the date of this event was June 1966: "a significant milestone was achieved in June, when a static tetrahedron was generated, using breadboard and prototype OGS hardware." And p. 5 establishes the date as June 28 at latest: "a status review was presented at Syracuse on 27 and 28 June, at which time the static tetrahedron was demonstrated." One of the attendees at this meeting was R. Rougelot. Also on p. 5: "The lack of an acceptable solution to the degenerate face problem constitutes a new problem area." This establishes June 28, 1966, as the date of first three-dimensional object rendering in grayscale, although clearly there were still problems at this date. But see note 321:*The two of*.

Figure 7.34 is from Nelson (1974), 108, in a section titled "Shades of Reality." Ted Nelson's description: "Don Lee, at the University of Illinois, produced his fine-toned pictures of spheres in 1966 . . . He made his pictures of spheres and polygons by calculating the boundaries, then checking for overlap and filling in with grays according to viewing angle. His program works only in special cases, but is interesting for its historical position; it was one of the earliest half-tone curvature systems.” Don Lee, who was a principal programmer for the Plato project (mentioned in the preceding Shapes chapter) at the University of Illinois, is deceased. I have not been able to verify the 1966 date. See arguments against it below.

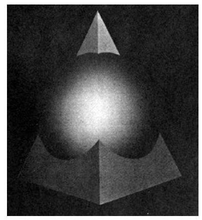

Figure 7.34

At *Spasim (1974) The First First-Person-Shooter 3D Multiplayer Networked Game* [http://web.archive.org/web/20090208002348/http:/www.geocities.com/jim_bowery/spasim.html, accessed Apr. 5, 2020], James Bowery states, “At the U of Illinois, he [Ron Resch] would place a 25 cent bet with the soon-to-be legendary PLATO system programmer, Don Lee, that Don couldn’t do 3D solids rendering with full shading over one weekend. That man was Ron Resch. Ron and Don had been discussing various tricks for dividing perspective drawing problems up into quadrants, and thought they were on the verge of something. Don took Ron’s bet, produced the first 3D ray-trace image of a tetrahedron intersected with a sphere over the weekend and then and took Ron’s 25 cents.” Resch died in 2009. Again, the 1966 date is not verified.

Jim Blinn, email Apr. 4, 2019, suggested this dating argument which I endorse: Ron Resch obtained a master of fine arts degree from the University of Iowa in 1966 and started teaching art at the University of Illinois that same year. Assuming normal dates, he would have received the degree from Iowa in about May or June 1966 and begun teaching at Illinois in about Aug. or Sept. 1966. So he wouldn’t have placed the bet with Don Lee until let’s say Aug. 1966 at the earliest, postdating the June 1966 date for the GE 3D image and thus coming in second. [In 2019 Iowa’s spring semester ended in May. In 2019 Illinois's fall term begins in August.] This argument fails if Resch taught summer school at Illinois in 1966.

Wylie et al. (1967), 56–57, shows several grayscale renderings of cubes and tetrahedra, but this report from Fall 1967 suggests that they don't have priority over GE. We note that this early effort from the University of Utah used Larry Roberts perspective, and that the third author was David Evans. Figure 7.35 is its Fig. 18, p. 57, of a tetrahedron at 512 by 512 resolution (the original apparently taken from an electronic gridded display, the quality further dimished by several levels of copying).

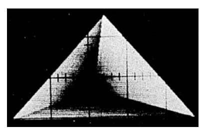

Figure 7.35

There was a spate of papers from 1967 to 1969 featuring "halftone" or grayscale shaded renderings. I don't treat them here since color renderings are my main interest. I'll mention only one, Bouknight (1969), since it cites D. Lee and mentions a future paper about his technique (which apparently did not appear). As Jim Blinn points out, the Bouknight paper suggests that Don Lee didn't produce his images until 1968: "The Warnock algorithm was implemented at CSL during the winter of 1968–1969 on the CDC 1604 computer using the in-house display system. . . . And important result arising from the effort to implement Warnock's algorithm at CSL was the development of an algorithm for producing half-tome images of structures composed of curvilinear surfaces such as sphere, cylinders, etc., by D. Lee at CSL."

A final bit of sleuthing by Robin Forrest, communicated via emails Apr. 11, 29, 2019, concludes re early grayscale shaded graphics images by Martin Newell (figure 7.36): "It must have been around 1969 or 1970 that the oil bucket image was produced on the 340 display [of a PDP-9 computer].” I had seen an estimate of 1967 for creation of this image and asked Robin about it. Martin Newell, email Apr. 12, 2019, stated: “The earliest images we created would have been in 1970 I believe. . . . The core group working on shaded images was myself, my brother Dick Newell, and Tom Sancha (sadly deceased).”

Figure 7.36

320:*The first color*: GE-NASA (1967) , a quarterly report on NASA-2 dated Apr. 20, 1967, states on p. ii: “the significant demonstration of a simulated forty-eight edge Lunar Module, dynamic and in full color, was performed using actual system hardware.” And on p. 1: “The forty-eight edge LM program has operated with the entire color display system with excellent results.” On p. 6, about a status meeting “2/28/67, 3/1/67”: “Demonstration of black-and-white twenty-four edge capability,” R. Rougelot one of seven in attendance. On p. 7, about a status meeting “3/30/67, 3/31/67”: “Demonstration of color forty-eight edge capability,” with R. Rougelot and R. Schumacker, two of nine in attendance. This latter note establishes the date of first color pixels as Mar. 31, 1967 (and the first three-dimensional shaded color object rendering also). The color samples used for the ground plane and the sky were not color pixels.

Schumacker et al. (1969), 113, “Electronic Scene Generator [NASA-2] installed at NASA Manned Spacecraft Center, Houston, Texas. Completed by General Electric 1967”; and from

Johnson (1993), 540: “A new NASA contract to provide greater capability than the first system was begun in 1966 and delivered to Houston by the end of 1967.”

We can surmise why the first-color-pixel achievement of these GE engineers went almost unnoticed. The accomplishment was buried in dense NASA technical reports rather than learned journals. And only a few persons, such as Apollo personnel, got to see the actual color pixels, in extremely expensive simulators in locations off-limits to the public.

320:*In 2018 I*: I visited with Rougelot and Schumacker on Feb. 27, 2018, in Rougelot’s home in Salt Lake City, cohosted by his daughter, Rhonda. We were joined later by Pete Doenges (“Don jeez”), another member of the simulator team, and his wife, Vicki.

320:*In 1951 Rougelot*: Email from Rod Rougelot, Feb. 21, 2018, “Don [Greenberg] was the first classmate I met on the cool autumn evening in 1951 when I arrived on the Cornell campus. We had arrived to begin the Freshman Orientation Camp and ended up in the same dorm that evening. We were in different schools and organizations, but maintained our association through graduation.”

In a phone call with Don Greenberg, in the week before Feb. 27, 2018, when I went to Salt Lake City to visit Rougelot and Greenberg, Don told me that he met Rod Rougelot as a Freshman at Cornell in 1951, that they came four days early for an orientation meeting held in a Boy Scout camp, and that they were in the same tent.

321:*The two of*: Besides Pete Doenges, who was also in attendance in Rougelot’s home, they mentioned during the 7-hour conversation these teammates on GE and (later) E&S teams: Ed Wild, Lew DeWitt, P. J. Zima, Michael Cosman, Ed Cheadle, Gary Watkins, John Warnock, Christine Barton, Alan “Ace” Erdahl, and John Mason.

Rougelot (1969), 264–265, gives credit to Moore's Law without mentioning it: "Reduction to practice [of 3D rendering in a JANAIR project in 1966 and in NASA-2 delivered in 1967] began in 1965 and was made possible, to a large extent, by the advances then being made in high-speed integrated circuits." The JANAIR (Joint Army-Navy Aircraft Instrumentation Research) project had only grayscale pixels but it had crude three-dimensional objects representing a carrier. Since this might be a first, I reproduce a JANAIR image here (figure 7.37), from 1966 [Rougelot (1969), 268, Fig. 6, caption: "JANAIR Contact Analog, Illustrating First Attempt to Depict Three Dimensional Environment Detail."]. But note 320:*The first grayscale* describes another grayscale rendering of a three-dimensional object on NASA-2, a tetrahedron, on June 28, 1966.

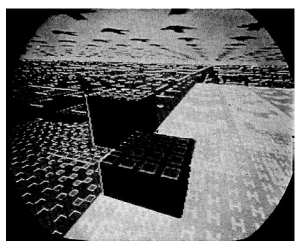

Figure 7.37

321:*In 1972 Rougelot*: The simulators they built sequentially at E&S were called CT1, CT2, . . . , CT6. Each system stretched the limits of the computer graphics that could be rendered in real time, each outdoing the previous system.

Sutherland also credited Schumacker and Rougelot's colleague Ed Wild with success at E&S. Schumacker and Rougelot told me that it was Ed Wild who introduced Peter Kamnitzer to NASA-2. They promised me an entertaining story of that encounter, but I should wait to hear it from Ed himself. Schumacker, in an email of Mar. 24, 2018, "Rod is going to try phone contact with Ed Wild in attempt to get conversation started—hope it works as you really should hear that strand directly from him." But the poor health of Ed's wife has intervened to keep me from interviewing him.

Evans & Sutherland Computer Corporation History, http://www.fundinguniverse.com/company-histories/evans-sutherland-computer-corporation-history/, accessed Apr. 5, 2020: "By 1972 the firm had developed LDS 2 [a calligraphic display] and other new products but had not generated any profits. At the same time it recruited three key engineers from General Electric. Rod Rougelot, Bob Schumacker, and Ed Wild had approached GE about using computers for pilot training, but GE was not interested at the time. GE's loss eventually proved to be a huge gain for E&S. . . . With the aid of the three former GE engineers, Evans & Sutherland entered what would become one of its key markets." Johnson (1993), 540–541, "Because the Apollo Support Department [GE} offer was not satisfactory to Rod Rougelot, he and Bob Schumacher [*sic*] left GE to join Evans and Sutherland, which later became a significant competitor in the computer-generated-image business."

321:*Schumacker remembered that*: Email from Bob Schumacker, Aug. 11, 2019: "Rod helped fill in some voids in my memory of the 'triangle demo.' Here's what we reconstructed. The demo occurred in 1965 (maybe very early 1966) after NASA 1 was delivered to Houston. The special purpose programmable hardware normally part of the textured surface system setup (frame rate) computations was repurposed to do frame-rate edge computations. Actual pixel rate edge and face computations were done with 3C logic cards (one flip-flop or equivalent gates per card) put together just for the demo. The update-rate of the display was 30Hz at more or less standard TV resolution. The triangle was one solid red color (no shading). Translation and rotation of the triangle was controlled by the NASA 1 special purpose programmable front end. The display of the dynamic triangle was quite compelling and left little doubt about the orientation dynamics of the triangle despite the solid color!"

Second email from Schumacker, Aug. 11, 2019: "The programmable part of NASA 1 served the role of a 'general purpose computer' in controlling the rotations (3 axes) and translation of the triangle. It had such unusual capabilities as vector coordinate rotations (CORDIC algorithm). The crux of the demo required building scan line and pixel rate hardware for the three edges out of 3C logic cards. The TV monitor rolled raster capability was not useful for this demo. All motion of the triangle was computed by general 3-D equations. | 3C = Computer Control Corporation, a company that was sold to Honeywell around 1966. In addition to making general purpose computers such as their DDP-24, they offered a set of logic 'cards'—basic building blocks such as flip-flops and gates that could be connected/configured by wiring the cards together via back-plane pins. These weren't 'integrated circuits' but they did put more than one transistor in a 'can' (I don't recall how many, but only maybe 2–4). Resistors and other passive components were discrete components on the cards, not integrated on silicon or even packaged in a 'can' along with transistors."

322:*Schumacker recalled, "The*: Second email from Schumacker, Aug. 11, 2019 (cont.), the complete statement: "The triangle demonstration convinced us that implementing any useful systems of even just a few polygons would be prohibitively big and expensive. Fortunately the first practical real integrated circuits came out about the time we bid the contract. It was Motorola's emitter coupled logic (MECL), ran at the blinding speed of 5Mhz, and offered a useful logic density. Motorola was still getting the bugs out of the fabrication process while we were designing! Fortunately they supported us well during the growing pangs. Rod [Rougelot] was the main person overseeing both the demo and the eventual contract hardware."

324:*In computer graphics*: The original of this illustration is about 4 inches wide, and it has a horizontal resolution of 32, for about 8 samples per inch. My Samsung Galaxy S8 displays at 572 display elements per inch. So the display element spacing on my cellphone (already an old one) is about 1/72nd of that shown in this picture. Since this is all approximate and product specific, I rounded up the density to 100 times denser.

325:*But there's a*: Re "Nobody actually replaces a geometrical model in computer graphics with a rounded version—with too-high frequencies removed." It doesn't even make sense to do so. To rid a model of too-high frequencies means we would have to know what the display resolution was. Since the virtual camera can be close to a model or far from it, that notion varies and can't be known in advance. And the actual display device resolution is an unknown in general. The whole idea of a geometric model is that it's resolution-independent. Getting rid of too-high frequencies is a Display Space matter, not a Creative Space one.

326:*I've used a*: I very carefully have not drawn a square around the subsample arrays, not wanting to invoke the dreaded "square pixel" notion. But, in fact, taking an average of subsamples distributed uniformly across a square area is essentially equivalent to the use of the box filter which is a major source of the square pixel illusion. The box filter is another approximation used in this subsampling scheme, to make the computations feasible.

327:*Reality is just*: I don't recall when I first said this, but it was part of my stump speech starting in the early 1980s. The earliest public record I've found is a 1986 article cited in Art in the Computer Age [Goodman (1987), 15]: "'Reality is a convenient measure of complexity,' says Alvy Ray Smith . . . 'But why be restricted to reality?'" And she in turn cites Philip Elmer, The Love of Two Desk Lamps, *Time*, Sept. 1, 1986, 66.

Another closely related version I often used was “Reality begins at 80 million polygons” (think of polygons as triangles), popularizing a calculation made by colleague Loren Carpenter at Lucasfilm in the early 1980s (with the assistance of Ed Catmull and Rob Cook). This was often misquoted as 80 million polygons *per second*, a real-time hardware formulation which didn’t interest us. We meant 80 million polygons *per frame*, a content producer’s formulation and a far more difficult goal to reach. (At 30 frames per second, our formulation implied 2.4 *billion* polygons per second.) Loren intended it as something we should strive for in our (non-real-time) work, an unreachable goal at the time when he expressed it. Our software should not break when our frame complexity reached 80 million polygons, as we assumed it would one day. And it did eventually, after the millennium. It had not done so by the time of *Toy Story 2* (1999).

Why 80 million? The argument was this: If you divide a visual scene into a grid of little square cells, where each cell contributes to one pixel, then each cell sees “about four levels of surfaces before the intersected surfaces completely obscure the ones behind . . . . Each level of surface comprises contributions from about eight polygons. Thus 32 polygons will contribute on average to each . . . pixel, hence 32 million polygons for each million pixels of frame resolution. At the time we considered frames with 2.5 million pixels, hence 80 million polygons per frame” [Smith (2000)]. It was a remarkably good guess considering how many questionable assumptions were made.

Note added in the last stages of preparing this book: On May 13, 2020, Loren Carpenter sent me notice that a graphics hardware system, Unreal Engine 5, running on Sony PlayStation 5, had achieved 80 million triangles per frame in real time. (Interestingly, the measure was triangles, not polygons.) Loren said, “They claim 20 million visible, which is exactly 80 million with a depth complexity of 4. Took 40 years and I'm glad I got to see it." So 40 years later—eight orders of magnitude later—that particular goal has been reached. It's a breathtaking achievement for those of us who were there at the beginning. See the demo at https://www.youtube.com/watch?v=qC5KtatMcUw&feature=youtu.be, accessed May 13, 2020.

328:*Neal Stephenson, Fall*: Stephenson (2019), 18–19.

331:*To help with*: What the Lucasfilm bloc has in common is that the individuals had nothing in common, other than early entry into Lucasfilm and not having been at NYIT. Rob Cook came from Cornell in upstate New York, Loren Carpenter from Boeing in Seattle, Eben Ostby came from Bell Labs and Vassar, Bill Reeves from the University of Toronto, and Tom Porter from Ampex in Redwood City, CA. A similar bloc is the NYIT bloc just above the Lucasfilm bloc. The two persons there had nothing in common except that they joined NYIT but were not of Utah (including E&S) or PARC. Tom Duff came from the University of Toronto (like Bill Reeves) and Ralph Guggenheim from CMU in Pittsburgh (like Dick Shoup).

331:*Similar strands combine*: Pixar had also done *A Bug's Life* (1998), *Toy Story 2* (1999), and *Monsters, Inc.* (2001). And DreamWorks had done *Shrek* (2001).

331:*Rod Rougelot and*: With the non-real-time system that the GE team created after NASA-1 and NASA-2, they gave us a first pass at two-dimensional antialiasing, in 1970. See note 162:*The first explicit and*.

Email from Rod Rougelot, Feb. 21, 2018, "As I recall, the motivation for the non-real-time system was our desire to stay together as a development group after ASD Daytona [of GE] blocked our participation in future NASA programs. . . . [W]e decided to begin looking at other real-time simulation applications that would not violate the Daytona restrictions. We needed a tool that could be used to demonstrate what needs future systems might serve. Lab management was pleased with our performance on the NASA II [NASA-2] program and supported our request to develop such a tool. . . . We bought a Sigma 5 for all the front end processing, and we built the special purpose hardware using some Edge Generator cards, Object Generator cards, and supporting cabinetry items 'left over' from the NASA II project. I think we used a rotating disk for the frame buffer, but I cannot recall the vendor. We added some video processing and camera control hardware to complete the system."

334:*In one of*: Email from Rod Rougelot, Feb. 21, 2018 (cont.), "Our work at E Lab [GE Syracuse] began to receive press attention after our announcement of the NASA II delivery. At that time, Rich Riesenfeld was teaching at Syracuse University. He called and asked if I would give an informal talk about the technology of NASA II. Don, who was back at Cornell building his computer graphics group at that time, heard about us, I think from Rich, but maybe some press releases. He called and we set up a visit to the Lab, where he described what he was doing. We suggested that he and his students could have access to our facility from 5:00 PM until 7:00 AM, M–F and all day on weekends, I believe. Our folks introduced them to the system, and the impressive film that was described in Don's article in Scientific American was the result of intense activity by the Greenberg team, with support from our team when needed. Don and I have stayed in touch since then."

In a phone call with Don Greenberg, in the week before Feb. 27, 2018, when I went to Salt Lake City to visit Rougelot and Greenberg, Don told me that he met Rod Rougelot who gave him use of the lab in Syracuse from 5 p.m. to 8 a.m.

334:*For months, on*: Greenberg (1975), 358, "A fifteen-minute movie was made four years ago by twelve dedicated architecture students and me working at the General Electric Visual Simulation

Laboratory in Syracuse. Since General Electric was on an eight-to-five shift, we worked from five-to-eight, three nights a week, for a semester . . . The maximum number colors was limited to sixty-four appearing on any single image, and thus neither edge smoothing nor smooth shading algorithms are included." See also Greenberg (1974). A 25-second version of the movie may be viewed at *Cornell in Perspective*, http://www.graphics.cornell.edu/online/cip/, accessed Apr. 5, 2020.

Marc Levoy, email of May 7, 2017, "It was every few days, but not every day. We sometimes worked until late in the evening, and we sometimes worked most or all of the night. We didn't stay anywhere. We worked. . . . I don't recall what Don [Greenberg] did while we worked—maybe hung around with Bob [Schumacker] and Rod [Rougelot], or went out to dinner with friends. He then brought us home, sometimes at 4am. I didn't have a car. . . . Creating the database of the buildings and quadrangles took 6–9 months, done during 1971–1972, as part of this project course. Each student was responsible for one building. There were probably a dozen of us. Mine was Sibley Hall, by coincidence the architecture department building. . . . Production of the movie itself was mainly during summer of 1972. This involved scripting the camera moves, entering them on a teletype or maybe directly on the simulator console, and waiting while the machine rendered the frames (roughly 30 seconds per render) and triggered the film camera. . . . Sound and editing was done in Autumn of 1972. The film was finished by mid-Autumn, as I recall."

334:*Known contenders for*: Marc Levoy, email May 7, 2017, "The film [Cornell movie] was finished by mid-Autumn, as I recall."

Ed Catmull, email Apr. 8, 2019, "I entered grad school in '71. My first project was actually a face turning into a bat. The second quarter, which would have started Jan of '72 is when I made the hand film," also, "Fred Parke and I were in the same class together in 1971. I'm not sure when he finished the film of his wife's face, or when I digitized Laraine [Ed's first wife]. I think Fred made the face after the hand because he had to work out the least square method of using two photos to generate three-D coordinates," and also "I recorded it [face to bat] on 16 mm film and I still have it. It is so short, maybe 24 frames, that it has never been projected. It has crude shaded polygons." And again, Ed, email May 28, 2019, "It [face-to-bat animation] was shaded. It was my class project in the Fall of '71, although I very well could have finished it in January, '72."

