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DISTINGUISHED LECTURES

Dominance of the Digital (1990–2016)[1]

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Abstract: This talk presents the theme that anchors the new third edition of *Leonardo to the Internet: Technology and Culture from the Renaissance to the Present*, which is organized around technical-economic-political "eras" spotlighting the long-term interactions of technology and culture. The book's first edition (2004) concluded with an optimistic assessment of global culture, then added a pessimistic assessment of systemic risk (2011). The eras point to socio-economic structures that foster and channel the development of certain technologies (and not others). This approach steers for a middle ground between social constructivism and technological determinism. This talk analyzes Moore's Law (1975–2005), widely hailed to explain, well, everything. By 1975 Gordon Moore appeared to accurately "predict" the doubling every 18 months of the number components on each integrated circuit. During these years chips expanded from roughly 2,000 to 600 million transistors; more important the "law" guided a technical revolution and an industry transformation. At first national and then international cooperative "roadmapping" exercises predicted the exact dimensions of chips in the future, and semiconductor companies all aimed exactly where their peers were aiming. So Moore's Law is a self-fulfilling prophecy supported for three decades by inter-firm cooperation and synchronized R&D.

Keywords: Moore's law, technological determinism, social constructivism, self-fulfilling prophecies, technological paths

[1] This paper was presented in Monte de Caparica (Lisbon Metropolitan Area, Portugal) as the 2nd CIUHCT (*Centro Interuniversitário de História das Ciências e da Tecnologia*) Distinguished Lecture, "The Dominance of the Digital (1990–2016)," at the Faculdade de Ciências e Tecnologia, Universidade NOVA de Lisboa, on December 4, 2018. *HoST* publishes its extended abstract.

Extended abstract

This paper is one part of a new chapter for my survey *Leonardo to the Internet: Technology and Culture from the Renaissance to the Present* (JHUP 2nd edition 2011).[2] It examines the present-day "dominance of the digital" as one of the techno-cultural "eras" creating this book's narrative structure. Moore's Law is often taken to be at the center of the computing and information revolution; it is a staple of journalistic and popular accounts of technology. Scholars such as Bill Aspray and Cyrus Mody have examined its impact on technology policy and the character of academic science, but few (apart from Ethan Mollick and Robert Schaller) have delved into its genesis and genealogy.[3] Even fewer have shown the enthusiasm of Paul Ceruzzi's "Moore's Law and Technological Determinism" (2005), which argues "Moore's law plays a significant role in determining the current place of technology in society (…). (…) raw technological determinism is at work."[4] In this section of my new chapter (one of four), my argument is that it needs to be understood not through before/after snapshots, let alone as "raw technological determinism," but rather through historical attention to narrative and process. I see three overlapping phases: preconditions prior to 1975; its emergence and shaping from 1975 to 2004; and the development of national and global networks for "roadmapping" and R&D synchronization through 2016.

Moore's Law is often traced to a 1965 article that Gordon Moore, then director of research for Fairchild Semiconductor, published in *Electronics* magazine.[5] Moore himself acknowledged no one paid any attention until 1975 when his 10-year prediction that the number of semiconductor elements on an integrated circuit would be 65,000 was confirmed. It became an article of faith. The US National Science Foundation identified Moore's Law as a "self-fulfilling prediction that drives industry-wide planning."

Several aspects of the US semiconductor industry before 1975 are notable. First, from the 1960s the industry was composed of companies that engaged in bad-faith cut-throat competition (the very opposite of cooperative arrangements that later emerged). Second, with

[2] Thomas J Misa, *Leonardo to the Internet: Technology and Culture from the Renaissance to the Present*, 2nd ed. (Baltimore: Johns Hopkins University Press, 2011).

[3] William Aspray, ed., *Chasing Moore's Law: Information Technology Policy in the United States* (New York: SciTech Publishing Inc, 2004); Cyrus C.M. Mody, *The Long Arm of Moore's Law: Microelectronics and American Science* (Cambridge, MA: MIT Press, 2017); Ethan Mollick, "Establishing Moore's Law," *IEEE Annals of the History of Computing* 28, no. 3 (July-Sept. 2006): 62-75; Robert R. Schaller, "Moore's Law: Past, Present, and Future," *IEEE Spectrum* 34, no. 6 (June 1997): 52–59.

