

Institutions, Infrastructures, and Innovation

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Innovators, institutions, and infrastructures are hidden but essential to innovation ecologies that produced important breakthroughs. This article provides examples and suggestions for spotting institutional and infrastructural factors important to any technological trajectory.

In April 2020, unemployment agencies were struggling to handle the massive uptick in jobless claims due to the coronavirus disease (COVID-19) pandemic. Their outdated software wasn't helping. Riding to the rescue was a group of mostly retired programmers, called the *COBOL Cowboys*, ready to help maintain and update the COBOL-based unemployment insurance systems used by at least a dozen U.S. states.[1] In June 2019, the U.S. Air Force announced it had recently finished upgrading its technology for the launch of nuclear-armed, intercontinental missiles from systems that used 8-in floppy disks.[2] Over 20 years earlier, previous COBOL cowboys and others rescued thousands of legacy systems in corporations and government from the so-called Y2K (Year 2000) bug. Without their efforts, software written decades earlier—when no one imagined that code containing two-digit "year" fields might still be in use at the turn of the millennium—might have caused potentially catastrophic software failures.[3]

Stories like these are easy to shake your head at while imagining the primitive grunts of computer cave-people speaking COBOL or Fortran and muttering "idiots" under your breath. Yet, "if it ain't broke, don't fix it" represents the normal state of affairs. This normal state is governed by background contexts—institutions and infrastructures—that usually (but not always) dominate over individuals in the development and deployment of technologies that often become "legacy" systems.[4] While heroic narratives of brilliant individual scientists and engineers are perennially popular (and partially true), deeper investigation by historians of technology often shows that institutions and infrastructures

Digital Object Identifier 10.1109/MC.2020.3035921
Date of current version: 14 January 2021

as well as many supporting players made their successes possible.[5–11]

Institutional influence is not, however, limited to sluggish updating or resistance to new technology. Technologies such as the GPS and the Internet could never have emerged as they did without institutional support. Case in point: the roots of one of the oldest and greatest IT companies, IBM, lie in an institution—the U.S. Census—that was written into the U.S. Constitution in the 18th century. IBM's earliest ancestor was the Hollerith Tabulating Machine Company, founded in 1895 to build tabulating machines for the U.S. Census Bureau.

The point here is that just as institutions must be understood as essential to technology's development and deployment.

Despite their profound and far-reaching effects, institutions and infrastructures can be difficult to see and understand. In this article, we provide some examples, drilling in on the institutional context of the Cold War and the role of the U.S. National Science Foundation (NSF) in shaping information infrastructures. We conclude by suggesting ways to identify institutional and infrastructural context that will be important to a given technology trajectory.

UNDERSTANDING INSTITUTIONS AND INFRASTRUCTURES

The word *institution* is incompletely and imprecisely defined but refers in general to enduring, socially significant organizations and structures, such as kinship systems (families), legal systems, and mass media. Institutions usually have status in law, outlive their participants, and shape the future. Governments and their major constituent bodies (courts, legislatures, and so on) are institutions. So are some international agencies, professional and industry associations, standard-making and standard-certifying organizations, universities, trend-setting corporations (especially multinationals), financial organizations, labor organizations, and religious entities.[12] All can have significant roles in shaping technology's development and deployment through encouraging, discouraging, adopting, abandoning, funding, and regulating.

Sometimes the institutional role is obscured by the misperception that "institutions" are all governmental, while in the United States, technology is usually developed and built by private companies. This is a mistake. First, institutions often provide funding and the "long view" required to sustain technological innovation until effects emerge, even as private companies provide the know-how to get technologies going. Second, many of the largest and oldest companies are themselves institutions. Banks, financial services, and insurance firms, for example, are among the oldest companies in the Fortune 500; the oldest, the Bank of New York Mellon, dates to 1784—five years before the U.S. Constitution was adopted. These such firms were among the first private enterprises to adopt successive generations of computing technology.

"Infrastructure" is equally imprecisely defined. The term is widely used to describe enduring, essential sociotechnical systems underlying modern societies. Capital-intensive electric power, highways, cable television, and telephone networks are all infrastructure but so are people-intensive public schools, emergency services, and legal systems. Since no infrastructure can operate without builders, trained maintainers, standards, management, and funding streams (whether public or private), infrastructures overlap to a considerable degree with institutions and may last even longer, as in the case of certain roads and buildings maintained in continuous use for more than a thousand years. The point here is that just as institutions must be understood as essential to technology's development and deployment, infrastructures cannot be fully described as built objects or technology alone; stripped of their human and organizational elements, all infrastructures would quickly collapse. The difference between institutions and infrastructures is that, unlike a corporation or government agency, infrastructures do not normally display centralized control and management. They are networks or networks of networks, composed of interlocking systems linked by standards, gateway devices, legal frameworks, human actors, and (nongovernmental) governance institutions—much like the Internet itself, a prime example of an infrastructure.[13]