Fred Parke, email Mar. 23, 2020, "The 1972 animation was not the first facial animation I did at Utah. When I first arrived in Utah in the fall of 1970, I started the three quarter computer graphics course sequence taught first quarter by Henri Gouraud and second and third quarters by Ivan Sutherland. During the second quarter, Spring 1971, Ivan's charge to the class was to create a 'new, interesting' image every week. This prompted me to start modeling 3D faces. This produced a series of progressively 'better' facial models and images. By the end of that quarter, mid-March 1971, I had a model with a mouth and eyelids that opened and closed and eye pupils that could look around. With that model I animated a sequence of 'flipbook' images that showed the moving mouth, eyelids and pupils . . . another animation I did in 1972 show[s] the transformation of a block letter H into a representation on an SR-71 [the Blackbird, a spy plane]. Both the H and the SR-71 had the same polygon structure." Figure 7.38 shows a remarkably lovely frame from Fred Parke's flipbook animation, dated Mar. 2, 1971 (date established in email from Fred, Sept. 8, 2020).

Figure 7.38

See also Catmull (1972) and Parke (1972a, b). This email from Ed Catmull concerns these two contributions, Apr. 8, 2019: “we attached our two films together when they were shown at an ACM conference in either ‘72 or ‘73.” The conference was held Aug. 1, 1972. Both Catmull’s and Parke’s animations were incorporated as monitor displays in *Futureworld* (1976) [https://www.youtube.com/watch?v=QfRAfsK5cvU&feature=youtu.be, accessed Apr. 5, 2020].

Henry Fuchs, in a conversation at Siggraph, July 31, 2019, told me about his experience in the same 1972 class at Utah. He created and animated a walking and running “man” made of rendered, intersecting ellipses. He did not submit his piece for publication as did Catmull and Parke.

336:*Depthbuffering, by the*: Wolfgang Strasser [Straßer in German] introduced depthbuffering first in his thesis, *Fast Generation of Curves and Surfaces on Graphic Displays*, in German. It also treated B-splines and antialiasing. Strasser was a computer graphics pioneer and leader in Germany. He died in 2015.

On May 1, 2019, Robin Forrest emailed me a copy of lab notes he had written and dated Nov. 23, 1970, that clearly describe depthbuffering. He and colleagues at Cambridge University read about a Princeton Electronic Products PEP-1 storage-tube display which could write to its screen either calligraphically or in raster order *and* it could read it in raster order. It could display with four bits (16 values) of intensity. In other words it was a 4-bit grayscale framebuffer. Robin described how to solve both hidden-line and hidden-surface problems using the intensity as depth. Unfortunately, he didn't get to implement his idea nor did he publish it. It's clear that once sufficient read-write memory was available, depthbuffering leapt into people's minds around the world.

338:*Calculating shadows therefore*: A particularly clever shadowing scheme was devised by Lance Williams at NYIT in 1978 [William (1978)]. It combined the point-of-view shadow computation described briefly in this paragraph with the depthbuffering technique of the preceding section, and was possible because NYIT had lots of pixel memory. A depthbuffer was first computed from the point of view of a light source. Lance called this a *shadow map*, a variation on texture maps discussed in the following section. Then the normal depthbuffer hidden-surface algorithm (from the desired viewpoint) is modified as follows: [Math] The depth is computed as before in depthbuffering. If the pixel is visible (not hidden by a previously stored depth) then its coordinates are transformed into the shadow map coordinate system. If the shadow map depth there is less than the depth of the pixel about to be stored in the depthbuffer, then it is in shadow and it's color or shade is modified accordingly. Multiple light sources require multiple shadow maps.

341:*Computer graphicists quickly*: The recommended choice for the ups at the corners is an average of the flagpole-at-the-center ups of the triangles coming together at a vertex. Suppose triangles, T, U, and V share a common vertex. Then the choice of up at that vertex is an average of the flagpole directions for T, U, and V. I'm not going to say more about this because Phong shading (discussed next) is superior.

If you look very closely at the figure—for example, at the lower right edge—you can spot the straight lines in the Gouraud-shaded object's silhouette. Gouraud also made the first wire-frame capture of a human face, of his wife Sylvie, and then used his shader to make her appear smooth

[Bellin, 2008]. Fred Parke, at Utah, then animated her model for the first face animation. Gouraud's adviser at Utah was Ivan Sutherland.

342:*But something wasn't*:Phong (1975), based on his 1973 PhD thesis at the University of Utah. He died young.

An excellent summary of shading details can be found in the computer graphics bible, *Computer Graphics: Principles and Practice* (3rd edition) [2014] by John Hughes, Andy van Dam, et al. This is my ultimate technical reference for this chapter, although it exceeds by far the sophistication level of this book. Its sophistication increased commensurate with the three orders of magnitude increase in Moore's Law power between the millennium and the book's publication in 2014 (and five orders of magnitude between the publications of the second and third editions).

343:*Richard "Dick" Shoup*:Gernsback's *Electrical Experimenter*, 1913–1920, became his *Science and Invention*, 1920–1931. Shoup eventually played first chair under Arthur Fiedler once (but not in the Boston Pops), and in the orchestra for the *Tiny Tim* show, and in everything from minstrel shows to an opera orchestra for a PBS production.

Biographical details of Dick Shoup are from several interviews I held with him in 1995–1999 in preparation for an earlier history *The Deletion of Time* which I didn't complete. Dick, born about a month before me, was one of my closest friends until he died in 2015. A memorial service for him was held at the Computer History Museum, which houses the Color Video System and SuperPaint in its collection.

343:*Dick got his*: CMU was called the Carnegie Institute of Technology in Shoup's time. Late in the long first day of registration there Shoup noticed one table that he'd missed, manned by a dean (Richard Wells) who was looking for people to sign up for an optional computer programming course, a new idea in academia. Vaguely aware of what this meant, Shoup said, “Can you tell me about . . .” but the dean interrupted, “What’s your name?” He quickly looked up Shoup’s SAT scores and said simply, “OK, you’re in.” Shoup took his first course from Alan Perlis, getting so excited that his parents wished he would stop talking about it. Perlis would be the first recipient of the prestigious Turing Award.

Gordon Bell built the Vax minicomputer at DEC that would figure highly in the future of Digital Light. The New York Institute of Technology, where the group which became Pixar began, purchased the Vax with serial number 1. CMU traditionally got serial number 1 for DEC computers, but in this instance the machine for CMU was delayed. It was decided to give both machines, for CMU and NYIT, serial number 1.

Bell’s wife, Gwen, founded the Computer History Museum, originally in Boston, now in Mountain View, CA. He would later figure in my post-Pixar career as an angel investor in my second company, Altamira Software. I cofounded Altamira, a PC software company in 1991, with Eric Lyons and Nick Clay. It was purchased by Microsoft in 1994.

Automata is pronounced “aw Tom ah tah.” My Dec. 1969 dissertation established for the first time that a one-dimensional cellular automaton (CA) could be a universal computer à la Turing. Each cell was much simpler than a universal computer, but an array of them working in parallel and neighbor-connected can compute anything that’s computable [Smith (1971)]. The popularity of CA at the time, due to a particular one called the Game of Life, led to the selection of my cover design for the *Scientific American*, Feb. 1971 issue. Because of that celebrity I was asked to form and lead a panel discussion at an IEEE computer conference in Boston that brought Shoup and me together [Minnick et al. (1971)]. CA were first explored by von Neumann (on a suggestion from

Stanislaw Ulam) in von Neumann (1966), left unfinished at his death, and completed by Arthur W. Burks.

343:*The day after*: The Berkeley Computer Corporation group included Butler Lampson, Peter Deutsch, Charles Simonyi, Jim Mitchell, and Chuck Thacker. My stint at PARC overlapped with this group. Butler Lampson won the Turing Award in 1992, and Chuck Thacker in 2009. Lampson joined Microsoft in 1995, a year after I did, as did Gordon Bell. Chuck Thacker (1943–2017) joined in 1997.

344:*Albert Einstein wrote*: To be exact, I joined NYU in September 1969, thirty-one years after Freeman's narrow escape in Mar. 1938. But several years before I joined NYU, I had made my first computer graphic image, in 1964, at the Physical Sciences Laboratory at New Mexico State University, my undergraduate college in Las Cruces, NM. My first job as a junior electrical engineer was to draw an equiangular spiral of many turns as an antenna design for the NASA-funded Nimbus weather satellite. It was clear that I was expected to draft the spiral. My supervisor was astonished when I delivered the drawing a day later. I had PSL's computer draw it, an idea that hadn't occurred to the older engineers. But computer graphics didn't "take" at that time as a career move for me.

344:*The wake-up call*: Ironically, the cap had a label inside: "Knitted by a blind person." The ski resort was Waterville Valley, NH, and the hospital was in Laconia, about forty miles distant.

I was in the full-body cast from Dec. 15, 1972, to Mar. 22, 1973 [Smith (1973), 95]. I spent approximately a year in Berkeley, co-taught (with Robert M. Baer) a one-term course on cellular automata at the University of California there, as a Visiting Associate Professor, before discovering the wonders at Xerox PARC.

Smith (1974) is my journal of the PARC days. From p. 67: “I had to wait a few days to return to Palo Alto (had to meet a Feb 28 deadline on the survey [see Smith (1976)]) but spent 12 hrs. on the machine next visit. It’s such an incredible invention I’ve decided to record this chronicle of my excitement and involvement with it.” Thus I began visiting PARC some time shortly before Feb. 28, 1974. I made my first two animations May 10 and 15, 1974 (pp. 70–71). I met Ron Baecker and Eric Martin there on June 11 (p. 74), and made my second set of animations June 18 and 20, 1974 (pp. 76–78). I submitted a formal proposal to PARC on July 23 (p. 85) and was told by Shoup that I was hired on July 31 (p. 94).

I was hired via a purchase order (no. 13438, original in my possession) which Dick Shoup, Alan Kay, Bob Flegal, and David Liddle helped obtain. The P.O. is dated Aug. 13, 1974, and its principal component was a “Professional Services Agreement | Professional labor services to be performed by Dr. Alvy Smith in providing animated video tapes at the Xerox, Palo Alto Research Center, Palo Alto, California in conjunction with the Computer Science Laboratory Color Video Graphics System, as specified by Dr. Shoup, service to include providing software and hardware tasks as agreed upon in support of production of subject tapes and in development of the system, subject to the following conditions: | Conditions: | 1. Term of Agreement: Shall begin on August 12, 1974 and terminate on December 31, 1974 or when agreement reaches 857 hours, whichever comes first. | 2. Method of Invoicing: To be invoiced via Xerox ‘Labor Services Agreement’ Form 118. Upon completion of filling out siad [*sic*] form, forward same to R. Taylor . . . [1 of 4 pages].”

344:*Dick was clear*: During the summer of 1968, Edgar Meyer worked at Brookhaven National Laboratory so that he could get access to the Brookhaven Raster Display (BRAD). He was able to program and draw red and green superimposed pictures to BRAD for stereo display of molecules of up to 256 atoms. BRAD was magnetic-drum based, so with moving parts and not what we're looking for. Figure 7.39 is Meyer's picture, which used two bits per pixel, for four colors, at old-fashioned video resolution [Meyer (2014)].

Figure 7.39

Ophir et al. (1968) described the hardware of BRAD. It stored each 512 by 512 frame on one track of a drum. One track consisted of 512 blocks, each representing one line of the frame, in interlaced order. One revolution of the drum caused display of one frame at 30 frames per second (the drum revolved at 1800 rpm). Eight heads in parallel read out the blocks and sent the bits to a "binary-to-video" converter to feed a standard analog television display. "Color displays can readily be added by reserving two additional drum tracks for each display unit." This implies that Meyer used a system with at least two color tracks, of one bit each, driving the red and green guns of a television monitor. Thus he essentially had a 2-bits per pixel display system at 512 by 512 pixel resolution. The initial cost of the system was $50,000 (or over $350,000 today).

In 1968 William Kubitz built a special-purpose system called a "tricolor cartograph," at the University of Illinois. He considered utilizing a standard computer memory for this system but dismissed it as too expensive. He used instead a magnetic disk memory and a standard analog color television for display. The system had eight fixed colors, specified with three bits (pushbuttons). All a user could do was interactively draw a closed curve and fill it with one of the eight colors, as shown in figure 7.40. The system had nominally 512 by 512 addressable points, but the disk stored video signals, not pixels. The binary locations were used to start and stop an analog signal in the appropriate places along a scanline, using the currently specified color. And the fill algorithm utilized was flawed. A user had to help it find the parts of an area it had missed. It's historically interesting, but mechanical and mostly analog. [See Kubitz (1968); Kubitz and Poppelbaum (1969); Smith (1978), 13, Appendix C—Brief History of Paint Programs. See a video demonstration of the tricolor cartograph, produced in 1969, at *Far Out*, https://www.youtube.com/watch?v=njp0ABKwrXA&feature=youtu.be, accessed Apr. 5, 2020, especially at about 8:22 min.]

Figure 7.40

At fabled Bell Labs, Joan E. Miller built a paint program based on 3-bit pixels, capable of 8 colors directly. Miller told me in a 1978 conversation that her developments occurred in 1969 and 1970. A contemporaneous development at Bells Labs of a 2-bit memory made of magnetic cores suggests that her development probably didn't use integrated circuits. So this color pixel effort and the two mentioned above were probably all Epoch 1 developments, pre-Moore's Law. But Miller's system created pixels from scratch and was digital except for color (see next paragraph).

From Smith (1978a), Appendix C, A Brief History of Paint Programs: "The earliest paint program with which I am acquainted is that of Joan Miller [C1], implemented at Bell Labs in 1969–70 on a 3-bit frame buffer. The user could draw lines and then alter the colors by turning potentiometers, so partially analog. More or less simultaneously, the 'tricolor cartograph' [C2] came into existence with eight fixed colors, including black and white." C1 cited a personal communication I had with Joan E. Miller in July 1978. C2 was Kubitz and Poppelbaum (1969).

[Note added 29 June 2023 after about two dozen email exchanges with A. Michael Noll]: A. Michael Noll implemented, probably in 1969 (paper submitted for publication in Mar. 1970), a 1-bit or 2-bit display system at Bell Labs. The framebuffer was held in main (core) memory of a computer, which was scanned out via a hardware interface to a (non-standard) video display. The framebuffer stored the odd scanlines above the even scanlines to accommodate interlaced display. The pixel resolution was 254 by 240. The 2-bit version displayed in grayscale. But later, in about 1972 or 1973, Noll added 4-color video display to this system. Fig. 4 of the following paper showed a display from a 1-bit version of this system of a "perspective projection of a four-dimensional hypercube which can be rotated in real-time": A. Michael Noll, "Scanned-Display Computer Graphics," *Communications of the ACM 14*, 3 (1971): 143–150. These brings into doubt the date of 1969–1970 claimed by Joan E. Miller for a 3-bit paint program at Bell Labs (a claim she, now deceased, made to me in July 1978). I suspect Miller wrote her software perhaps 1972–1973, since Noll had no record of her doing so. Another woman, Laurie Spiegel, also wrote an early paint program there, probably in 1973 (by Noll's memory) or 1974 (by hers, email June 26, 2023).

345:*Dick was also*: Shoup (2001), 37, "SuperPaint was not the first such frame buffer nor the first digital paint program." A Ramtek engineer (whose name I failed to record) told me at a Computer History Museum talk in about 2015 that he'd beat Shoup to an 8-bit framebuffer. I've found no documentary proof other than Shoup's vague reference (p. 37) to "the first commercially available frame buffers by Ramtek (1972–1973), the Paint program by Noll and Miller at Bell Labs (1969), the Tri-Color Cartograph analog-disk-based paint system by Kubitz and Poppelbaum at the University of Illinois (1968).” I don’t know the bit-depth of the Ramtek framebuffers that predated Shoup’s framebuffer. The manuals for the Ramtek 9000 series in 1977 provided RGB with four bits each and a grayscale channel with 8 bits [Ramtek (1977a), appendix A, 2; Ramtek (1977b), chapter 1, 5–8].

345:*Nevertheless, there were*: SuperPaint also had a colormap mode of 4 bits in, 24 bits out mode. It had the appropriate video control and sweetening devices necessary at the time, including a drop-out compensator and a waveform monitor. A Nova minicomputer was the controller, not an Alto. SuperPaint came online in Apr. 1973 [*The* SuperPaint *System (1973–1979*, http://web.archive.org/web/20020110013554/http://www.rgshoup.com:80/prof/SuperPaint/, accessed Apr. 5, 2020].

345:*Figure 7.20 shows*: There are only 16 colors in this picture. Shoup wrote his SuperPaint program to use 4 bits of each pixel for a menu screen and the other 4 bits for the “canvas” screen. A tap of the stylus on the edge of the tablet switched between display of the menu and display of the canvas. But I wrote programs that used all 8 bits of each pixel. Most of the videos I made on SuperPaint used 256 colors.

SuperPaint used a colormap with 256 rows, one for each possible pixel value. And each row held a 24-bit color description. In 4-bit mode, the colormap effectively had only 16 rows. The same colormap was used for both the low 4 bits of each pixel and the high 4 bits. In other words, both the canvas and menu had the same colors.

The HSB (also known as HSV) sliders implemented color selection using hue, saturation, and brightness (or value) rather than red, green, and blue. I finally published the RGB to HSB color transform algorithm in Smith (1978b).

Shoup implemented the SuperPaint framebuffer with shift-register chips, not RAM or random-access memory. RAM was still too expensive, so he opted for the cheaper shift registers. Random access to pixels was implemented in software. The next framebuffer to be implemented a couple of years later was the E&S framebuffer, designed by Jim Kajiya. He opted for RAM chips then. The price of that first RAM framebuffer product was $80,000 for 512 by 512 pixels, eight bits each. $80,000 in 1975 is about $383,000 now. It addressed pixels by memory page and page offset, so pixel access was also implemented in software but much faster than the software access to Shoup's shift-register memory.

True hardware random access of pixels was implemented with a special order to E&S by NYIT about a year later—for a device called the "buni." In other words, the software interface was converted to hardware to make it very fast. The next five framebuffers purchased by NYIT cost $60,000 each, and all had bunis. The original framebuffer was also refitted with a buni.

That strange name originated as follows: We drew a box labeled "FB-UNI" (and pronounced it "Eff Bee You nee") on our specification for this device, meaning framebuffer-to-Unibus (an official internal DEC bus). The E&S engineers shortened this to "fbuni" and pronounced it "Eff bunny." Since the NYIT grounds featured dozens of cottontail bunnies, we chuckled and shortened it further to "buni" and pronounced "bunny," of course. And the subroutine that allocated bunis to users was called "snare." (And the book *Watership Down* (1972), by Richard Adams, a classic children's rabbit book, was popular then.)

348:*After my first*:The bouncing ball is p. 22 (as labeled) and the walk cycle is p. 24 of the Blair (ca. 1949) how-to book.

In my 9-page proposal letter to Xerox PARC, dated July 19, 1974 (copy in my possession), p. 7: "One of my first intuitions on seeing the machine was that it would be a fine instrument for making animated films. So I immersed myself in 'classic' animation in preparation for using the machine this way. For example, I took a course in the subject from Steve Smith, a professional animator. What deeply impressed me from this schooling was the utter drudgery of the classic approach." See note 210:*As a child*.

348:*When I arrived*: Eric Martin's *The Ever-Popular Bouncing Ball* animation created on SuperPaint, Sept. 1, 1974, Xerox PARC, can be seen at https://www.youtube.com/watch?v=nHkxem785B4&feature=youtu.be, accessed Apr. 5, 2020, at about the 13:59 mark.

I visited Ampex in Redwood City, CA, for a month in 1977 installing Paint, a program I'd written at NYIT. Ron Baecker, Eric Martin, and I briefly shared a house in Redwood City [corroborated in an email from Eric, Sept. 28, 2015, "Yes, I do dimly remember our Redwood City/Ron Baecker/You experience fondly."] While I was there I conceived of Paint3, the first 24-bit paint program, and wrote it immediately upon return to NYIT.

From Ron Baecker, email Aug. 5, 2019: "I went to PARC not because of Superpaint, but to build a picture-driven animation system in and on top of Smalltalk, which was a joy. The system was called Shazam; you can see Eric doing some animation with it in some of Alan's videos. The amazing thing is that I managed to talk Alan [Kay] into not only hiring me for the summer of 1974 but also Eric and my grad student Tom Horsley, who was a super programmer. I still remember the steaks and caesar salads and bloody Marys on the patio in Redwood City, watching Nixon go down in flames that summer." (Nixon resigned Aug. 8, 1974.)