[4] Paul E. Ceruzzi, "Moore's Law and Technological Determinism: Reflections on the History of Technology," *Technology and Culture* 46, no. 3 (2005): 584-93, on 586 and 593.

[5] Gordon E. Moore, "Cramming More Components onto Integrated Circuits," *Electronics*, April 19, 1965, 114–117.

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a component defect rate of 12 percent at the time, the industry's quality control was terrible; no sizable integrated circuits were possible.

Nation-wide quality control at chip consumers Univac, IBM, and HP, induced component vendors like National, Fairchild, Motorola and others to adopt new production techniques like clean rooms. Quality improved, and large integrated circuits, or chips, were feasible. By the mid 1970s, the dominant Intel (successor to Fairchild) took up Moore's Law to form its corporate culture. Its leadership, including Moore himself, published articles in *Science* and *Scientific American*, while noted Cal Tech professor Carver Mead (who likely coined "Moore's Law") engaged in Moore's law evangelism (using devices he obtained from Moore himself). Intel CEO Craig Barrett put it explicitly: "we don't adhere to Moore's Law for the hell of it. It's a fundamental expectation that everybody at Intel buys into."[6]

The cross-industry cooperative "roadmapping" exercises starting in the 1990s were an unprecedented institutional means that [a] responded to the perceived threat of US military forces dependent on foreign electronics; [b] impelled the US semiconductor industry to adopt cross-firm cooperation; and [c] eventually permitted the "law" to shape the global semiconductor industry. In 1997, Gordon Moore said, revealingly, "If we can stay on the SIA Roadmap, we can essentially stay on the [Moore's Law] curve. It really becomes a question of putting the track ahead of the train to stay on plan."[7] The national (US) technology roadmap was called the "most detailed reincarnation [of] Moore's Law."[8]

The international roadmaps began in 1998 under the auspices of the industry-leading trade associations from US, Japan, Europe, South Korea, and Taiwan. By 2003 more than 900 companies participated. Each biennial roadmap made detailed predictions for the next 15 years. The roadmap from 1992 predicted that feature sizes would shrink by five times, that gates per chip would expand by sixty times, and that supply voltages (a critical measure for battery-powered cell phones) would drop to just 1.5 volts. These measures provided long-term targets for companies across the world to coordinate their R&D efforts, to plan the next generations of manufacturing facilities, to specify the wavelengths for their chemical-resists, and much else.

Unwittingly, the 1992 roadmap predicted the end. It indicated that in 2004 non-portable chips would exceed 100 watts in heat dissipation, which (as Intel found that same year) resulted in

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6 Quoted in Brent Schlender, "Intel's $10 billion gamble," *Fortune*, November 11, 2002.

7 Ed Korcynski, "Moore's Law Extended: The Return of Cleverness," (interview with Gordon Moore) *Solid State Technology* 40, no. 7 (July 1997): 364.

8 W. Maly, "Special Address. Moore's Law and Physical Design of ICs," *Proceedings of the 1998 International Symposium on Physical Design* (New York: Association for Computing Machinery, 1998), 36.

overheating that caused "heat death" (and the practical end of Moore's Law as a simple scaling measure). Whereas digital electronics from 1965 through 2004 relied simply on making component sizes ever smaller, since then "multi-core" processors (CPU's) and more complex computer architectures have become the industry norm. Progress has dramatically flattened, with clock speeds and thermal power plateauing around 2006 forward. The last international technology roadmap for semiconductors (ITRS) was in 2013, and ITRS itself was wound up in 2016.

Moore's Law, as Carver Mead noted in a 1996 interview, "is really about people's belief system, it's not a law of physics, it's about human belief, and when people believe in something, they'll put energy behind it to make it come to pass."[9]

[9] University Video Communications, "How Things Really Work: Two Inventors on Innovation, Gordon Bell and Carver Mead [video recording]" (Stanford, CA: UVC, 1992).