And in a final twist, Eric Martin joined Ed Catmull, Dick Shoup, and me on a visit to animator Frank Thomas at Disney, Jan. 3, 1977 [from handwritten trip notes I made, http://alvyray.com/Pixar/documents/Disney1977Visit_EdAlvyDick.pdf, downloaded Apr. 5, 2020].

Another early animation on Shoup's system explained how Gary Starkweather's laser printer worked, animated by Bill Bowman [*The* SuperPaint *System (1973–1979*, SLOT animation, http://web.archive.org/web/20020110013554/http://www.rgshoup.com:80/prof/SuperPaint/, accessed Apr. 5, 2020].

348:*When I met*: Email from David DiFrancesco, Apr. 4, 2018: "Computer Image Corp is where I went to work . . . in '71 and I worked with Lee Harrison who I mentioned to Dick [Shoup] at a lecture he gave to a bunch of ASIFA and NABET members one night in SF. He ask[ed] me to come up to the podium after my question at the end of his talk because he knew Lee and asked me to come down to PARC, as there was someone there he wanted me to meet . . . that was you." ASIFA is the International Animated Film Society (founded in France). NABET is the National Association of Broadcast Employees and Technicians. See *Scanimate News Report*, https://www.youtube.com/watch?v=SGF0Okaee1o&feature=youtu.be, accessed Apr. 5, 2020, and *Scanimate News*, http://www.scanimate.net/, accessed Apr. 5, 2020.

349:*David loved machines*: Brough ("Bruff") owners are an interesting lot. Arthur Conan Doyle owned a very early one. T. E. Lawrence (of Arabia) owned eight of them, one bought for him by George Bernard Shaw. Lawrence died on one. David never missed a showing of *Lawrence of Arabia* (1962), because he couldn't believe what director David Lean had done. For verisimilitude, Lean had one of the rare Broughs actually wrecked for the opening scene of the movie, the crash that killed Lawrence. The Brough, called the Rolls Royce of motorcycles, was the first production bike to go over 100 miles per hour. David made a pilgrimage to Nottingham to visit George Brough's factory. [From personal conversations with David DiFrancesco and several years of admiring the Brough Superior up close.]

350:*David DiFrancesco, familiar*: I have a copy of the NSF proposal in my collection [DiFrancesco and Smith, 1974]. It's indeed one page long. Excerpts: "We believe we are dealing with a new medium, a marriage of video and digital computers. The most pleasant and most natural direction this union leads is to digital, real-time, interactive animations—any flight of fancy, not just 'cartoons.' . . . We think dealing with images in this way is important because of the order or two of magnitude increase in the ease of animation. And animation is the key to the future of visual information."

350:*And it was*: The last entry in my PARC journal [Smith (1974), inside back cover, or p. 98] is: "End of an era: given final No by Xerox (Jerry Elkkind [*sic*] & Bob Taylor) Thurs. Jan 16, '75 ~3 p.m. . . . It's been wonderful. I believe extension of my access was not granted in a decision based on fear." Well, fear of stockholders anyway (see next paragraph).

The problem might not really have been about color. The buttoned-down Xerox management in upstate New York had been embarrassed by a Dec. 1972 article in *Rolling Stone* magazine by Stewart Brand [Brand (1972)]. The article, titled "Fanatic Life and Symbolic Death Among the Computer Bums," was about *Spacewar* and the hippies at PARC. It was published in book form in 1974. PARC was camouflaged as Shy Research Center, Stanford Industrial Park, Palo Alto, but it didn't take much to decipher the ruse.

I started unofficially and sporadically at PARC just before Feb. 28, 1974 [p. 67]. I was hired July 31, 1974 [p. 94], and officially hired by purchase order Aug. 12, 1974. The original P.O. limited my hire to Dec. 31, 1974, but was modified on Oct. 31, 1974, to terminate on Dec. 1, 1974. By either measure I worked past my official authorization. So I worked unofficially (unpaid) at PARC for about six months (Feb.–July 1974) and officially (paid) for about six more (Aug. 1974–Jan. 1975).

In my possession is a letter from me on Xerox letterhead, dated Dec. 30, 1974, to a professor at the Polytechnic Institute of New York in Brooklyn asking that personal belongings, which I had left behind at NYU when I precipitously departed, be sent to Xerox PARC. (PINY had inherited the EECS Dept. of NYU by this time. Apparently I was still officially part of the department but "on leave." This letter then was also my final and official resignation "to pursue a career more oriented to media than academia.") So clearly I was still at PARC on this date and assumed I'd be there longer to receive the goods.

I had managed to produce, besides the NEA video with David, another one called *Vidbits*, in Dec. 1974, perhaps the first Digital Light video art with raster graphics. Before my departure from PARC, Bob Taylor sat with me and Shoup to ensure that I edited out every mention of Xerox or PARC in *Vidbits*. Years later, Shoup would chuckle about how that disavowed video was what won an Emmy for PARC (and himself) [from a Shoup quotation in Perry and Wallich (1985)]. I attended that 1983 Emmy award ceremony with Shoup.

Also in my possession is a memo on Xerox letterhead from me to Bob Taylor, dated Mar. 4, 1975: "Dear Bob: As you know, I worked under contract at PARC from August 15, 1975 [*sic*], to December 31, 1975 [*sic*]. During this time, at Xerox expense and using Xerox equipment, I created several videotapes for which I would like to obtain Xerox permission to copy . . . [7 tapes described] . . . from which I have removed all mention of any connection with Xerox . . . ." He granted the permission.

I owe great thanks to Jim Meyer, PARC's video expert, for mentoring me in analog videotape technique. Jim has been an independent, highly skilled video producer in Berkeley for many years with his company, Ideas in Motion.

350:*I shouldn't have*: But Taylor was a true visionary. His vision was a grand one—the personal computing environment as we now know it, complete with window-based user interface, mouse, laser printer, word processing, and internet. His vision was different from ours, another example of someone with a different vision helping us with ours.

In 2017 I resolved to visit Taylor. Too late I'd understood what he'd done and wanted to thank him for giving me a crucial break. His son Kurt, Dick Shoup's friend, answered the phone only to inform me that Bob was dying, and did a few days later. To his credit Dick Shoup always maintained that I was wrong about Taylor, despite Taylor's lack of enthusiasm about SuperPaint. They played tennis together regularly for the rest of their lives.

350:*So Xerox blew*: Xerox rejected the Alto as a product in 1976 [D. K. Smith and Alexander (1988), 176]. In fact, Dick Shoup did add color to Alto before the end of the project. Strictly speaking, Xerox rejected the Alto, not the concept of "personal computer." They tried at other "personal computers" but they were too expensive to really fit that category.

I hadn't heard of GE's NASA-2 simulator yet, so I believed that Xerox had the only industrial-strength color pixels in the world.

350:*Whatever the reasons*: Dick Shoup called the framebuffer of SuperPaint a "picture memory." It's a better term but didn't catch on. "Buffer" in "framebuffer" implies that it's only a temporary and unimportant storage place, or buffer, between something important, the computer, and something else important, the display. But, in fact, the framebuffer was the most important part of the system in our eyes. Shoup's Color Video System, with its framebuffer, computer, and video processing units, was the size of a small refrigerator.

David and I must have made our trip to Utah in late Jan. 1975 (after my termination Jan. 15) or early Feb. 1975 (before our first visit to NYIT, Feb. 12–13). We drove across sun-drenched but snow-covered Nevada, possibly the remnants of the Great Storm of 1975, Jan. 9–12, 1975 [*Wikipedia*, Great Storm of 1975, accessed Apr. 5, 2020].

351:*We heard that*: Email from Jim Kajiya, Apr. 24, 2017, "Ivan [Sutherland]'s startup was with Gary Demos and based on the business opportunity enabled by the frame buffer. I was hired [at E&S] as the project engineer on the frame buffer. I spent a couple of weeks struggling with Ivan and Gary's architecture for the frame buffer. Turning it into real hardware was going to be very expensive and didn't make all that much sense to me. When I told Ivan about my struggles one day and gave me one of his many golden pieces of advice. He said something like, 'the Frame buffer is your project—you're the project engineer and the owner. If you don't like something about the design you can change it so that it will work." After that, I threw out a lot of the architecture, simplified it, and designed all the pieces in short order. His lesson to a young engineer has lasted my whole life.'"

The first time the name Gary Demos registered with me was in the circuit designs for the E&S framebuffer. Kajiya must not have thrown out this one circuit. It jumped out at me because it was not a planar circuit design, as was normal, but a circuit in orthographic projection. The extra design fillip alerted me to its designer, Gary Demos, whose name was on the page. I recorded the name not yet knowing the role he would play.

Kajiya and I would rejoin at Microsoft in the 1990s.

351:*Our hopes that*: Another argument against our being invited to Utah was that they had already hired an artist there. It was the first time I heard the name Judson Rosebush, who would start an early computer graphics company, Digital Effects Inc., in New York City in 1978. At the time of our Utah visit he was with the Everson Museum in Syracuse, NY, assembling a catalog on video artist Nam June Paik [Rosebush (1974)]. His appointment in Utah fell through, but he was in and out of my life from then on. He compiled one of the earliest computer graphics histories that I know of [Rosebush (1979)]. Nam June Paik appears in *Cybernetic Serendipity* [Reichardt (1968), 42].

351:*"Who should we*: The other Utah acquaintance was (the late) Robert McDermott, who took David and me under his massive wrestler's wings at Utah and taught us the ropes. He worked with Ron Resch at Utah on a famous 25-foot Ukrainian Easter egg (or *pysanka*) sculpture in Vegreville, Alberta [*Wikipedia*, Vegreville egg, accessed Apr. 5, 2020]. It was designed with computer graphics in Utah and assembled for the first time in Vegreville. McDermott got his PhD with this work. Ron Resch appears in *Cybernetic Serendipity* [Reichardt (1968), 66].

351:*"That's not a*: Edward Riggs was a Puritan who immigrated to Massachusetts in 1633. In my direct descent from him was Bethuel Riggs, a fire-and-brimstone-breathing Regular Baptist elder who started churches in early Kentucky and Missouri. One of his nine children, Nathaniel Riggs, rebelled by joining Joseph Smith Jr. and the early Mormons in 1831. Nathaniel eventually migrated to Salt Lake City and was married (sealed) to his third wife by Brigham Young himself in 1852. See Smith (2006). And a Smith great aunt of mine became a Mormon.

351:*Alexander Schure, president*: Gartel and Streich (1981), last page of the main article, an interview in *Millimeter* magazine. More of the quotation is: "Anything the human mind can perceive, we will be able to compute. Our vision will speed up time, eventually deleting it." Also, on the first page of the article: "Edward [*sic*] Catmull and Alvy Ray Smith, currently heading up Lucasfilm's advanced research group, both originated at N.Y.I.T., they will presumably lead the group that will help Lucas become the first director to use digital effects within a major motion picture." This was an inaccurate prediction about Lucas.

Marshall McLuhan had said something similar about time in 1964, "The effect of speeding up temporal sequence is to abolish time," in McLuhan (1964), 196. The full quotation is: "Positively, the effect of speeding up temporal sequence is to abolish time, much as the telegraph and cable abolished space. Of course, the photograph does both." McLuhan's point seems to be that a photograph, taken in an instant, lasts forever thus obviating time. And a temporal sequence of them does too. But Schure was no McLuhan.

Alexander Schure was born Aug. 3, 1920, Canada, died Oct. 29, 2009, Massapequa, NY, son of Harry Joshua Schure, a shoe store proprietor (1921, 1930), cigar manufacturer (1929), and antique rug salesman (1940), and Bessie Ginsberg, both born in Russia [*US Social Security Death Index, 1935–2014*, all source records in this paragraph at https://www.ancestry.com, accessed Apr. 5, 2020]; 1921 Canadian Census, Hamilton, Ont.; *1930 United States Federal Census*, Manhattan, NY, family immigrated to Canada in 1905 and to US from Canada in 1924; *1940 United States Federal Census*, New York City; *US City Directories, 1822–1995*, Rochester, 1929. He married Dec. 7, 1943, New York City, Dorothy Rubin, *New York, New York, Marriage License Indexes, 1907–2018*. See also in-depth analysis in Smith (2019). The Harry J. Schure Hall at NYIT is named for Alexander Schure's father.

351:*Alexander Schure, the*: Richard Gilbert went to New York for the holiday season of Dec. 1974, when he must have learned what his uncle Alex Schure was doing. Ed Catmull and Malcolm Blanchard might have arrived by then (see note 355:*Malcolm Blanchard, another*), but if so, they didn't have anything to show yet. So Schure must have been bubbling with the Pete Ferentinos-induced visions and told them to Richard. David DiFrancesco and I visited NYIT in Feb. 1975 and came back totally enthused by what we'd seen. Rubin (2006), 103–112, details Schure's visit to Evans & Sutherland, instigated by Pete Ferentinos, in 1974. [N.B. the picture on p. 107 of Rubin (2006) is of a "researcher demonstrating Ivan Sutherland's Sketchpad." The researcher is, of course, Tim Johnson, of the Triumvirate, and he is demonstrating his own program Sketchpad III, not Sutherland's Sketchpad. At least, Johnson isn't misidentified as Sutherland as he typically is.]

Richard Gilbert's father married Alex Schure's sister, Esther, a concert violinist. Alex Schure was born in Canada of Russian immigrants (from Mogilev, now in Belarus). His father brought his family to the US in 1924 when Alex was 4 [Smith (2018)].

352:*De Seversky was*: "Alex Prokoffieff-Seversky" and his mother Vera escaped from Russia via the Trans-Siberian Railway to Vladivostok. There they boarded a Japanese steamship, the *S.S. Siberia Maru*, that departed Yokohoma, Japan, and arrived in San Francisco on Apr. 21, 1918 [Libbey (2013), 43; *California, Passenger and Crew Lists, 1882–1959*, at https://www.ancestry.com, accessed Apr. 5, 2020, M1410, San Francisco, 1893–1953, 107, has him 23 yrs. 10 mos., her 40 yrs. 8 mos., he an aviator engineer, both Russians, both last resident in Petrograd, referencing Mr. B. Prokoffieff-Severses [*sic*] there, his intent "To join Russian Naval Aviation Service. Washington D.C.," his mark of identification: "Right leg wood below knee," both born in Russia, he in Simferopel [Crimea] and she in Tiflis [Georgia]].

353:*De Severksy settled*: He founded Seversky Aircraft Corp. on Feb. 17, 1931 [Libbey (2013), 95]. It was renamed Republic Aircraft (later Aviation) on Aug. 30, 1939, after Seversky lost the presidency of the company [Libbey (2013), 163]. The movie *Victory Through Air Power* (1943) can be seen at https://archive.org/details/VictoryThroughAirPower, accessed Apr. 5, 2020, in Technicolor. De Seversky makes appearances at 21:18–24:00, 44:18–47:15, and 58:05–1.01:26. Gabler (2006) tells the de Seversky and Walt Disney story well. A deeper treatment is chapter 13 of Libbey (2013), the only biography that's been written about de Seversky. The US Air Force was founded in 1947. Libbey (2013), 212, "Near the time when the movie Victory Through Air Power opened in New York City, Walt Disney, wife Lillian, and daughters Diane and Sharon stayed for several days at the de Seversky mansion on Long Island Sound." This was in the village of Asharoken on the north shore of Long Island in the Town of Huntington, not the current de Seversky Mansion on the NYIT campus about 20 miles distant.

I've tried unsuccessfully to learn how the two Alexanders met. It was an important meeting, for Schure in particular. The only mention of NYIT in the de Seversky biography, Libbey (2013), is this (p. 273): "de Seversky had good help from an expert consultant on air pollution control, Dr. Bertram Spector, who served as vice president for research at the New York Institute of Technology." This was in the 1970s and doesn't explain the relationship.

353:*In 1964 de*: The de Seversky mansion was *supposedly* featured in the movies *Three Days of the Condor* (1975) and *Arthur* (1981). Schure does make appearances in *Condor* at 35:40–46, greeting a helicopter as Cliff Robertson deplanes, and 35:54–57, holding a car door open for him. The mansion itself must have ended up on the cutting room floor however, but it does appear in *Arthur* at 40:43–41:05 in an exterior shot and then continues for several minutes in interior shots.

A *New York Times* article published Apr. 26, 1921 [*New York Times* (1921)]: "The place is one of the most beautiful on Long Island. It adjoins Harbor Hill, the home of Clarence Mackay. Near by estates are those of Harry Payne Whitney, Otto H. Kahn, J. Pierpont Morgan, Thomas H. Hitchcock, and Elbert H. Gary.

"The house was designed by Carrere & Hastings, and the furnishings were supplied by Charles of London, who obtained in Europe a rare collection of antiques which adorn the interior. The house is of brick with marble trimmings, and is set in the midst of a woodland park. A natural lake lies in front. Mrs. Alicia du Pont, for whom the house was built, did not live to see it completed. She was the first wife of Albert I. du Pont . . . ."

A *New York Times* real estate article [Shaman (2001)]: "Fronting on busy Northern Boulevard east of Glen Cove Road is one of Long Island's still intact Gold Coast estates—101 acres of rolling fields and woods with a magnificent Georgian-style mansion designed by the architectural firm of Carrère & Hastings for Alfred I. du Pont, a one-time head of E. I. du Pont de Nemours & Company, the chemical company.

"The house, known as White Eagle when it was built in 1917, has undergone some extensions and alterations, but its architecture has basically been maintained. Purchased in 1972 [*sic*] by the New York Institute of Technology, whose Old Westbury campus is next door, and renamed the de Seversky Conference Center, the ornate 41,000-square-foot mansion has been used for . . . .

"The Russian-born Alexander P. de Seversky, who died in 1974, was an aviator, inventor and founder of the Seversky Aircraft Corporation. As a trustee of the college, he was instrumental in the acquisition of the mansion. . . .

"The nearby Old Westbury campus of the New York Institute of Technology, which the college purchased in 1964, once belonged to Cornelius Vanderbilt Whitney, son of the sculptor Gertrude Vanderbilt Whitney, who founded the Whitney Museum of American Art. The college owns the Whitney stables and outbuildings and a 30-room house modeled after a French chateau. The former main Whitney residence is now the clubhouse of the Old Westbury Golf and Country Club."

See also *New York Times* (1963), Sept. 5, 1963: "The purchase of a 286-acre tract of the former Cornelius Vanderbilt Whitney estate in Old Westbury, L. I., by the New York Institute of Technology was announced yesterday. . . . The Old Westbury property was bought for about $2,000,000 . . . ."

353:*But then a*: Rubin (2006), 103–141, tells the story of NYIT in great detail. Since I was a source to Michael Rubin for some of it, I can't cite it as a source here. But he devotes much more space to the subject than I do here. In particular, see pp. 108–109 for his treatment of Ferentinos's seduction of Schure, many details of which didn't come from me.

354:*"We were 10*: Larry Roberts made a similar prediction about virtual reality and three-dimensional computer graphics. In an email from him, May 8, 2017, "The virtual reality setup Ivan and I created using my 3-D displays and my Lincoln Wand 3-D acoustic sensors was able to view in real time as one moved their head. Likely due to speed this was not re-created for decades. It was realizing that we were decades away from 3-D graphics becoming something of practical commercial utility that had me switch to networking." Roberts is now (2019) deceased.

I asked Sutherland about the ca. 1974 company in a May 2017 Skype conversation. Its name was to be The Picture/Design Group, he told me, and his cofounder was to be Glen Fleck, who had collaborated with the famous designers Charles and Ray Eames. The classic Eames Lounge Chair was their design, but they also created large exhibits, with Fleck as a key part of the design team. These included the IBM Pavilion at the New York World's Fair of 1964, with a multimedia show called *Think*, and in 1971 *A Computer Perspective: Background to the Computer Age*, also sponsored by IBM.

Llisa Demetrios, granddaughter of Charles Eames and a personal friend, in an email of May 15, 2017, verified that Glen Fleck was a fundamental part of the Charles and Ray Eames studio from the late 1950s to 1973, and participated in all major design achievements of that studio. She cited the *Eames Design* book which catalogs the Eames Studio achievements. Among them are:

Exhibit: "1964–65 IBM Corporation Pavilion for the New York World's Fair—script for *Think* developed by Glen Fleck, Ralph Caplan and IAL Diamond in cooperation with Charles."

Book: Charles Eames and Ray Eames. Glen Fleck (ed.). *A Computer Perspective: Background to the Computer Age.* Cambridge, MA: Harvard University Press, 1973; repr. 1990.

Film: *A Computer Glossary*, made by Charles and Ray Eames with Glen Fleck, music by Elmer Bernstein, 1973, produced by IBM.

355:*Malcolm Blanchard, another*: Malcolm Blanchard was the first systems programmer for the Lab. This is the deeper kind of programming where Ed and I didn't excel. Malcolm was mentioned in the Dawn of Digital Light chapter in the discussion of early antialiasing.

Catmull and Wallace (2014), 20–22, states that he received an exploratory phone call from NYIT in Nov. 1974, and moved "within weeks" into his new office there. This suggests that he and Blanchard joined NYIT probably in Dec. 1974 but perhaps Jan. 1975.

355:*The second two*: I joined the second week of Apr. 1975. David DiFrancesco and I visited NYIT during a blizzard which we deduced from weather records must have been Feb. 12 or 13, 1975 (see next paragraph). I returned to California to pack up and move. I attended a conference in the Netherlands during the first week of April to present my last cellular automata paper [Smith (1976)] and returned to NYIT.

From *A History of New York City Snowstorms (1950–2018)*, https://thestarryeye.typepad.com/weather/2013/01/new-york-city-snowstorms-1979-2011-.html, accessed Apr. 5, 2020: "Feb. 12, 1975 – A quick-moving winter storm delivered the biggest snowfall of the winter, with 7.8" piling up between 8AM–3PM. Snow fell at the rate of one-inch per hour for five consecutive hours. This was the biggest snowfall of the eight winters from 1970 thru 1977." David and I drove across Manhattan in this storm from Nutley, NJ, to NYIT on Long Island. And then back to NJ. We might have waited one day and made the trip on 13 Feb.

355:*The geometry-based*: The "deleting time" epigraph is a glimpse into the strange mind of Uncle Alex Schure. Another peek is the organization chart (figure 7.41) handed to us during the early days at NYIT, when we were still only four. It surprised us for several reasons. We had no reporting structure that we knew of, except to Schure, the owner. Ed Catmull was our de facto head, but it meant nothing special to us then. We'd never heard of Pollack and Politzer, nor of the Learning Management and Resources Center. We had met van Sicklen once but he wasn't one of us. David didn't officially work for the Lab yet. "Alvo" was as wrong as my zany title, Information Quanta. This "organization" was never mentioned again.

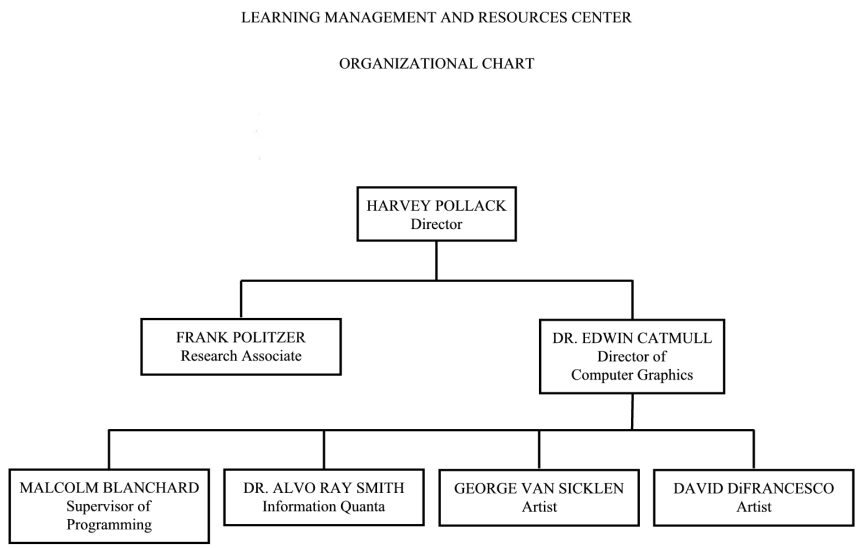

Figure 7.41

The only mention I've found of Pollack in NYIT context is this, from Schure (1961), *Basic Transistors*, iii, "I should like to acknowledge the assistance of the staff of the New York Institute of Technology, and in particular Mr. Harvey Pollack, who organized the text material."

355:*The NEA sent*: Email from Youngblood, July 6, 2018, "It was Stan [Vanderbeek] who invented the phrase 'Expanded Cinema' . . . ." Vanderbeek had made early computer art with Ken Knowlton at Bell Labs, one piece being exhibited in the Museum of Modern Art as I wrote this chapter (2018). The MoMA show, called *Thinking Machine: Art and Design in the Computer Age, 1959–1989* (Nov. 31, 2017–Apr. 8, 2018), spelled his name VanDerBeek. This description comes from https://www.studiointernational.com/index.php/thinking-machines-art-and-design-in-the-computer-age-review-moma, accessed Apr. 5, 2020: "Stan VanDerBeek. Poemfield No. 1, 1967. 16mm film transferred to video (color, silent). 4:45 min. Realized with Ken Knowlton. Courtesy

Estate of Stan VanDerBeek and Andrea Rosen Gallery, New York. Photograph: Lance Brewer. © 2017 Estate of Stan VanDerBeek." Nearly all other pieces in this show were calligraphic.

356:*And they didn't*: During the NYIT years, David and I lived on the nearby McGrath estate, in the chauffeur's quarters. The estate was called "the compound" by "the family," and we were "the tenants," all spoken in a peculiar conversational tone called a Long Island honk, according to Tom Wolfe's *Mauve Gloves & Madmen* (1976). Wolfe taught us about Locust Valley Lockjaw and other dialects of the honk that were, he said, prep school identification displays among the wealthy. We soon discovered that the sister of the man in "the big house" was married to David Rockefeller. DiFrancesco had found the place, a three-bedroom house with a fireplace above a four-car garage, by striking up a friendship with "son of big house," a fellow Vincent motorcycle enthusiast. The compound was our bit of heaven in Great Gatsby land.

Wolfe (1976), in the essay called Honks and Wonks, claimed that one in the know could identify which prep school a person had attended by the particular honk spoken. Locust Valley is a community on Long Island slightly north of Old Westbury where NYIT is located and of Brookville where the compound is located.

The arts were always a fundamental part of the Lab at NYIT. Artist Darcy Gerbarg from the art scene in Manhattan expanded her repertoire into computer painting at the Lab in the late 1970s. And in the early 1980s Rebecca Allen collaborated with dancer and choreographer Twyla Tharp there, only one of Allen's many works employing computer graphics. Prolific movie scorer Carter Burwell spent several years in the early 1980s at the Lab (after I departed) and worked with Allen and Lance Williams.

Darcy Gerbarg, *Artist Talk for Syracuse University September 2015*, http://www.darcygerbarg.com/bio-presentation/, accessed Apr. 5, 2020: "In the late 1970's I started using computers in the research labs where they were inventing computer graphics: NYIT, and SynthaVision [MAGI] (most of the animation for movie Tron was done at this lab [that is, MAGI]) to name two labs."

Rebecca Allen's site, http://www.rebeccaallen.com/home, accessed Apr. 5, 2020, from her Work Highlights.pdf, available under "About" there: "1982 The Catherine Wheel | Created a dancing computer generated character who plays the role of St. Catherine in choreographer Twyla Tharp's 90 minute performance film, 'The Catherine Wheel', with music by David Byrne. This is one of the first and most intricate examples of 3D computer generated human motion and the first to be aired on television. | Dan Rather from CBS News featured this work as the theme for a news special on 'Man and Machine'. Produced at: Computer Graphics Lab / NYIT."

Carter Burwell's site, http://www.carterburwell.com/carter/carter_bio_facts.shtml, accessed Apr. 5, 2020: "From 1982 to 1987 he worked at the New York Institute of Technology where he began as a computer modeler and animator, but ended up as Director of Digital Sound Research. During this time he worked on many computer-animated television spots and films, ultimately contributing models and animation to the Japanese anime *Lensman*." Among the many films he's scored are *Blood Simple* (1984), *Fargo* (1996), *Being John Malkovich* (1999), and *The Kids Are All Right* (2010). And one that particularly matters to this book, *Joe's Apartment* (1996).

Catmull, DiFrancesco, Duff, and I had departed NYIT before Allen and Burwell arrived, just missing them. Lance Williams kept the tradition of working with artists alive after our departure.

356:*There was an*: From *MSI/CAORF Trains How To Avoid Ship Accidents Before They Happen*, http://magazines.marinelink.com/Magazines/MaritimeReporter/198912/content/msicaorf-trains-accidents-200573, accessed Apr. 5, 2020: "The flagship facility of MSI [Marine Safety International] is the Computer Aided Operations Research Facility (CAORF), located on the grounds of the US Merchant Marine Academy at Kings Point, NY Originally built by the Federal Government as the National Maritime Research Center, CAORF houses one of the most sophisticated ship simulators in the world . . . The CAORF facility is so unique that both the Coast Guard and the National Transportation Safety Board have contracted to study the Valdez accident 5,000 miles away from the point of its occurrence—at MSI/CAORF."

Christine Barton alerted me (email Mar. 12, 2019) to the long history of small tankers in New York Harbor. For example, the *Wikipedia* article on New York Harbor, accessed Mar. 12, 2019, states: "The Port of New York and New Jersey is the largest oil importing port . . . in the nation." A similar, more modern concern centers on LNG (liquid natural gas) tankers.

356:*The view out*: Puglisi et al. (2000), 61: "The 25th anniversary of the initial operation of the Computer Aided Operations Research Facility (CAORF) is the month of July in the year 2000." See Fig. 2, p. 72, of this publication for a cutaway drawing of the unique building that housed CAORF. On p. 66 is this description of the VBSS (Visual Bridge Shiphandling Simulator): "The system is a high fidelity visual ship-maneuvering simulator that provides the student a complete marine environment. Using a 240 degree field of view visual scene, full bridge mockup with complete equipment compliment [*sic*], environmental effects (wind, water current, depth, channels/banks), and totally realistic 6 Degree of Freedom (6 DOF) own ship and passing ships hydrodynamic effects, the system realistically replicates the marine scene and ship behavior." This description was written in 2000.

Nobody I've quizzed can recall if the World Trade Center towers were in the database. They had been completed in Apr. 1973, perhaps too late to be included in the database. P. J. Zima probably could have remembered but he died in 2003 [obit., *Paul "PJ" Zima*, https://www.legacy.com/obituaries/mercurynews/obituary.aspx?n=paul-zima-pj&pid=1225356, accessed Apr. 5, 2020]: "In 1974 he was recruited by John Warnock (who later co-founded Adobe Systems) to join Evans & Sutherland Computer Corporation where he developed computer graphics software and graphic models, including the New York Harbor simulator for the US Maritime Academy and NASA Space Shuttle training simulators."

357:*CAORF was engineered*: Interview trip to Salt Lake City, Feb. 27, 2018. CAORF led to the "breakthrough simulator contract" with KLM in 1973. Pete Doenges joined the CAORF team in Sept. 1973.

357:*Schumacker had attended*: Email from Christine Barton, May 12, 2019: "I was on my way to on-site testing in Great Neck and I was told that the recently delivered frame buffer was at NYIT. I was given Catmull's contact info, called him up and visited him at the initial ground floor small office used by the group at the time."

357:*Christine had network*: Email from Christine Barton, Apr. 14, 2017: "In 1971 I was working at the Illiac Project at NASA Ames. I was working with the systems group . . . After working at the Illiac Project, I went to work for John Warnock at the California office of Evans and Sutherland, because we had people who could write operating systems and compilers, while Salt Lake City could only build hardware for a computer generated simulator of New York Harbor . . . I worked on the operating system, but another employee in California (P J Zima) wrote a compiler to describe the terrain of New York Harbor, using descriptives like point, polygon, etc. using labels for points, polygons, objects. It was used to build the database that was processed in real time while the simulator was running. . . . when we delivered CAORF (the harbor simulator), the contract did not require us to deliver the database compiler. When we didn't deliver it, we expected the customer, the Merchant Marine Academy, to know it obviously existed and ask for it for additional money. They didn't. They took delivery and hired two women who prowled through collections of point and polygon declarations with absolutely no identifying labels. I didn't work on it; I just observed it and used it."

Smith (1978a), appendix B, lists the equipment available at NYIT then, including six E&S framebuffers (512 by 512 by 8 bits each) and twelve Genisco framebuffers (512 by 512 by 8 bits each).

357:*And Christine made*: In an early demo tape from NYIT appear the following two-dimensional animations: (1) *Cold Duck*, by professional animators at NYIT; (2) an octopus by Ed Catmull; (3) a cat by Malcolm Blanchard; (4) a Basset hound by Christine Barton; (5) and a stomping foot by me. All used Ed Catmull's *Tween* two-dimensional interpolating animation system.

Barton also created a tiling program that I used to create one of the first, if not the first, digital music video, for the group Earth, Wind & Fire and their album *All 'n' All* (1977). This video was used as evidence in a patent trial in England in the 1980s, with which some of us were involved. Barton, in email of June 29, 2018, acknowledges the help of Lance Williams in writing the code for the tiling program.

Holloway House was featured in a slick full-page magazine ad for Johnny Walker Black Label Scotch whisky. It featured side-by-side mansions (in faked proximity), with Holloway House on the left, at dusk with porch lights on. The caption read, “I was wondering if I could possibly borrow a cup of Johnny Walker Black Label.” It ran in the *New York Times Magazine*, Mar. 6, 1977. Holloway House was home to NYIT computer graphics people Christine Barton, Tom Duff, and Lance Williams. It also housed background artist Paul Xander and his family of eight. Holloway House featured a “pet” crow who lived indoors, an overgrown (reputed) bear pit on the estate grounds, and a hulking pre-War black boiler in the basement adorned with a swastika.

358:*Two people who*: I take as definitive these notes on chapter 8 from Jim Blinn, Apr. 6, 2019, “In summary: Summer 1975—Lance and Garland at NYIT; Summer 1976—all three of us [Williams, Stern, Blinn]. At the end of the summer I returned to Utah and Lance and Garland stayed.” These memories vary slightly from the memories of others:

Email from Lance Williams [now deceased], June 15, 2017: “I came to NYIT in the summer of 76, initially housed at the CW Post dorm . . . Dr Schure invited me to return to NYIT as an employee, which I perceived disconcerted Ed.” C. W. Post College was named for the inventor of Post *Toasties* breakfast cereal. It’s located just east of NYIT and is part of Long Island University.

Email from Garland Stern, June 15, 2017: “I, too, keep wondering when I wound up at NYIT. I think it was in '76, but I don't recall visiting before that. I don't think Lance was employed there before I became, but we might have discussed his visit before I went.”

My memory is that Lance and Garland visited for a summer, probably the summer of 1975, and came together. They returned to Utah to continue their graduate studies. Each returned separately to NYIT as permanent employees, probably in 1976. Garland eventually moved in with David DiFrancesco and me in the chauffeur's quarters on the McGrath estate ("the compound").

359:*More importantly, Lance*: Stockham was both an audio and a digital imaging expert, teaching his students both at Utah. Henry Fuchs, email July 31, 2019: "Half of Stockham's group was doing audio, the other half was doing image processing. Stockham taught us about sampling in both audio and image domains." Fuchs won the Coons Award in 2015, and is a professor at the University of North Carolina at Chapel Hill. He gained early prominence by building special-purpose hardware for rapidly generating pixels, called Pixel Planes. He was inspired by display difficulties suffered by Ivan Sutherland's head-mounted display (from a conversation with him at Siggraph 2019, July 31, 2019).

361:*Meanwhile Garland Stern*: Schure (1981), publisher's summary: "Recently, NYIT produced a half-hour educational film, Measure for Measure, which successfully mixed conventional animation with computer-assisted animation using two different methods."

362:*Garland's program, called*: Another way to summarize the stop-gap measure of scan-and-paint is this: Scanning at video resoution was cheaper than computation at the time.

362:*The pixel creation*: Smith (1979) describes Tintfill: "This paper presents an algorithm for the more difficult problem of filling areas with shaded boundaries (eg, a white area surrounded by a curve consisting of several shades of gray). These images may arise from digitizing photographs or line drawings with a scanning video camera . . . When an area in such an image is to be filled with a new color, it is desirable to have the fill algorithm understand the shaded edges and maintain the shading with shades of the new color instead of the old. The tint fill algorithm presented here accomplishes this task. Its name arises from its ability to change only the tint (hue and saturation) of a pixel, leaving the value (blackness) unchanged."

363:*Meanwhile, an artist*: Smith (1978a) describes *Paint* in detail. Smith (2001) gives a history of paint programs. The earliest 8-bit programs were by Dick Shoup, 1972–1973 (although the system he usually demonstrated was 4-bit), Xerox PARC; Jim Blinn, 1974, Utah; Garland Stern, 1975–1976, Utah and NYIT; me, 1975–1976, NYIT; Jules Bloomenthal, 1976, Utah; Marc Levoy, 1976, Cornell; and MIT students, 1976.

363:*Early in the*: A peculiarity of our NYIT framebuffer was that it had a 12-bit colormap. It had 8-bit pixels so could only display 256 colors, but these colors could be chosen from among 4,096 possible colors (12 bits' worth) with the colormap.

364:*He would soon*: Jim Blinn, in notes sent re this chapter on Mar. 30, 2019, did the calculations: eighteen E&S framebuffers (equivalent to six 24-bit framebuffers) had 1,572,864 pixels; Iphone X has 2,740,500 pixels; Lumia 950XL has 3,686,400 pixels; Galaxy Note 8 has 4,262,400 pixels. So current cellphones generally have about twice as many pixels as all eighteen NYIT framebuffers.

364:*We went crazy*: Smith (1978a), appendix B, Paint3, the RGB version of *Paint*, described full-color painting for the first time, including what became known as "airbrushing."

365:*Why did we*: We had a cute name for "alpha f plus one minus alpha b," since we used it so often. We called it a *lerp*, short for linear interpolation. So we would lerp one picture to another. Lance Williams introduced this terminology.

366:*Alpha used in*: There are two uses of alpha in this figure. One is a pixel-by-pixel alpha that defines the shape of the disk. The other is, as in the preceding figure, a global alpha applied to the entire image to cause the cross dissolve. At each pixel it's the product of the two alphas—the local one in the disk pixel and the global image-wide one—that forms the effective alpha. So inside the disk, the effective alpha per pixel is just the image-wide alpha. Outside it, the effective alpha is zero. Along the antialiased edge of the disk, it's the product of the two.

368:*Alpha may have*: A normal pixel has its red, green, and blue values stored in the RGB channels, and its alpha (opacity) stored in the A channel. A premultiplied pixel has alpha times red, alpha times green, and alpha times blue stored in its RGB channels, and alpha in the A channel. So every time a premultiplied image is restored from a file over another image, three multiplications are avoided (because they've already been done). For a megapixel image, that's three million multiplications saved.

I use "technical Academy Award" instead of the formal "Scientific and Engineering Award of the Academy of Motion Pictures Arts and Sciences." It's not a standalone Oscar but a gold-plated award with Oscar in bas relief.

368:*The company I*: Notice that if alpha is 0, then the RGB channels of an image in premultiplied form are 0, and there is no way to recover what the red, green, and blue values might have been. The image just doesn't exist at pixels with alpha 0, thus the remaining pixels with non-0 alpha define that image's *shape*. The pixels with alpha 0 don't even have to be stored, although they often are. Once you have shaped images, or *sprites*, then you can treat them just like geometry-based pictures. So there is no reason to have two creation programs, one for pixel-based images (cf. Adobe Photoshop) and one for geometry-based images (cf. Adobe Illustrator). One interface suffices for all. The most popular program extant that uses this notion is Microsoft PowerPoint.

I cofounded Altamira Software Corporation with Eric Lyons and Nick Clay in late 1991. We brought our product Altamira Composer to market, then promptly sold the company to Microsoft on Sept. 27, 1994, when I became Microsoft's first Graphics Fellow. I created many figures in this book, including several in this chapter, using Microsoft *PhotoDraw*, based on Altamira technology.

369:*One who didn't*: Blinn (1992b), 87, "I worked for the NYIT Computer Graphics Lab for three months during the summer of 1976, while I was a graduate student at the University of Utah . . . Alex (we all called him Alex, much to the consternation of the rest of the institute's employees, who only referred to him as Dr. Schure) hired Ed Catmull, a recent Utah graduate, to head up the lab. Ed (we called him Ed, much to the consternation of no one) then built a staff consisting of Alvy Ray Smith, David DiFrancisco [*sic*], Christie Barton, Malcom [*sic*] Blanchard, and Bruce Laskin. The other Utah graduate students who came out with me were Lance Williams and Garland Stern."

Bruce Laskin was an 18-year-old wunderkind who had lost his parents and been treated by Alex Schure and his first wife Dorothy, as a surrogate son. Laskin was a bright young engineer who interfaced the IVC 9000 broadcast-quality 2-inch videotape recorder to the Lab's computers, after being told it was impossible by the IVC engineers. Thus NYIT had the first ever computer-controlled frame-accurate videotape recorder, an underappreciated productivity amplifier.

370:*Blinn first worked*: Email from Jim Blinn, Jan. 31, 2019, "Here's the timeline as I remember it. | Summer 1976–I was at NYIT doing various things. Among them was implementing a patch drawing program that did texture mapping, but just for the color of the object. | End of Summer 1976–Back to U of U. | Fall 1976 at U of U–I wanted to make some images of atoms that looked like balls of yarn, to give the impression of whizzing electrons. Came up with the basic idea for bump mapping but the frame buffer at Utah broke and I couldn't try it out. | Christmas 1976–I flew out to NYIT to try it out on your working frame buffers. The version I tried was extremely preliminary, just to see if it could make interesting images. I found a black and white texture of a basket weave in someone's file stash and used it to just add a small amount to the X component of the normal vector. Then shaded according to that modified normal. This was certainly not orientation independent or animatable. I just wanted to see if the general effect was something that was worth pursuing. I made a couple of images that David D[iFrancesco] photographed for me . . . | Early 1977–Back at U of U: frame buffer fixed. I worked out a proper normal vector perturbation method that actually tied the perturbation to the surface properly. Did some simple flip-book animations using the E&S frame buffer microprogrammability to check this. The first attempts had a sign error that was only apparent in the animation. Finally got it all working and this went into my Thesis along with a bunch of other stuff. It used a somewhat clunky means to define the perturbation function though. Made leather donut, strawberry, etc. pictures for thesis. | Summer 1977–Started at JPL. | Late 1977, early 1978–finally got around to writing it up for Siggraph. Also figured out a better way to define the surface perturbation function. This is what went into the Siggraph paper. | Mid 1978–Paper was accepted and Dick Phillips (program chair) invited me to make a color image for the cover. | Mid 1978 sometime–I visited NYIT to work on the design of the cover (since no full color frame buffer at JPL). I brought along the updated version of the bump mapping function. I also worked on the cover at III (Demos' outfit). My goal was to make the cover using the two different facilities at both ends of the country to show unification within the graphics community (ha). But the III part never gelled. Lance took over the rendering of the image at NYIT and produced the final cover image."

371:*Duane Palyka was*: Leavitt (1976), cover (figure 7.42), and 61–64. This book resembles *Cybernetic Serendipity* but about a decade later (eight years actually). Artists mentioned in the book and also in the present book are Leslie Mezei, Edward Zajec, Duane Palyka, Kenneth Knowlton, John Whitney (Sr.), and Lillian Schwartz. Notable others are Vera Molnar and Charles Csuri, both also included in a recent exhibit at MoMA in New York City (*Thinking Machines: Art and Design in the Computer Age, 1959–1989*, Mar. 30, 2018), Herbert Franke, a longtime friend of mine in Germany, and Jacques Palumbo, whose original artwork adorns my in-law's home.

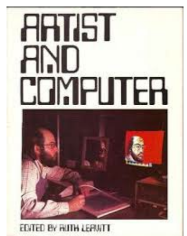

Figure 7.42

Notes on chapter 8 by Jim Blinn, Apr. 6, 2019, "The image on the cover here is of Duane Palyka (using my [i.e., Blinn's] paint program to do a self-portrait)."

Email from Ephraim Cohen, June 22, 2017, "Duane Palyka and I were the two non-students at UU [University of Utah]. I was hired by Ron Resch to do programming and math. Ron suggested I become a student, but I was fed up with school stuff and wanted none of it anymore, so I just took the grant money & typed. I am not sure what Duane's situation was, but he also just had a job in the CS department and use of resources. We have had conversations about the deleterious effects of the PhD on the psyches of its recipients."

372:*Ed Catmull and*: My first programming language had been Algol, and I'd used BCPL at Xerox PARC, so I knew there were logically beautiful alternatives to plodding Fortran.

372:*Ken Thompson and*: David DiFrancesco, email May 3, 2018, remembered the delivery of the NYIT copy: “It was Dennis Ritchie and he came in his new *yellow* Corvette Stingray and hand delivered Unix C on a 9 track tape in 1976 at NYIT. | It was the third copy he made and delivered to us, and one had been given to some branch of the US Gov’t and one to (I think) Bell Labs.” [Cf. *Wikipedia*, Unix, accessed May 3, 2018: “In 1975, the first source license for UNIX was sold to Donald B. Gillies at the University of Illinois Department of Computer Science.”] So it might have been just C he delivered, not the entire Unix system.

Tom Duff, who spent years at Bell Labs, insisted that the yellow Corvette was famously Ken Thompson’s and put me in touch with with him. Ken Thompson, email Mar. 13, 2019, “it was i. if you knew dennis, he and corvettes go together like fish and bicycles. i also remember driving out to nyit . . . i got ’72 vette. it was green, later painted yellow.”

C has gone through changes over the years, with C++ being a well-known modern variant. MacOS X, now macOS, is a well-known variant of Unix, and Linux is “Unix-like.”

372:*None of us*: The Lab needed a replacement for our systems programmer, Malcolm Blanchard, who had departed, the Lab’s first and rare loss. Bill Reeves, email Nov. 15, 2018, re Tom Duff: “Tom and I were at [University of] Waterloo at the same time: 1970–1974. . . . We both graduated in 1974 and both started at the Univ of Toronto in the fall of 1974 as PhD students. . . . At U of T, we both independently decided to join Ron Baecker’s Dynamic Graphics Project (DGP) and he became our supervisor. I did not know Ron before this. At U of T, Tom and I . . . spent many a night hacking away at Unix and our MSc research projects in Baecker’s DGP lab.”

373:*When Tom heard*: Tom was not a founding employee of Pixar because he left to join Bell Labs in 1984. I hated to lose him, but I understood the force of the call from Bell Labs. And he did rejoin Pixar in 1996.

Tom has always been interested in music. Until the Covid–19 crisis, he held frequent salons in his home in Berkeley, near mine. Each featured some visiting avant-garde musician or group passing through the Bay Area. Far-out musicians knew they had a venue at Tom's house.

In Jan. 2020, Tom announced his retirement from Pixar, but while proofing this book I received an email from him on 21 Dec. 2020, that said "I'm retiring from Pixar next month," implying Jan. 2021.

373:*I leave it*: Price (2008) covers the period post-NYIT to the Pixar IPO. I at first ignored Price's attempts to contact me. I understood that he was writing a business book of some sort. But then he revealed that his last book had been a history of Capt. John Smith, which I devoured. A historian! Not a journalist. I told him that I had an attic in Seattle filled with Lucasfilm and Pixar documents. Two days later, Price was in that attic, having jumped immediately from Washington DC to Seattle to peruse the archive. Most journalistic attempts at Pixar "history" have turned out to be Steve Jobs hagiographies. The one exception, other than Price's book, is Isaacson (2011) which has much of the metastory right, although not fully appreciating the role of Ed Catmull. It gets the whiteboard incident between Jobs and me about right. However, it essentially ignores the technical details of the company, including its platoon of geniuses, who were crucial.

374:*In particular, Tom*: Ralph Guggenheim, email Aug. 5, 2016, related his "laundering" at 3 Rivers Computer Corp. between NYIT and Lucasfilm: "Ed must have called me in early 1980 about the editing project. I told him I was ready to leave. 3 Rivers was a spinoff from CMU to productize their vector graphics system . . . , founded by Raj [Reddy] and friends from the CS Dept. They're the ones who recommended I get a post-graduation job at NYIT. I had a vacation trip to canoe in the Everglades in March '80 with friends. I drove to Florida and stopped in Pittsburgh on my return to see if I could get a 'summer job' at 3 Rivers. They needed someone to write Siggraph demos for their new Perq computer, which was perfect for me. I drove back to NYIT and gave notice. I must have left there in May or June. No one at the Lab could believe that I'd leave a 'plush' job at NYIT for a startup! Ed flew me out to LA in July to discuss his thinking about the editing project and meet folks at Discovision, the laserdisc manufacturers. Then we flew to SF in time for the July 4th LFL [Lucasfilm] picnic. I recall you and I . . . hiking around the hills of the ranch. You were still in offices on Bank St. [San Anselmo]. After Siggraph, I took 3 weeks driving cross-country and backpacking. I arrived the day after Labor Day to report for work at the Tunstead [also San Anselmo] office/laundromat."

Other members of the Lab at NYIT up until the time of our departure were Leslye Alexander, Kaare Christian, Rose Cruz, Bruce Doll, Kim Donaldson, Bruce Laskin, Dick Lundin, Tracy Peterson, and Karl Sklar. Visitors of extended stay during our tenure included Rebecca Allen, Jim Blinn, Frank Crow, Ed Emshwiller, and Paul Xander.

374:*We had a*: Marc Levoy and classmates Chris Odgers and Bruce Wallace (and others) introduced a two-dimensional digital animation program into the Hanna-Barbera animation studio in the 1980s. Levoy was director of the Hanna-Barbera Animation Laboratory from 1980 to 1983, according to his *Wikipedia* page (accessed May 9, 2018), also email from Levoy, May 30, 2018. See Smith (1978b) for the color transform.

Another amazing coincidence: William Hanna of Hanna-Barbera, was born in Melrose, NM, population about 600, 25 miles straight west of Clovis, NM, hometown to both Jack Bresenham and me.

375:*An early relationship*: Email from David DiFrancesco, Aug. 26, 2016, "We got in touch with MAGI who set up a meeting with Celco at MAGI in Westchester. You and I and Ed went up there for the meeting with Paul Constantine and Carl Ludwig to show off their first incomplete CRT 70 mm film recorder. Carl was a consultant to Celco at the time. He was responsible for the electronics that converted the digital signals, and sent them to the recorder's fancy proprietary yoke system controlling the CRT beams. They showed us Polaroid and transparency film samples of the animation MAGI was producing at the time. Besides Peter Foldes's *Hunger* and the pieces you and I had made at PARC plus the Computer Image piece I made in Denver at Lee Harrison's company and our experiments with *Tween* this was the third or fourth early CG we ever saw. Paul and Carl admitted that they hadn't perfected the Celco 70 mm recorder yet but were curious about what we were doing and eventually weeks/months later came to visit us at NYIT. We decided we couldn't wait for Celco, and bought a Dicomed film recorder from Minneapolis. This proved to be, with a lot of mechanical and electronic tweaking, a better deal for us to be able to record decent flat fields than any other medium to date in 1975 and 1976. This recorder I used to make the film we ultimately showed to George Lucas that got Ed hired and eventually you and me at Lucasfilm."

375:*We had discovered*: Ed Emshwiller was inducted into the Science Fiction Hall of Fame in 2007 (along with Gene Roddenberry): "During his career as a commercial visual artist, Ed Emshwiller (1925–1990) dominated the field of science fiction magazine and book cover art. Between 1951 and 1964 he created over 400 cover paintings and hundreds of interior illustrations, winning five

Hugo Awards for Best Artist. He provided many of the covers for *Galaxy* and *The Magazine of Fantasy & Science Fiction* during this time. Emshwiller's work combines astonishingly realistic renderings with surreal elements. He evoked wonder as easily as humor or horror, and his lively imagination led him to create many original covers that magazine editors would assign writers to build stories around. Emshwiller also created fine art during this time, and exhibited in several shows. Always looking for new ways to expand his artistic interests, Emshwiller turned to film and video art in the 1960s, creating features, documentaries and the ground-breaking short *Sunstone* (1979), one of the first computer-generated films"
[http://web.archive.org/web/20071014112914/http://www.empsfm.org/press/index.asp?articleID=892, accessed Apr. 5, 2020].

376:*Sunstone would become*: *Circulating Video Library Catalog* (1983), curated by Barbara J. London, Assistant Curator, Video, Department of Film, The Museum of Modern Art, New York City, NY: MOMA, 27: "*Sunstone* (1979) U.S.A. By Ed Emshwiller. Computer animation by Alvy Ray Smith, Lance Williams, and Garland Stern at the New York Institute of Technology."

Ken Knowlton or other Bell Labs creator may have a raster piece in MoMA's collection. The color would have been added in post-production in any case. As reported elsewhere in this chapter I've seen an exhibit at MoMA of a Stan Vanderbeek and Ken Knowlton piece, but don't know if it's part of the collection nor, if it is, when it was acquired. See note 355:*The NEA sent*.

I take for the beginning of HDTV the public launch, Oct. 29, 1998, of the American Advanced Television Systems Committee (ATSC) HDTV system, during the live coverage of astronaut John Glenn's return mission to space on board the Space Shuttle *Discovery* [from Internet Archive, accessed July 9, 2019: *Broadcasting & Cable*, Nov. 2, 1998, article by Paige Albiniak, “HDTV: Launched and Active”].

377:*The painted pixels*: Furthermore, Texas was a tour de force that could use up to 10 of NYIT’s 18 framebuffers in one computation.

377:*Jim was a*: From the *Wikipedia* entry for James H. Clark, accessed July 31, 2019: "Clark began taking night courses at Tulane University's University College where, despite his lack of a high school diploma, he was able to earn enough credits to be admitted to the University of New Orleans. There, Clark earned his bachelor's and a master's degrees in physics, followed by a PhD in computer science from the University of Utah in 1974.”

378:*One morning Schure*: I obtained the following from Christine Freeman, Pixar archivist, email Apr. 19, 2019: “Ed [Catmull] recorded his recollections of the Jim Clark affair at the time. Your versions of the story pretty much line up, except that Ed did the firing. And there were two instances in which Jim Clark wrote to Dave Evans, after which Alex somehow had the letters. Jim smoothed things over after the first one, but things were never the same. The second letter was a job request of Dave Evans, and Alex said he wanted him gone immediately.”

378:*We were surprised*: Smith (1977), 2, from digital photocopies of the original notes, made on Ramada Inn stationery [via http://alvyray.com/Pixar/Disney1977Meeting.htm, accessed Apr. 5, 2020]. I’ve cleaned this up for easier reading. Here’s the actual record: “We were surprised & pleased that Don Duckwall . . . showed up and expressed positive (but not overwhelmingly so) reactions: ‘I believe you can now do bubbles.’ Suggested he might be interested in us for special effects. A large group (~30) people showed up for the seminar—most were young eager guys who loved what they saw—especially the 3-D stuff."

379:*They seemed to*: Smith (1977), 3–4. I started writing a history of Pixar (never completed) in 1999. The following reminiscence comes from the draft: "Frank's office walls were covered with Sir Hiss development sketches (for *Robin Hood*) and *Rescuers* model sheets. He claimed that Walt himself had dampened out animation with interest in the theme parks and that only the giant success of *Jungle Book* (highest return ever at that time) revived interest in animation. He claimed that the young animators were more nostalgic than the old. Then he walked us down the halls lined with signed Tenggrens and reacquainted me with the highest quality: Jiminy Cricket in *Pinocchio* had 27 colors! The evil witch in *Snow White* had five colors in just her eyes!"

379:*The technical people*: Gabler (2006), 546, 590, Ron Miller was first a USC football player then, briefly, a Los Angeles Ram.

379:*But Tubby did*: Lance continued to work on *The Works* with a group at NYIT for several years, before folding to the reality of Moore's Law.

381:*Then suddenly the*: Remarkably, Francis Ford Coppola had contacted me indirectly just hours before the George Lucas indirect contact. In this case the call came from Bill Etra, a video synthesizer expert in Manhattan and an early acquaintance from the video art scene. He told me that Coppola wanted to use computers in filmmaking. Was I interested? Well, of course I was, but I didn't trust the Coppola approach. Etra knew little about computer graphics. That he was the contact didn't make sense to me, or to Ed when I told him about it. We dismissed the approach from further consideration.

382:*He went on*: These details are from Ralph Guggenheim, email Aug. 5, 2016. It continues, "Another part of the conversation ran something like this: Gindy said, 'Look, I've talked to a bunch of people already who claim to be able to do this stuff (3D animation) but they all stop when I ask them if they can make a spaceship fly around on the screen.' 'But we do that everyday here, I replied. 'You do?!?!?!,' he sounded totally surprised. 'You're the first person I've spoken to who can do that! We should talk about you running this effort at LFL.' I mulled over the conversation with Gindy and called him back a few days later, saying "I don't think I'm the guy with the breadth of experience to run this research effort you have in mind, but I'm working with people who are the leading experts in the field, mentioning you and Ed. Let me talk to them and get back to you."

382:*Lucasfilm did make*: Many years later Richard Edlund gave Ed Catmull that belt buckle [email from Ed, Mar. 19, 2019].

383:*Lucasfilm hired Ed*: Notes from Jim Blinn, Mar. 30, 2019: "I was one of the 'competitors' that the Lucas outfit called to see if I was interested in running their computer division. I told them I would make a terrible manager and that I was happy at JPL anyway. When they asked for ideas for other possible recruits I didn't bring up Ed at first since I thought he was happy at NYIT. But when I asked them who else they were talking to, and they mentioned Ed, I immediately said, 'Yes, him. Hire him'. I expect they would have anyway, but was glad to push it forward a bit."

384:*David DiFrancesco set*: Gary Starkweather and Bala Subramanian were independent contractors with Lucasfilm, mostly via David DiFrancesco. [I just heard while editing this note that Gary died in Dec. 2019.]

In 1984 DiFrancesco was invited to present to a Royal Photographic Society conference in Cambridge, UK, the first paper on the complete laser scan and recording of digital computer graphics effects in a motion picture. See DiFrancesco (1984) and also DiFrancesco (1989). David also gained insight from George Mergens, founder of Photo Electronics Corp., in Palm Beach, FL, and from Dan Gilbert at MacDonald Dettwiler in Vancouver, BC.

384:*We needed framebuffers*: A history of Ikonas is online at http://www.virhistory.com/ikonas/index.htm, accessed Feb. 19, 2020.

385:*Alex Schure had*: Jim Blinn, notes on chapter 8, Mar. 30, 2019, mentions that Tom Porter had earlier experience with an E&S framebuffer and a paint program on it (written by Jules Bloomenthal) at the National Institute of Health in about 1978, with software from Utah provided, and installed by, Blinn.

385:*A paint program*: Paint3 used an application of the alpha idea on a small scale. The brush in Paint3 was a shape specified by its alpha. In fact, a brush was a small image with only an alpha channel. Its color channels were assumed to hold the current color so didn't have to actually exist. A popular brush shape was a cone, opaque in the center (alpha 1) and sloping steadily down to transparent at its circular edge (alpha 0). Suppose the current color is red. Then the red of the brush would be combined with whatever colors lay beneath the brush as the current location, using the alpha times f plus 1 minus alpha time b formula described earlier. In the case of Paint3, f is the red of the current color, and b is the color of a pixel already in the framebuffer. So red fully replaces the color in of the pixel under the center of the brush, where alpha is 1. The colors of pixels falling outside the edge of the cone aren't changed at all. And the colors of pixels under the sloping sides of the cone are mixed with the red of the brush according to the alpha value of the brush there, somewhere between 0 and 1.

385:*In designing our*: For space reasons, I've omitted all hardware and manufacturing personnel in Lucasfilm Computer Graphics from the main text. They were, in alphabetical order, Don Conway, Doug Hagemeier, Dennis Jennings, Bill Kaiser, Mark Leather, Adam Levinthal, Matt Martin, Jeff Mock, Lane Molpus, Tom Noggle, Glenn Sharp, Rodney Stock, Jim Wilson, and Bruce Young. Rodney Stock led the engineering group initially, then Jim Wilson took over. Doug Hagemeier led the manufacturing team. These people were crucial to the survival of Pixar. Later, at Pixar, Chuck Kolstad was important as vice president of manufacturing, and he served for a short time as CEO.

386:*I proposed to*: The two others present were Jim Blinn and Rodney Stock, and the hamburger café was in Ignacio, near Novato, in Marin County.

386:*I immediately got*: Siggraph, the Special Interest Group on Computer Graphics and Interactive Techniques, in the ACM, is a most important annual conference. It deserves a written history itself. It began in the early 1970s as a small academic conference. Under the leadership of Tom DeFanti, it exploded circa 1980 into a massive conference of twenty to forty thousand attendees annually, featuring a spectacular airing of each year's best computer graphics productions utilizing the best available audio-visual technologies (much of this before the Great Digital Convergence simplification). Its success is surely based on its continuing rich mix of business, entertainment, academia, and art.

Tom began his career studying real-time computer animation under artist Chuck Csuri at Ohio State University. His academic career has featured real-time applications, including video art, virtual reality, and CAVEs (all of these often done in conjunction with long-time collaborator Dan Sandin), at the University of Illinois, and now at University of California at San Diego. For

CAVEs, see *Wikipedia*'s entry for "Cave automatic virtual environment" (with a recursive acronym).

388:*At Lucasfilm Rob*: From Cook (1984), "Shade Trees," it's clear that he was inventing a language despite use of the word "trees" in the title. Meanwhile, Ken Perlin fresh from a stint at MAGI (a company discussed more fully later in this chapter), was working on the same idea, calling it a language, and taking it further than Cook by the time he published at Siggraph in 1985 [Perlin (1985)]. It was Perlin's PhD dissertation work at NYU.

392:*Neal Stephenson, Fall*: Stephenson (2019), 18. This should probably read "every object in the universe in the light cone of the observer" to take the speed of light into account. Escher's famous piece is called *Hand met Spiegelende Bol*.

394:*Ray tracing had*: Whitted (1980) reported work actually done in 1979. Email from Turner Whitted, Aug. 31, 2020: "Spheres and checkerboard, along with the movie, were shown as part of the paper presentation at Siggraph 79 in Chicago. Back in those days a couple of papers from each Siggraph conference were forwarded for publication in CACM. A thin supplement to the conference proceedings containing the Siggraph version of the papers was handed out to attendees, but supposedly avoided the problem of duplicate publication. | Publication of the spheres and checkerboard paper in CACM got delayed until June of 1980 partly because I was busy working with Jim Blinn to combine our two Siggraph 78 papers along with a non-Siggraph submission from Loren Carpenter and Jeff Lane into a January 1980 CACM paper."

Whitted (2018) said, "Ray casting for image generation had been pioneered by Arthur Appel [Appel (1968)}, at IBM, and commercialized by Robert Goldstein and associates [Goldstein and

Nagel (1971)], at MAGI. MAGI had originally utilized multi-bounce ray tracing to track radiation within tanks."

An excellent survey of the history of physically based rendering can be found in Pharr et al. (2018): "Physically based approaches to rendering started to be seriously considered by graphics researchers in the 1980s. Whitted's paper (1980) introduced the idea of using ray tracing for global lighting effects, opening the door to accurately simulating the distribution of light in scenes. The rendered images his approach produced were markedly different from any that had been seen before, which spurred excitement about this approach."

394:*Central Dogma renderings*: Unfortunately, hyperrealism has been taken by the art world to mean something like photorealism with emotion. Radiosity is another important contributor to realism that I don't further treat here. It adds colors to objects reflected from other objects, and came from research at Cornell. See also the *Wikipedia* page for Gilles Tran.

One of the most curious aspects of rendering within the Central Dogma is the honoring of camera artifacts as part of the proper representation of "reality." Thus artifacts such as circles of confusion, depth of field, and lens flare are simulated. These are important (particularly depth of field) in the case where computer-graphic images are mixed with real-world images taken by a camera—for example, in special effects for movies or in augmented or mixed reality. The art critic Blake Gopnik (and my brother-in-law) suggested to me, on Aug. 4, 2020, that the Central Dogmatic tendency to treat artifacts of camera technology "as necessary and natural features of representation, which of course they aren't. . . . [is] based on a desire on [graphics programmers'] part to appeal to the eyes of an audience trained on Hollywood films made with lenses and cameras."

394:*One of the*: Yellott (1983). I happened to stumble on this exciting article just as Rob Cook was explaining his new random sampling idea to me. The article that immediately followed it, Williams and Collier (1983), was also interesting, extending the Rhesus monkey results to humans. The yellowed *Science* pages that I tore out then and still have with me are covered with underlined portions such as this: "Thus, the visual system avoids the aliasing distortion of high frequencies inherent in any regular arrangement of image sampling elements and simultaneously minimizes sampling noise for low frequencies that fall within its potential Nyquist bandwidths [i.e., twice the highest Fourier frequency]."

396:*The math shows*: The math is explained in Cook (1986). [Math] The kind of randomness used is called *Poisson disk* randomness. The monkey retina photoreceptor distribution is shown in Yellott (1983) to have Poisson disk randomness. We got the Poisson disk terminology from this article.

396:*Consider the audaciousness*: Fur (and hair) was another modeling technology initially developed during the 1985–2000 Moore's Law steps. Kajiya and Kay (1989) introduced a scheme that, like particle systems, renders complexity without geometry. It combined three-dimensional texture maps with ray tracing to produce the eye-catching picture in figure 8.17.

Figure 8.17

The rendering of hair and fur continues to evolve. An instructive video about hair modeling in Pixar's *Brave* (2012) is online at https://www.khanacademy.org/partner-content/pixar/simulation/hair-simulation-101/v/hair-simulation-intro, accessed Feb. 19, 2020.

399:*A box filter*: Genius Jim Kajiya, while a professor at Caltech, generated "the rendering equation," the theoretically ideal way to render a scene [Kajiya (1986)]. Research continues to search for ways to efficiently compute the rendering equation.

399:*Ed Catmull, in*: Based on an original suggestion about "dithering" from Rodney Stock, one of Pixar's hardware engineers.

400:*Tom Porter, in*: *1984* was the cover of the July–Aug. 1984 issue of *Science84*, which is a lay magazine from the same society that publishes the scholarly journal *Science*, the American Association for the Advancement of Science.

Jim Blinn paid homage to 1984 with a 1985 computer animation in episode 15 of the wonderful science series *The Mechanical Universe*, online at https://www.youtube.com/watch?v=B44InZz-_pE&feature=youtu.be&t=591, accessed Feb. 19, 2020, at about 9:52–10:10 into the entire episode.

402:*After Ed Catmull*: Email from Tom Duff, Aug. 3, 2016: "I took my dad on a vacation trip to San Francisco in December 1979 . . . While we were there, I had a dinner with Ed [Catmull] at which we danced around the subject of whether he could hire me. It was pretty clear that he was excited about LFL [Lucasfilm Ltd.] but unwilling to say or do anything about hiring me for fear of Alex and Louis [Alex Schure's son, manager of the Lab] coming after him. | A few days after I returned to Long Island, Louis gave me a substantial raise, nearly doubling my salary, having decided for himself what the San Francisco trip was about. I waffled over what to do for a month or so and finally decided that if Ed wouldn't talk to me while I was still working at NYIT that I would just have to quit and take my chances. So one morning in January, having worked all night, I handed in my resignation when Louis came in, effective the beginning of July, and went home to Holloway House to get some sleep. | A few hours later, I was wakened by my phone ringing. A voice came on the line saying, 'Hello, this is Susan Anderson calling for Tom Duff. To whom am I speaking?' Only when I assured her I was who she was after did she say, 'Please hold for Ed Catmull,' and put Ed on the line. | Ed said, 'So I hear you've quit your job.' Louis had called him immediately after I had handed him my resignation letter, threatening to sue for hiring me away, and Ed saw no reason not to do what he'd been (wrongly) accused of. | We arranged for me to start at LFL the next January (1981), and I filled the time starting in July working for a small software company in Chicago (the Mark Williams Company) that had hired a bunch of my friends from U of Waterloo to implement a UNIX clone. Bob Swartz, the CEO of Mark Williams had called me while I was trying to decide whether to quit NYIT (again a phone call out of the blue and 'I hear you're leaving your job' when he had no way of knowing), and his offer of a temporary position helped push me over the line. | Eventually my LFL hire date got moved earlier, to November 1980. I remember leaving Chicago at the end of October with the first snowflakes of winter landing on my windshield as I backed out of the driveway." So Tom "laundered" himself through Mark Williams Company, and started at Lucasfilm in Nov. 1980.

Susan Anderson would be our administrative assistant and later Ed Catmull's second wife. She was later manager of buildings and operations at Pixar.

402:*Bill and Eben*: Eben Ostby recently retired (2019) from Pixar, where he had been vice president of software. He got a technical Academy Award in 1998 for work on an animation system and helped create many of Pixar's shorts, starting with *Luxo Jr.* (1985), and feature-length movies, starting with *Toy Story* (1995).

402:*Some things just*: Reeves (1983).

403:*Tom Duff, Bill*: This overly simplifies Blinn's decision process. According to a note from him Mar. 30, 2019, "the primary reason I returned to JPL was—Saturn. Voyager 1 had returned some great data about the Saturn system and I really wanted to make more pictures of Saturn using that data, and JPL was the only place to do it."

404:*Jim Blinn's Voyager*: This is a compressed version of the actual process of creating the shot. The full details are available in Smith (1982), an article written at the time for *American Cinematographer*.

The mountains cooling and turning green was accomplished by the appropriate choice of colors for rendering the fractal mountains. They changed as time elapsed. The sea rising was nothing more than a flat surface, replacing all fractal detail below a current notion of "sea level," and rendered an ocean blue.

405:*I knew a*: I must've been given this crucial insight by one of George's technical directors because I never knew George well enough to have deduced it on my own.

405:*And that's what*: The frame shown here does not appear in any Lucasfilm movie. It's a composite I made, front to back, from a fractal planet surface (with atmosphere) by Loren Carpenter, a cratered moon (before fractal growth) by Tom Duff, a texture-mapped earthlike planet by Tom Porter (using a painting made by Chris Evans), and a star field also by Loren. It's the time sequence of the Genesis Demo collapsed into one frame (with slight rearrangement to satisfy my esthetic choices). I call such a picture a "one-frame movie" because it's directed like a movie and features a cast of talented stars, also like one. I consider it my piece but it relies on creative elements from the cast.

406:*But the 1982*: *Star Trek II: The Wrath of Khan* was released on June 4, 1982, and *Tron* on July 9, 1982.

407:*The Moore's Law*: A sampler of the vibrant computer graphics effects industry in the early 1980s: Robert Abel and Associates, started in 1971 doing special effects for movies and moved into computer graphics effects in the early 1980s. R/Greenberg Associates (RG/A), 1977, would graduate to digital computer effects in the 1980s and become the future home to Ephraim Cohen. Digital Effects, 1978, was founded by Judson Rosebush, Jeff Kleiser, and others, the first computer graphics house in New York City. Pacific Data Images, 1980, and Digital Productions, 1981, are discussed in later sections. NYIT would turn the Lab into Computer Graphics Laboratory Inc. in 1981 after our departure. Cranston/Csuri Productions, 1981, came out of the computer graphics department at Ohio State University, directed by Chuck Csuri, an early computer artist featuring calligraphic art and exhibited at MoMA in New York. Omnibus Computer Graphics Inc., 1982, arose from a Canadian business group and eventually purchased Robert Abel and Associates and Digital Productions. Alias Research, 1983, later merged with Wavefront Technologies, founded in 1984, to become Alias/Wavefront. Duran Duboi, 1983, BUF Compagnie, 1984, and Thomson Digital Image, 1984, were founded in France. Computer Film Company, 1984, formed in London, was later acquired by Framestore, founded in 1986, also in London.

407:*The director Steven*: "Former Disney CEO Ron Miller recalls his own 'Tron' legacy," by Leo N. Holzer, Dec. 15, 2010, http://jimhillmedia.com/guest_writers1/b/leo_n_holzer/archive/2010/12/15/former-disney-ceo-ron-miller-recalls-his-own-quot-tron-quot-legacy.aspx, accessed Feb. 19, 2020. Miller was president of Walt Disney Productions starting in 1978 and was promoted to CEO from 1983 to 1984. He is recently deceased (Feb. 9, 2019) [Ron Miller, Former Disney CEO and Walt's Son-in-Law, Dies at 85, by Thom Geier, Feb. 10, 2019, https://www.thewrap.com/ron-miller-disney-ceo-walt-son-in-law-dies/, accessed Feb. 19, 2020].

Bonnie MacBird, who co-wrote the story for *Tron* (1982) with Steven Lisberger, would marry Alan Kay.

407:*The digital production*: The *Tron* Bit scenes reportedly occupy about two minutes. A Bit scene can be seen at *Tron – Bit*, https://www.youtube.com/watch?v=BbBqPkdheFg&feature=youtu.be, accessed Apr. 5, 2020. It's about 43 seconds long, including substantial intercutting with live-action (only) footage. But no matter how measured, the computer graphics screen time in *Tron* exceeds that of *Trek*. See Sorensen (1983) for a detailed discussion of *Tron* production.

Email from Jim Blinn, Jan. 23, 2022, "The character of the 'bit', which you described on page 407 of your book as being blue and yellow, was actually and a yellow octahedron for YES and a *red* stellated-something-or-other for NO, with a blue shape as the quiescent state between them. (I actually thought that was a kind of dumb representation of a bit.) See about 59 minutes into the movie. Sorry I didn't catch the color problem in my proofreading." I checked the YouTube snippet listed above, and Jim is correct.

Email from Ken Perlin, Feb. 17, 2019, "I think the decision on the part of Richard Taylor [visual effects director, Robert Abel and Associates] to go with simple Phong (not Gouraud) shading was both aesthetic (so it would better match the physical painted sets) and practical (because our ray tracer was slow)."

407:*The most memorable*: The *Tron* light cycle sequence can be seen at *Tron (1982) – "Light Cycle Battle,"* https://www.youtube.com/watch?v=-BZxGhNdz1k, accessed Feb. 20, 2020. At about 0:29 into the 3:05 minute sequence, a wireframe representation of a light cycle is rendered into colored and simply shaded polygons. This is the frame grabbed for figure 8.12.

See also *Toon Story: John Lasseter's Animated Life*, by Mike Lyons, *Animation World Magazine*, issue 3.8, Nov. 1998, https://www.awn.com/mag/issue3.8/3.8pages/3.8lyonslasseter.html, accessed Apr. 5, 2020; *What Will Tron: Legacy's 3D VFX Look Like in 30 Years?*, by Anne Thompson, *Popular Mechanics*, Dec. 9, 2010, https://www.popularmechanics.com/culture/movies/a11706/are-tron-legacys-3d-fx-ahead-of-their-time/, accessed Apr. 5, 2020.

408:*Mathematical Applications Group*: MAGI was founded by Philip Mittelman. The graphics group, MAGI/SynthaVision, was started by Robert Goldstein, with Bo Gehring specializing in design and Larry Elin in film and television. Larry Elin hired Chris Wedge.

The 1984 MAGI demo reel is at *MAGI Synthavision 1984 Demo Reel*, https://www.youtube.com/watch?v=Ivk_LPQP6Ag&feature=youtu.be, accessed Apr. 5, 2020. The credits are a who's who of this early company: John Beach, Tom Bisogno, Jan Carlee, Christine Chang, Martin Cohen, Larry Elin, Paul Harris, Carl Ludwig, Gene Miller, Tom Miller, Ken Perlin, Joshua Pines, Herb Steinberg, Eugene Troubetzkoy, and Chris Wedge, with special thanks to (founder) Phil Mittelman. See also the MAGI demo reels for 1974, *MAGI/SynthaVision Sampler (1974)* [https://www.youtube.com/watch?v=jwOwRH4JpXc&feature=youtu.be, accessed Apr. 5, 2020] and 1980, *MAGI Synthavision Demo Reel (1980)* [https://www.youtube.com/watch?v=lAYaX6NuI4M&feature=youtu.be, accessed Apr. 5, 2020].

408:*The historical flows*: The 1984 MAGI demo reel (see the preceding note) contains the Wild Things test at 1:28–2:04/3:22. For this project MAGI created a scan-and-paint system much like the one created in the late 1970s at NYIT. It excelled in several ways: It had an airbrushed look to the "opaqued" areas and handled shadows, despite being a two-dimensional system principally. There are many details to be found in Ken Perlin's blog at http://blog.kenperlin.com/?p=2314, accessed Apr. 5, 2020.

Ken Perlin, email Feb. 17, 2019, "The 'Wild Things' test originated in a brainstorming meeting I had with John Lasseter at Disney headquarters a few months after the release of TRON. I showed John some image processing techniques I had come up with at MAGI so he could see that this was possible, and then John and I agreed that he would lead a content team and I would lead a technical team. Disney and MAGI both signed off on our hare-brained scheme, and the rest is history." Perlin was a MAGI employee 1979–1984, worked on *Tron* (has a credit in it), and has taught computer graphics at New York University for many years, where he founded and directs the NYU Media Research Lab. He won a technical Academy Award in 1997 for his graphics achievements, including one called Perlin noise.

409:*Chuang learned computer*: Chuang (2006), and a note from Jim Blinn, Mar. 29, 2019, "Last Siggraph Richard Chuang told me that he learned computer graphics from watching the videos of the Berkeley course that Ed and I and you and Loren taught." Chuang, email Mar. 31, 2019, verified Blinn's account, "Yes. I learned real 3D CG from that class while I was an engineer at HP's RF & Microwave Lab in Palo Alto. It was broadcast live over microwave from Berkeley to HP." Also informed by conversations with Glenn Entis, who mentioned that in Ed Catmull's class at NYIT, one of the classes was taught by Lance Williams and another by me. Another member of this class was Gene Miller, a contributor to early computer graphics at MAGI and Digital Effects, working on *Tron*. He married the artist Darcy Gerbarg.

Glenn Entis, email Sept. 2, 2018, "I started at Ampex late 1980, working on your code, until I left to help start PDI in April 1982. Tom [Porter] overlapped with me for a month or so – long enough to train me on your code, before he re-joined the band at Sprocket [Lucasfilm]. That was where I met Rodney Stock, Adam Levinthal, Mark Leather, etc. Also, years later, I gave a deposition for the good guy UK legal team challenging Quantel's patent on alpha blending. The question was – did I recall and understand your published work on that topic (answer: 'yes')." Stock, Levinthal, and Leather later became hardware engineers at Pixar.

409:*John Whitney Jr.*: See Wayne Carlson's extensive computer graphics book, Carlson (2017), 180-185, for Digital Productions details. See also Demos (2005).

From a Skype conversation with Ivan Sutherland, May 9, 2017: "I invested in his [Gary Demos's] company." In a subsequent Skype conversation, Jan. 23, 2018, he told me that he thought his investment was equity, but Whitney and Demos treated it as a loan, to Ivan's dismay.

Bob Sproull, in an email of July 25, 2019, states, "I believe I contributed to writing the business plan for Digital Productions, probably at the suggestion of and along with, Ivan Sutherland. But I have no idea whether anything I wrote ever was used."

In a phone call, Demos told me that John Whitney Jr. was also supposed to be part of Sutherland's Hollywood company, as a marketing person. I didn't get validation of this from Sutherland, however.

410:*Ed and I*: Coppola invited me down to his studio in Los Angeles while making *One From the Heart* (1982). He had reconstructed downtown Las Vegas on a sound stage there, with fake casino marquees ablaze with thousands of blinking lightbulbs. He hosted a giant banquet on this set, with large circular tables scattered throughout the streets of "Las Vegas." Teri Garr starred in the movie.

410:*We thought they*: The *Westworld* (the movie, not the TV series) contribution was a pixelated world view, it still being assumed that pixels were little squares, and computers would see it that way. Thus it was not a Digital Light advance—a retreat really [Price (2013)].

Email from Ed Catmull, Mar. 19, 2019, "My hand film was actually a class project in my first year of graduate school."

410:*John and Gary*: IMDbPro, *Looker* (1981), https://pro.imdb.com/v2/title/tt0082677/details, accessed Apr. 5, 2020.

411:*I will never*: Mike Seymour, *Founders Series: Richard Chuang PDI to Cloudpic*, https://www.fxguide.com/fxfeatured/founders-series-richard-chuang/, accessed Apr. 5, 2020. This is a good summary of Richard's career.

411:*John and Gary*: Digital Productions claimed 27 minutes of the *The Last Starfighter* were computer generated. I have a paper in my possession, "Analysis of 'The Last Starfighter,'" dated Aug. 27, 1984, by Loren Carpenter. In it, Lucasfilm whiz Loren analyzed every frame of the film and found 12.1 minutes of three-dimensional computer-generated imagery and 5.3 minutes of simpler two-dimensional effects. Loren, in an email, June 12, 2018: "Somebody at ILM [Industrial Light & Magic, the special effects division of Lucasfilm] got a release print and we put it on a Kem [film editing machine] . . . The 27 number must (might) have been what they delivered to the editor." The purpose of the paper was to estimate what Digital Productions was charging per second.

411:*Although we rendered*: Craig Reynolds, who famously introduced flocking (as in birds flocking and fish schooling) to computer graphics, suggested the No Jaggies logo concept. On 12 Dec. 2020, Mary Whitton sent me a photograph of a No Jaggies T-shirt in her collection (figure 8.18), apparently never worn. It is clearly signed "© C. Reynolds 1981" just under the logo.

Figure 8.18

Craig Reynolds remembered the history of this logo in an email of 13 Dec. 2020:

"The history as I recall is that around that time (~1980) I was struck by the ascendance of anti-aliasing work, how point sampling just didn't cut it any more, and how our rendering at triple-I was embarrassingly behind the times. I have a vague sense that it might have been triggered by an issue of CACM (that had a simple rendered image on the cover?) and one or two papers about graphics. Or it might have been in the aftermath of a conference. Anyway I felt 'we' ought to have a firm policy against tolerating aliasing in 'our' images. (We = triple-I or the SIGGRAPH community in general.) This led to thinking about using the (then relatively new?) prohibition symbol to create a 'no aliasing' icon. I drew the design by hand on some graph paper. Some time later I sent it (perhaps a photocopy?) to Pat Cole . . . This was during the time Pat was working at [Lucasfilm].

"Then the history was mostly out of my hands. She or other [Lucasfilm graphics people] decided this ought to be on a tee shirt. I think she asked me for permission, they were printed, then distributed at the next SIGGRAPH. Since I never throw anything away. I may well have that original sheet of graph paper somewhere. I suspect I wrote my name and date on the sheet. But asserting a copyright does not sound like the kind of thing I would have done . . . Probably, Pat just thought she was 'doing the right thing' by acknowledging my authorship and adding the ©."

Jim Blinn cleverly paid homage to the No Jaggies logo in episode 3 of *The Mechanical Universe*, online at https://www.youtube.com/watch?v=szCChCc58dg&feature=youtu.be&t=495, accessed Apr. 5, 2020, at about 8:15–8:19 into the entire episode.

413:*According to Ed's*: John Lasseter visited us at Lucasfilm in Feb. 16, 1983, according to an audio diary entry that date made by Ed Catmull (email Mar. 19, 2019) which mentions "John somebody who was an animator in charge of this new film, The Brave Little Toaster." This matches my daytimer entry "DISNEY" for the same date. Christine Freeman, Pixar archivist, has found another visit by John to Lucasfilm on May 11, 1983 (also from one of Ed's audio diary entries). Again, my daytimer backs this up with Disney meeting on that date: "disney 2." But the Disney archives meeting was so emotionally powerful to us that John Lasseter's name only then burned itself into our brains. It's inconceivable that we wouldn't have recognized him after that wonderful event. Ed didn't recognize him at the Feb. 16 meeting—he was "John somebody'—impossible if the archives meeting had already occurred. And although I attended the Feb. 16 and May 11 meetings, I have no memory of them, consistent with John's not having yet made an impression on me, as he definitely did at the (clearly later) archives meeting.

413:*Luckily, a couple*: In fact, although John was verbally fired, Disney softened somewhat and continued to employ him until the Wild Things test was done, with the understanding that he was gone after that. Paik (2007), 39–40, covers this story, but with this correction: *The Road to Point*

Reyes picture was completed in Apr. 1983 so couldn't have influenced John as reported there. The bulk of *Point Reyes* was done Apr. 2 to May 6, 1983, increasing its resolution from 1 framebuffer's worth to 16 framebuffers' worth (.5K by .5K up to 2K by 2K) so John could have seen the finished, high-resolution result on his second meeting, May 11, 1983.

413:*There was only*: I received Lasseter's first sketches for *André & Wally B.* on Oct. 19, 1983, in an envelope apparently mailed to me from Walt Disney Productions in Burbank. This suggests that he had not quite yet joined us. In a stack of sketches were a reimagined André and several suggestions on how to model him from ellipsoids. So he was aware of the project and was intent on making a contribution. This is consistent with my daytimer entry "John Lasseter" for Oct. 12, 1983, and the week of Nov. 7–11, 1983, blocked out for "John." Also, my entry for Feb. 6, 1984, is "John Lasseter 2 months." So he was off and on until sometime probably early in 1984 when he became permanent.

416:*A little-known*: Laurin Herr, president of Pacific Interface Inc. which specializes in business between American and Japanese companies, discussed with me just before Siggraph 1984 the possibility of "a movie either based on the Stone Monkey fable or a story dealing with the Oriental concepts of the cosmos, similar to the TV series done by Carl Sagan several years ago . . . Dr. Smith replied that he was familiar with the Stone Monkey fables and was certainly interested in hearing more about the project" [from a report to the Japanese from Herr, dated Sept. 27, 1984, and addressed to Ed and me]. [All documents mentioned in this annotation are in my possession.] The report further mentions our meeting at Siggraph (July 1984) and the premiere of *Andre & Wally B*. Shogakukan sent a formal letter of agreement to proceed on Oct. 6, 1984, via Herr. Ed and I sent a formal letter Oct. 11, 1984, to Laurin confidentially informing him (and thus Shogakukan) that we were starting a new company and that Monkey would be an appropriate first production. Shogakukan management visited Lucasfilm Dec. 17, 1984. From an Herr report, dated Aug. 16, 1985: We [meaning as I recall Loren Carpenter, John Lasseter, and myself, with Herr translating] met with Shogakukan representatives in Monterey, CA, in July 27–30, 1985, to review three treatments that had been separately prepared for the movie's story. Also noted in that report: Carpenter had been involved in story treatment meetings preparatory to Monterey. From further Herr reports, Carpenter and Lasseter were heavily involved in deeper story development at various meetings in Dec. 1985 and Jan. 1986.

416:*People representing the*: The Monkey King (Sun Wu Kong) is an ancient Chinese storybook character. Hundreds of tales are told to Asian children about Monkey, a character who is too young to handle his godlike powers. The mismatch always leads him to high mischief and dire trouble. Almost every person from China, Japan, Korea, or Malaysia I've asked has known about Monkey. Lance told me to think of Monkey as the Asian Mickey Mouse, which isn't at all accurate but does measure the cultural impact of both. I spent a month in China in 1978, as part of a US delegation of computer scientists, and returned laden with twelve volumes of Monkey stories and drawings.

I was a member of the IEEE Computer Society Delegation to the People's Republic of China, Sept. 29–Oct. 18, 1978, visiting Beijing, Nanking, Shanghai, Wuxi, Hangchow, and Kuangchow, featuring eighteen banquets, including dinner with the Chairman of China, Hua Guo Feng, in the Great Hall of the People on Tiananmen Square, Beijing, Oct. 1, 1978. In a letter from me to my parents, in my possession, dated Oct. 3, 1978: "Our delegation dined with Chairman Hua at a state dinner two nites ago." I also have the 120-page report of the delegation's trip. We entered via Tokyo and departed via Hong Kong for a total trip duration of one month.

419:*I argue this*: There are competitors to the naming of this "law." Another name is "Crow's Law," named for Frank Crow. He presented a talk at Siggraph that showed the average frame of a Siggraph show film was computed (produced) in the same time but that the number of polygons and cpu cycles rose on a power curve similar to Moore's Law.

419:*George and Marcia*: This is a simplification of a complex series of reorganizations, spinoffs, joint ventures, product sales, and other business dealings. For example, Lucasfilm Games became a separate organization within Lucasfilm in May 1982 and became LucasArts in 1990, according to the LucasArts *Wikipedia* page, accessed Sept. 5, 2018. One of its earliest games was *Rescue from Fractalus!*, released Mar. 1984, featuring work by Pixar fractal expert, Loren Carpenter. Two business associates at Lucasfilm who helped us through this process were Bob Doris and Mary Sauer, who later became cofounders, with Andy Moorer, of Sonic Solutions, a 1987 startup by the developers of Lucasfilm's SoundDroid.

The Droid Works technology was integrated into Avid Technology by 1993.

419:*Ed immediately agreed*: The left book is Purcell (1983). There's a sticker inside its front cover for the Cottage Bookshop, San Rafael, CA, which was a popular bookstore on Fourth Street until it closed in 1986. I'm almost positive that the bookstore we visited that day was The Clean Well-Lighted Place for Books in Larkspur Landing, but that sticker suggests my memory is wrong. I hypothesize that Clean Well-Lighted Place had purchased inventory from Cottage Bookshop. Right is Levin (1983). I've lost my copy but I found this one online. It was most recently reprinted in 2013.

419:*"What will the*: We did examine the deep details of a digital effects and commercials house before understanding its limitation. I have in my possession a document "GFX Inc. Animation Services Business Plan," dated Jan. 1985. It's a detailed business plan for the "strength in computer animation of the current group." The listed competitors for commercials were, in decreasing order of perceived strength, Digital Productions, Robert Abel, Omnibus, Cranston/Csuri, Pacific Data Images, MAGI. An 18-page appendix, "Animation Production Requirements," dated Dec. 7, 1984, by myself, Bill Reeves, John Lasseter, and David DiFrancesco, served as the fundamental costing document.

420:*And, we had*: I called my friend and homeboy Jim Clark, one of the few people I knew who had actually started a company—a hardware company in fact. He'd cofounded Silicon Graphics Inc. "How do we do it?" I asked Jim. "Ah, Alvy," he said in his West Texas drawl, "It's *real* easy. It'll take you about a year to learn all the words and then you'll have it." I should've noticed that he didn't volunteer to invest. In Fisher (2018), 198, Jim Clark is quoted about this event: "How do you tell a good friend: 'Hey, you have got a shitty idea!' I was not going to tell them that."

421:*Finally, it came*: "then" should be "them" in the last sentence of this paragraph (typo caught by reader Rishi Chopra, email Oct. 6, 2022).

422:*The first idea*: A document titled "Potential Investors III," dated June 21, 1985, in my possession lists 36 venture capital and investment banking firms approached.

422:*Then we turned*: A document titled "Potential Investors I," dated June 21, 1985, in my possession lists 10 corporations, or groups of corporations, which had stated interest at that date, including GM ("Head of CAD/CAM visited 6/20. Very positive") and Philips ("Technical people from Holland will come next week").

422:*We dealt with*: Perot ran for US president unsuccessfully in 1992 and 1996.

In preparation for the first meeting at Lucasfilm with the GM representatives, the Lucasfilm business managers tried to get Ed and me to lay off employees to lower salary expenses for a potential funder. We refused, understanding that it was the talented people that a funder wanted, not the technology that changed every few months. We told Lucasfilm to fire us instead and won the point.

422:*Then Philips decided*: Drebin, Carpenter, and Hanrahan (1988) describes a novel volume visualization rendering technology based on voxels, which are three-dimensional samples of the real world (*not* little cubes!) The idea was so powerful that it led the National Library of Medicine to institute the Visible Human Project, the first three-dimensional database of the full volume of a real human being. I served as a Trustee of NLM (1988–1992) during the first years of this project, a completely unexpected honor. This was image processing, not computer graphics. It was sampling taken into the next spatial dimension and definitely part of Digital Light.

422:*It came down*: My calendar for 1985 has “NY” written across Nov. 6 with the day before empty. I have the signed letter of intent with GM et al., dated Nov. 7. My calendar has Philips at Lucasfilm on Nov. 13 and 14 and EDS present all day Nov. 15. Apparently, there was an attempt to salvage the GM-Philips deal. I have a stack of seven letters, signed by Ed Catmull, all dated Nov. 18, 1985, asking for a decision by Dec. 16, 1985. These were addressed to seven outstanding local VC firms asking for interest in coinvesting with GM and Philips. I don’t believe they were sent. The revised deal was to be $5 million for each of GM and Philips and $2 million for an additional VC. GM and Philips would own 25 percent each, the VC 20 percent, and the employees 30 percent.

422:*But the deal*: For years I told the story this way: On the very day of our meeting with GM downtown, Perot was telling the GM board of directors uptown that they had made a big mistake with Hughes. But pesky reality says otherwise. The Perot versus GM day was Nov. 4, 1975. My story was off by two days, but the effect was the same. See Levin (1989), 250–261, for a blow-by-blow description of Perot's unprecedented attack on the GM board and its president Roger Smith.

The evidence that objections weren't raised at GM board meetings comes from Levin (1989), 251, "as far as he knew, no one had voted against anything in a GM board meeting since the Depression," and 255, "If there is any spirited discussion or dissent over an item to be decided by directors, it normally occurs in the committees. By the time an item of business reaches the full GM board for approval, it is more a formality or a news item than a question still to be debated."

John von Neumann's daughter, Marina von Neumann Whitman, was eventually on the board at GM, the first woman. I learned in an email exchange with her in May 2013 that she wasn't on the board at the time of the Perot clash and hadn't known about the potential deal with Lucasfilm/Pixar.

423:*The deal was*: All forty of the original employees of Pixar can be found at http://alvyray.com/Pixar/, accessed Apr. 5, 2020, from my personal bound copy of Pixar's founding documents (three volumes) in my possession. There were five such copies: one each for Ed and me (with our individual names emblazoned in gold on our respective copies), one for Lucasfilm, one for Steve Jobs, and one for the attorneys. Ed and I signed each important signature page representing Pixar, Jobs signed representing the investor, Doug Johnson signed for Lucasfilm. The list of forty founding employees, including Ed and myself, and their percentage ownership in Pixar is listed in Pixar's 1986 Stock Purchase Plan, Schedule B-1, a copy of which is in my possession.

424:*We kept the*: Emphasis on flows from the past, and a lack of space, has kept me from mentioning several other key Pixar people on the software side in the early days: Bob Drebin and Charlie Gunn were founding employees of Pixar. Sam Leffler was a founding employee and our chief Unix guru. Leffler was a principal creator of so-called Berkeley Unix, and was one Unix whiz who remained true to systems, not graphics, software. Mark Leather, a hardware engineer (so otherwise omitted), was a founding employee and wrote an exceptional "layer paint" program in addition to helping develop the Pixar Image Computer.

Between Pixar's founding on Feb. 3, 1986, and Dec. 31, 1986, the date of an organization chart in my possession, we were joined by other notable graphics programmers: Pat Hanrahan, H. B. Siegel, Steve Upstill, and Paul Heckbert. The aforementioned Bob Drebin, with Loren Carpenter and Pat Hanrahan created Pixar's novel volume visualization technique that so impressed the medical division of Philips that they almost funded Pixar (with GM) [Drebin et al. (1988)]. Pat Hanrahan created the all-important interface to RenderMan, and has had a very successful career as Stanford professor and entrepreneur (cofounder of Tableau Software). Steve Upstill wrote *The RenderMan Companion*, explaining it all for the first time [Upstill (1990)].

Other notable programmers with us at Lucasfilm but who didn't join Pixar were (1) David Salesin (1983–1985), who helped with *Andre & Wally B.* and other shorts, worked briefly at Pixar in 1987, and has had a remarkable career at leading companies, and (2) Michael Hawley (1984–1986), who also has had an outstanding career at MIT's Media Lab and other leading places, and produced, until his recent death, his own annual conference EG (Entertainment Gathering).

424:*The fifth jewel*: The list of films produced on CAPS is online at *Wikipedia*, Computer Animation Production System, accessed Sept. 2, 2018. The last use of CAPS was in 2004. As mentioned in the Movies and Animation chapter, Tom Hahn led the CAPS implementation team at Pixar. Also in the group were Michael Shantzis and Peter Nye.

425:*But Pixar was*: My journal entry for Mar. 6, 1991: "3/6/91 Board meeting at Next . . . 'NEW PIXAR' formed, owned 100 percent by SJ [Steve Jobs]." I have in my possession a copy of the formal plan of that date. The "refinancings" preceding this one took the form of increased debt of Pixar to Jobs totaling finally about $40 million, the effect of which was dilution of employee equity. In other words, as the excessive debt continued to increase, the more unlikely it became that employee equity would ever be worth anything. Chuck Kolstad, during his tenure as Pixar's CEO, came up with the idea of freeing Pixar of this tremendous debt, essentially a swap of Pixar's debt to Jobs for all employees' equity. This resulted in the Mar. 6, 1991, deal and Chuck's resignation that same date. My journal entry for Mar. 21, 1991: "it was Chuck's idea to convince Steve to relieve Pixar of $40M debt . . . Chuck dreamed it up, worked on it very hard with tax people, lawyers, and accountants—and then got his head cut off when Steve did it. Of course, SJ presented this 'gift' as his idea to Pixar."

Christine Freeman, Pixar archivist, found evidence of one of the dilutions, email Apr. 18, 2019: "They [Pixar Finance] found me board minutes from May 25, 1989, in which a new stock plan was created. It was 'deemed in the best interests of the corporation to sell and issue 2,800,000 shares (the "Shares") of the corporations Common Stock to the person named below (the "Purchase") at a price of $ .18 per share . . .' The notes go on to say that Steve had told the board that he'd guaranteed $22 million in loans in the past and was 'willing to provide additional guarantees on the condition that the Company provide NeXT with non-exclusive licenses to certain aspects of the Company's Renderman technology,' and then it indicates that he was going to provide the Board with a proposal 'outlining the terms on which he would continue to provide the Company with loan guarantees for working capital purposes.' From Ed's notes at the time there was also new stock issued which resulted in 90 percent dilution."

425:*Jim Lawson, co-developer*: Jim Lawson, email Apr. 2, 2019.

425:*Pixar's sixth and*: RenderMan was coined by Pixar engineer, Jeff Mock. The analog Walkman was introduced in 1979 and reached its highest popularity between 1987 and 1997, selling during its lifetime 385 million units [*Wikipedia* entry for Walkman, accessed Apr. 3, 2019]. It was the predecessor of digital audio devices such as Apple's iPod, released at the millennium (2001) [*Wikipedia* entry for iPod, accessed Apr. 3, 2019]. RenderMan was announced in May 1988 ["Renderman Interface to Link Modeling, Rendering Packages," *Infoworld*, May 23, 1988, p. 6, https://books.google.com/books?id=4T4EAAAAMBAJ&pg=PA6&hl=en#v=onepage&q&f=false, accessed Apr. 5, 2020].

In the same vein, I wrote a pixel imaging language at the time and called it *IceMan*. Ice stood for Image Computation Environment.

425:*The path to*: Email from Rob Cook, June 1, 2019: "Loren designed and wrote the first renderer called Reyes in 1981 just before I was hired. It's the one that was used for rendering the mountains in the Genesis Effect. The second renderer called Reyes was co-designed by the two of us in 1982–1983, and as far as I know the first one was never used again after 1983. This 1983 Reyes is the renderer described in our 1987 paper, and it's the one that Pat [Hanrahan] and Jim [Lawson] built a RenderMan interface for. Loren designed the overall micropolygon approach, and I designed the shader and hider (with Monte Carlo sampling), but we actively debated and discussed all aspects of the work. I did 100 percent of the coding for it because Loren was off writing his Fractalus game. In early 1984 we worked together to port it to the Cray."

426:*The person who*: Pixar was founded Feb. 3, 1986. Hanrahan was hired Mar. 12, 1986. Although not one of the forty founding employees, he was definitely there in the early days of the company. He departed Pixar on Apr. 28, 1989, for a faculty position at Princeton.

427:*The tradition of*: Hanrahan and Lawson (1990). Pat Hanrahan in his 1989 introduction to Upstill (1990) gives credit to almost everyone in software at Pixar in the development of RenderMan.

427:*Creating a good*: A comparably successful standard is Adobe *PostScript*, by John Warnock and Chuck Geschke, which formalized two-dimensional geometry and enabled the desktop publishing industry. The predominance of the .pdf file type, built atop PostScript, is evidence of the standard's success.

427:*RenderMan, published in*: Upstill (1990), vii, gives full credit to the architect of RenderMan, Pat Hanrahan, and to the "RenderMan Mafia," consisting of Tony Apodaca, Darwyn Peachey, and Jim Lawson.

427:*And the industry*: Email from Loren Carpenter, Sept. 3, 2018, "The Oscars (2001) were for the computer science that led to movie quality cost-effective rendering technology. Mine was mostly for the Reyes algorithm, Rob's was for programmable shading and sampling, and Ed's was for a lot of really basic stuff like curved surface math." The complete list of winners of the technical Academy Award for RenderMan in 1993 were Loren Carpenter, Rob Cook, Ed Catmull, Tom Porter, Tony Apodaca, and Darwyn Peachey. The Coons Award went to Ed Catmull in 1993, Pat Hanrahan in 2003, and Rob Cook in 2009.

428:*But I had*: Isaacson (2011), 244–245. I used different words and more detail to describe the event to Isaacson, but his rendition, apparently double-checked with other people who were present, is close enough to give the gist of this personally shattering event. My version can be found at http://alvyray.com/Pixar/documents/The_Whiteboard_Incident.pdf. The only word I object to in Isaacson's version is "sneer." I was much too frightened to sneer.

429:*Ed Catmull closed*: My 1991 journal states:, "7/1/91 Mon. Pixar & Disney sign movie agreement! We celebrated w[ith] champagne today @ Pixar. Becomes public info next Mon." Also from the journal: "9/9/91 Mon. Lisa [Ellis] pays me last Pixar check. I start packing my office." Also: "Signed the deal!!! [Altamira funded by Autodesk] 9/6/91 Fri."

The mention of Pixar stalwart Lisa Ellis reminds me of another large swath of Pixar founding employees and co-owners not otherwise represented in this book but fundamental to the early events herein. These came with us from Lucasfilm: Neftali Alvarez, Annie Arbogast, George Cagle, Susan Anderson Catmull, Shannon Collins, Lynn DeKeyser, Janice Diane, Lisa Ellis, Craig Good, Pam Kerwin, David Johansen, John Seamons, Deirdre Warin, and Sara Wright. These represent administration, animation services, finance, human resources, maintenance, marketing, operations and facilities, and sales departments. Barbara Koalkin and Kay Seirup (Kay with us for a while at Lucasfilm) were early at Pixar in marketing. Bill Adams was early at Pixar as vice president of sales. This is not an exhaustive list. Beth Sullivan was with us at Lucasfilm then joined Pixar a couple of months after its founding.

429:*Jobs saw this*: The patent was US Patent No. 4,897,806, Pseudo-Random Point Sampling Techniques in Computer Graphics, inventors Robert L. Cook, Thomas K. Porter, and Loren C. Carpenter, assignee Pixar, issued Jan. 30, 1990.

Microsoft asked me, soon after I joined in 1994, to break the Pixar motion-blur patent. I told them [in my paper "Analysis of the Pixar Patent on Stochastic Sampling for Computer Graphics," May 15, 1995, in my possession] that the patent was a good one and couldn't be broken. Microsoft then asked several respected computer graphicists at Microsoft Research for help. Jim Kajiya, in particular, when asked if he could break the patent, replied in my presence, "No, I tried to solve the problem that Pixar solved and couldn't do it." The other experts said similar things. The result was that Microsoft paid a license fee of several million dollars to Pixar for the patent. And so did SGI, Jim Clark's company.

430:*PDI created several*: Online see PDI pieces *Opéra Industriel* https://www.youtube.com/watch?v=qLEg_P5Crt0&feature=youtu.be, *Burning Love* https://www.youtube.com/watch?v=O7SycLUH-NM&feature=youtu.be, and *Locomotion*, https://www.youtube.com/watch?v=gATcdqgkWVA&feature=youtu.be, all accessed Apr. 5, 2020. Also, 38 videos from PDI are available at *PDI Historical Compilation*, https://www.youtube.com/playlist?list=PLJv789O10fmzl_YpDecrd3wI1qUg7XD4M, accessed Apr. 5, 2020.

430:*Not giving up*: Darnell was trained in the Experimental Animation program at CalArts. Lasseter and Bird were in the Character Animation program. See Darnell's *Gas Planet* online at YouTube, https://www.youtube.com/watch?v=GOHSL250wwQ&feature=youtu.be, accessed Apr. 5, 2020.

430:*In 1994 Jeffrey*: Dreamworks SKG was founded Oct. 12, 1994, with a $500 million investment from Microsoft cofounder Paul Allen.

430:*DreamWorks SKG bought*: According to *Wikipedia*'s entry for Pacific Data Images, accessed Mar. 19, 2019, DreamWorks's original position in PDI was 40 percent. In *Wikipedia*'s entry for DreamWorks Animation, accessed Mar. 19, 2019, DreamWorks took a 90 percent position in PDI in 2000.

Dreamworks brought out another animated movie shortly after *Antz* (Oct. 1998): *The Prince of Egypt* (Dec. 1998) used both two-dimensional and three-dimensional animation.

430:*PDI and DreamWorks*: Sito (2013) is devoted to computer animation. It expands more fully on PDI and Dreamworks (and other facilities) than I do and should definitely be consulted for further information. See particularly chapters 12–14.

431:*Chris Wedge, director*: From a TEDxOrientHarbor talk at Orient, NY, Sept. 17, 2017, *Bigger Than the People Who Made It*, by Chris Wedge, published Nov. 10, 2017, https://www.youtube.com/watch?v=MFu80MB2tGw&feature=youtu.be, accessed Apr. 5, 2020, 14:19–14:51.

431:*Meanwhile, Wedge was*: *Bunny* can be viewed at https://www.youtube.com/watch?v=Gzv6WAlpENA&feature=youtu.be, accessed Apr. 5, 2020.

431:*Ice Age (2002)*: The full list of cofounders of Blue Sky Studios is Chris Wedge, Carl Ludwig, Eugene Troubetzkoy, Alison Brown, David Brown, and Michael Ferraro. The company is now located in Greenwich, Conn., and owned by 20th Century Fox (in turn owned by 21st Century Fox).

433:*As for tyrants*: Eventually Schure's own children forced him out of NYIT, blaming the financial straits of the school on his investment in the Lab. Decades later, in 2011 at a Manhattan dinner, the then president of NYIT, Edward Giuliano, accused me of the near financial failure of NYIT (now a successful worldwide university). "But, Ed," I insisted, "Schure never let us see the books. We had no idea of where the money came from, nor did we control the budget." He relented, because it was true. Giuliano had brought the school back from the brink. Ed Catmull and I estimated that Schure invested about $15 million, at least, in the Lab, or about $36.5 million in today's dollars. There were smatterings of income from commercials, TV spots, and short animations, but no profit since NYIT was a non-profit organization at the time.

Roy Disney used his family influence twice (and board position once) to overthrow the managements of Disney. The first restructuring brought in Michael Eisner and Frank Wells in 1984, who proceeded to do the CAPS deal with Lucasfilm (inherited by Pixar) in 1986. The second brought in Bob Iger in 2005, who finally had Disney purchase Pixar in 2006.

433:*Steve had nothing*: Fisher (2018), 203. Perhaps Steve Jobs's most puzzling move was to support the production of *Tin Toy* (at Lasseter's urging) and other shorts even though the company was burning through *his* money and the productions just added to the loss. Some say—and he certainly claimed later—that this was his vision. But I never ever heard an articulated vision from him about movies. I suspect it was more of a gut hunch: Something that looks that good must be worth something somehow. If it was, then it paid off spectacularly for him. Nevertheless, he would have sold Pixar in a trice for $50 million during the pre-*Toy Story* days to free himself from the financial losses.

433:*But Jobs leapt*: The offending phrase from the Pixar IPO prospectus of Nov. 25, 1995, 47: "Mr. Jobs is the founder of Pixar and has served . . . as its Chief Executive Officer since February 1986." A document composed from the "Management" pages of six Pixar business plans for the years

1985–1989 shows that Ed Catmull and I were listed as co-founders of the company, and nobody else. Ed Catmull was listed as CEO in three, Chuck Kolstad in one, and Steve Jobs in none. It's available at the "Pixar" entry on *Wikipedia*, footnote 3 ("Proof of Pixar Cofounders"), accessed June 23, 2018. The forty founding employees of Pixar are listed in a page from the founding documents, footnote 2 of the same entry.

Jobs would have sold Pixar to anybody during the last several of those five hellish years for $50 million to make himself whole and not embarrassed. I helped write the business plans for several of those failed attempts. One in particular stands out: Ed and I approached, on Jobs's urging, H. Ross Perot, who was then out of GM and had funded NeXT. Perot wasn't interested in Pixar.

Catmull (2014), 53, suggests that one of the offers was from Microsoft for $90 million, and that Jobs held out for $120 million. I don't recall a Microsoft advance at all, so it must have happened after I left in late 1991. I heard about it from the Microsoft side when I joined them in 1994. Nathan Myhrvold, Microsoft's CTO who was responsible for purchasing my company Altamira Software, thought Jobs wasn't serious about considering Microsoft.

According to the Pixar prospectus (for the public offering of 6,000,000 shares of common stock to the public), Steve Jobs held the lion's share of Pixar stock, 30,000,000 shares. A financial person, Lawrence Levy, unknown to me and other Pixarians, was there only to take the company public for Jobs and then was gone. He held options on 1,600,000 shares. Ed Catmull and John Lasseter also held options on 1,600,000 shares each. Ralph Guggenheim held options on 1,000,000 shares, and Bill Reeves on 840,000. All these were options to buy shares at 20 cents each and vested over time. At the close of the first day of the IPO, the stock was selling at $39 per share [*Los Angeles Times*, Nov. 30, 1995], making Jobs worth $1.17 billion that day. And Catmull and Lasseter were worth about $62 million (once their options vested over time and they paid the 20 cents option price per share). As is typical of worth statements, none of these take into account the substantial loss due to capital-gains taxes that come due upon exercise of options.

434:*A canon is*: Online *Oxford Living Dictionaries*, https://www.lexico.com/definition/canon, accessed Apr. 5, 2020, for the word *canon*, (meaning 2): "A collection or list of sacred books accepted as genuine. | '*the biblical canon*'."

435:*The revolution proceeds*: As evidence that it's always unsafe to pronounce Moore's Law dead, IBM announced—while this book was in final production—a new 2-nanometer chip technology due to go into volume production in late 2024 [Michael Kan, "IBM Unveils 2-Nanometer Chip Process, But Actual Products Are Still Years Away," *PC Magazine*, May 6, 2021, online at https://www.pcmag.com/news/ibm-unveils-2-nanometer-chip-process-but-actual-products-are-still-years, accessed May 10, 2021].

436:*The answer lies*: *Soxel* is a successful coinage, I believe, for the audio sample, or *sonic element*. I was hoping for an equally felicitous abbreviation for *display element*, but failed. Of the dozen or so abbreviations I tried, none seemed spot on, so I've opted to spell out "display element" everywhere. Perhaps this is appropriate since display elements vary with manufacturer and device—whereas pixels and soxels are universals.

Our notion of display element includes both emitted light, as from electronic displays, and reflected light, as from the printed page. For convenience, our usual wording assumes the electronic emitted-light version.

436:*A display element*: The most obvious attempt to force square display elements on us is the Digital Light (!) Processing element (from Texas Instruments) used in many movie theatres. Each DLP display device is essentially a little square mirror that tilts slightly using semiconductor technology. If you approach the screen in such a theatre, you can see the black lines defining each square. The idea is to sit far enough back that the eye schmudges away the black lines. Presumably this achieves, by exceeding the resolution of the retina, the overlapping of spread pixels that results in a continuous display that the little mirrors themselves don't provide. It's a clever solution, one has to admit, despite its "little-squareness." (Strictly speaking, a DLP display element isn't a little square. Two of its opposing corners are cut off for technical reasons.)

437:*That curious word*: To keep these ideas simple and intuitive, I've usually omitted two concepts. Music is actually the sum of waves of different frequency, amplitude, *and phase*. Phase is the relative placement of one wave to another. Similarly the waves in a visual scene can vary in relative placement, or phase. But since a visual scene is two-dimensional, there is another placement consideration: The waves can proceed in spatial directions at different angles to one another. Thus a visual scene is a sum of waves of different frequency, amplitude, *phase,* and *angle*.

438:*I'm writing this*: Drum Castle, near Aberdeen, maintained by the National Trust of Scotland. The shop is in the Mains of Drum nearby.

442:*G. Spencer Brown*: Brown (1973), 3. These are the first two statements of G. Spencer Brown's elegant derivation of simple logic from the act of making a mark or, equivalently, drawing a distinction.

443:*The histories of*: As mentioned previously (see note 249:*Computer graphics by*) I considered calling picture-oriented computer graphics CGI, short for computer-generated imagery. CGI is often used in the movie industry to mean three-dimensional computer animation. Here, for example, is *Wikipedia*: "the term 'CGI' is most commonly used to refer to 3D computer graphics used for creating scenes or special effects in films and television" [under "Computer-generated imagery," accessed Dec. 3, 2019]. But I have several objections to the term CGI, as detailed in the previously mentioned note.

450:*The movie chapter*: But the animation industry has not forgotten Ub. As I write this note (Feb. 2020), I've just been notified by Jim Blinn, who features often in these pages, that he's been awarded the Ub Iwerks Award by ASIFA-Hollywood at their 47th annual Annie Awards, Jan. 25, 2020 (https://www.youtube.com/watch?v=5BfO5otap0o&feature=youtu.be&t=4177, accessed Apr. 5, 2020). ASIFA is the Association Internationale du Film d'Animation (the International Animated Film Association). The Ub Iwerks Award (a small zoetrope) is for technical excellence in animation. Ed Catmull and Bill Reeves have also received this award, according to Jim.

452:*Several digital pictures*: I agree with reader Rishi Chopra (email Oct. 6, 2022) that the last sentence would read better as: "Even if it costs millions of dollars."

455:*Step 1 (Moore's*: I purposely omit the one counterexample, red (only) pixels demonstrated at General Electric in 1966 not using integrated circuits, hence not Moore's Law, because this was an internal proof-of-concept event.

458:*Of current interest*: The pass-through mode may be important ethically. Many people are uncomfortable in the presence of someone wearing a device that might be recording them without permission.

458:*The artist Darcy*: See Darcy Gerbarg's work at http://www.darcygerbarg.com/, accessed Apr. 5, 2020. She has been a longtime digital artist, one of the first, beginning with work on early paint programs in the 1970s (including the ones I wrote at NYIT). She currently works in her Manhattan studio and in Ken Perlin's lab at NYU. Here are her descriptions of two different techniques she uses:

"In the 3DVR world I use Tiltbrush to digitally 'paint' a 3D light sculpture. I walk around, through, in and out, under, over it, taking digital snapshots, which I think of as cropped images. When I shoot them, using the camera option in Tiltbrush, these cropped images all appear to have void black backgrounds. I then take these snapshots into Photoshop and bring up the background color, which turns out not to be a black void but rather dark color that shades according to the lighting algorithm used in the VR environment. I am at that point treating the picture in Photoshop as I would any other 2 dimensional picture and further develop the color, forms and aspect ratio, possibly even cropping it further, to make a finished painting."

"I 'paint' the VR light Sculpture the same way, but instead of taking snapshots into Photoshop, I take the entire 3D model with its color and shading, into Unity and put it on my Android phone. I then can use my phone, with some custom software written by Fengyuan Zhu, FY, who was one of the PhD students in Ken's lab and is now in Toronto, to place my VR Light Sculpture in any real world setting and take snapshots of this composite 3D scene with the phone. The VR light sculpture that I see through the phone's camera, is a 3D model which I can walk through, around, etc. and place in the real environment at will, taking snapshots with the phone's camera. The real environment, be it outside in nature or inside a building is of course 3D: it's the world we live in, the real world. I then take these snapshots, taken with the phone, which feature parts or all of a 3DVR light sculpture and the real world I'm seeing it in, that I was walking around in, into Photoshop and work on them to create finished paintings."

Tilt Brush was created, in crude form, in 2014 by Drew Skillman and Patrick Hackett. It was improved and released in 2016 for the HTC Vive VR device and then in 2017 for Oculus Rift. It was acquired by Google and is available through them. It has won numerous awards.

In a limited sense, Darcy uses Mixed Reality: Her cellphone program establishes the location of the floor in her room or studio and a sense of azimuth angle. This is, in a small way, giving a three-dimensional model to the real-world imagery.

460:*As I write*: Microsoft has HoloLens version 2 and Magic Leap has Magic Leap One as I write (July 2019). I glimpsed other related technologies at Siggraph 2019. One by Nvidia is described in some detail in a formal Siggraph 2019 paper, Kim et al. (2019), which also serves as an introduction to the field and a survey of the current state of the art. Like Magic Leap, the Nvidia (prototype) device does or will track the pupil and display directly to the retina. The Nvidia technology uses pass-through real-world imagery and superimposes the virtual world over it. The synthetic graphics is generated at higher resolution and focus for the fovea than the periphery—called *foveated rendering*. Since inverse computer graphics isn't used, in this case, to derive three-dimensional structure from the real-world imagery, the synthetic imagery is displayed semi-transparently over the real-world imagery "like the emissive ghosts depicted by science fiction 'holographic' projections"—that is, à la *Star Wars* (1977). Don Greenberg works with Nvidia and further tells me (Dec. 2019) that *foveated display* is also on the horizon at various companies.

Reader Rishi Chopra (email Oct. 6, 2022) suggested a rewording of the first sentence, the part following the colon, and I have done so: "Microsoft is pursuing its HoloLens device and Magic Leap its direct-to-retina approach."

460:*The event is*: As mentioned elsewhere, I use "technical Academy Award" to abbreviate a "Scientific and Technical Achievement Award of the Academy of Motion Picture Arts and Sciences (AMPAS)." They are also called the "Sci-Tech Awards." The 68th Scientific & Technical Achievement Awards ceremony of AMPAS was held Mar. 2, 1996, at the Regent Beverly Wilshire Hotel, Beverly Hills, CA, hosted by Richard Dreyfuss. Source: https://www.imdb.com/event/ev0000003/1996/1, accessed Apr. 5, 2020. *Toy Story* was released on Nov. 22, 1995, and Pixar went public on Nov. 29, 1995.

460:*Dreyfuss began with*: Dreyfuss's words were recorded by Ed Catmull shortly after they were uttered, and Ed shared his transcribed notes with me in 1999 as I prepared an article for *Scientific American* magazine.

461:*In 2000 I*: Smith (2000), the *Scientific American* article. The subtitle (or "deck") was: "Characters, scenes and entire movies have been crafted digitally. But can animators create realistic digital humans to star in computer-generated films? Actors want to know."

461:*And it's what animators*: A memorable example was a conversation with actor Brian Cox at a dinner in New York City in 2010. Cox has appeared in dozens of stage, cinema, and television roles, including a stint as King Lear in London, Winston Churchill in *Churchill* (2017), and the news mogul Logan Roy in the television series *Succession* (2018–2019). I asked his opinion of my actors/animators theory. "Of course, it's the same skill. That's why I've sponsored a school of computer animation in Dundee [Scotland, his home town]." Then he invited me to give a talk in Dundee at the graduation of a class of computer animators, which I did (Dundee University, Duncan of Jordanstone College of Art & Design, May 2011).

461:*What I wrote*: See Robertson (2009) for an in-depth description of the *Benjamin Button* accomplishment: “When Benjamin is young, actors of different ages and sizes always perform his body, but his wrinkled face and head, from his clavicle and shoulders up, is always computer generated. Benjamin’s face is digital during his bath, when he crawls into a tent with young Daisy and she touches his face, when he struggles to walk during a revival, when he meets his father, when he gets drunk in a bar, when he works on the tugboat, and all the coming-of-age moments in between.”

462:*But . . . 2020 has*: A brief survey of recent de-agings can be seen in the video *How These 10 Actors Were De-Aged for Their Movies*, https://www.youtube.com/watch?v=twKiEzjeH-M, accessed Apr. 5, 2020. An excellent description of de-aging in recent movies, including *The Irishman*, is Robertson (2019).

462:*A word of*: “Deepfakes have garnered widespread attention for their uses in celebrity pornographic videos, revenge porn, fake news, hoaxes, and financial fraud” [*Wikipedia* article for “Deepfakes,” accessed Dec. 3, 2019].

463:*George Dyson, third*: Dyson (2019), 184–185. The first law of AI is by W. Ross Ashby, the second by John von Neumann, this third by Dyson.

466:*It was John*: This event brought Dyson’s third law of AI home to me.

466:*For what it’s*: Zhu, Park, Isola, and Efros (2017). Notice that the rocks in the background have taken a subtle zebra-like striping as well.

467:*Italo Calvino, Invisible*: Calvino (1974), chapter 6, “Cities & The Sky,” 1 (Eudoxia), 96–97.

Bibliography (Extended)

This full bibliography accompanies the Annotations. It includes all the References of the book as a subset. It has, in addition, references made only in the Annotations and sources I used for research but didn't directly reference.

Abbreviations:

ACM: Association for Computing Machinery

AFIPS: American Federation of Information Processing Societies

IEEE: Institute of Electrical and Electronics Engineers

JPL: Jet Propulsion Laboratory, California Institute of Technology

NYIT: New York Institute of Technology, Old Westbury, Long Island, NY

PARC: Xerox Palo Alto Research Center, Palo Alto, CA

Siggraph: Special Interest Group on Computer Graphics and Interactive Techniques of the ACM

SMPTE: Society for Motion Picture and Television Engineers

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Picture Credits (Extended)

See the Bibliography for expansion of bibliographic references.

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Introduction

0.3 Courtesy of the Hispanic Museum & Library.

1: Fourier

1.12 By Alvy Ray Smith.

2: Kotelnikov

None.

3: Turing

None.

4: Dawn

4.28 Eckert et al. (1950).

4.29 Courtesy of Robert Schumacker.

5: Movies

5.21 By Alvy Ray Smith.

5.22 CC BY–ND 3.0 Unported license. By Alvy Ray Smith, 2018.

6: Shapes

6.41–42 By Alvy Ray Smith.

7: Shades

7.34 Nelson (1974), 108.

7.35 Wylie et al. (1967), 57, Fig. 18.

7.36 By Martin Newell, 1970.

7.37 Rougelot (1969), 268, Fig. 6.

7.38 By and courtesy of Fred Parke, ca. 1971–1972.

7.39 Meyer (2014).

7.40 *Far Out*, https://www.youtube.com/watch?v=njp0ABKwrXA&feature=youtu.be, accessed Apr. 5, 2020, ca. 8:22, 1969.

7.41 By Alvy Ray Smith.

7.42 Leavitt (1976), cover.

8: Millennium

8.17 Kajiya and Kay (1989), 280, Fig. 16. By permission of Jim Kajiya. ©ACM.

8.18 By permission of Craig Reynolds. Photograph courtesy of Mary Whitton.

Finale

None.

Acknowledgments In Memoriam (Extended)

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