David calls institutions the "carriers of history"[14] because they help create "path dependence," also known as "lock-in," to particular procedures, practices, research directions, and technological systems due to what infrastructure gurus Bowker and Star called "the inertia of the installed base."[15] In the 1960s, as computing became embedded in the routine operations of organizations and institutions, such as major corporations and governments, it became an essential industry. Then-new "computer science" was institutionalized as a department in academic institutions in that decade as well as in business schools under names such as "data processing" and "management information systems."[16] As it spread to smaller businesses and personal devices became cheap and ubiquitous, computing and network infrastructures became essential elements of modern "network societies."[3,17]

Some aspects of the way this occurred historically intertwined with institutionalized discrimination on the basis of sex and race. The costs of discrimination can be high, as seen in Hicks' (2017) analysis of discrimination against women that crippled the British computer industry for three decades.[18] More recently, organizations dominated by white men developed systems for face recognition and criminal justice sentencing recommendations that resulted in systemic (even if unintentional) racial and gender error or bias.[19,20] When rapid change is the norm, institutional influence (including institutionalized racism and gender bias) can be too slow to notice. On the timescale of institutions, three decades is not terribly long, but in "Internet time" it is forever. Yet even in Internet time, the "installed base" of devices, standards, knowledge, ethical and safety cultures, technical support, and other elements of infrastructure facilitate some new directions while constraining others—especially those that depart from the long-settled practices of major institutions.

INSTITUTIONS AND COMPUTING IN THE COLD WAR

Digital computing as we now recognize it was developed during World War II and expanded dramatically afterward, especially during the early Cold War.[6] The profound respect and support enjoyed by many American governmental institutions in the 1940s and 1950s can be difficult to fully appreciate from today's vantage point in a polarized political climate of distrust. The U.S. Departments of War (Army) and Navy, supported by the new federal Office of Scientific Research and Development (founded in 1941), had led in the victory over the Axis powers. Universities and engineering schools had rallied to supply leadership, labor, knowledge, and innovation to the cause, ending with a scientific marvel (and terror), the atomic bomb. New technology was developed at breakneck speed in massive collaborations with virtually limitless government funding (aviation, radar, proximity fuses, antiaircraft guns guided by analog computers, nuclear weapons for the Allies, rocketry and jet propulsion for the Axis). During postwar reconstruction, major new international institutions were created, including the United Nations, the North Atlantic Treaty Organization, and the World Bank. Within the United States, the new U.S. Department of Defense merged the Army, the Navy, and the (new) Air Force—the latter especially important because it controlled nuclear weapons and the bombers that would deliver them.

The Navy's Office of Naval Research funded numerous computer projects immediately after World War II. But by 1950, the Air Force proved even more influential when, recognizing the threat of a Soviet nuclear attack on American soil, it initiated a groundbreaking effort to invent and build a national, computer-controlled, air defense system, known as the *Semi-Automatic Ground Environment (SAGE)*. Each of the 23 SAGE "direction centers" housed two huge, identical IBM vacuum-tube computers, duplexed so that if one failed or needed maintenance, the other could instantly take over. To provide a larger picture of the U.S. airspace, each direction center linked to neighboring centers via leased AT&T telephone landlines. Modems, computer networking, duplexing, magnetic core memory, and numerous other computing "firsts" of the SAGE project were all developed, built, and funded by government institutions in partnership with academic and corporate research laboratories, including Massachusetts Institute of Technology (MIT), Lincoln Laboratories, the MITRE Corporation, and IBM—which earned the majority of its income in the 1950s from SAGE-related work.[21] Later in the Cold War, the (Defense) Advanced Research Projects Agency (ARPA/DARPA) of the U.S. Defense Department spent heavily on computer networking, artificial intelligence, computer graphics, and integrated circuit development.[22] Meanwhile, procurement for myriad military and government computing projects supported the early computer industry.[6,23,24]

INSTITUTIONS AND THE RISE OF THE INTERNET

The Internet story is relatively well known but also relatively misunderstood. It grew out of multiple data networking endeavors.[7] In the late 1960s, numerous private firms in the United States, such as Tymshare, Control Data, and Compuserve, were marketing "computer utility" services based on what were called *remote-access networks* (essentially dial-up modems accessing mainframes). European posttelephone-and-telegraph (PTT) agencies entered the arena, relying on the International Organization for Standardization (ISO)'s X.25 networking standard (1976) and its successor, the Open Systems Interconnection (OSI) standard. Both of these standards were written for an envisioned context in which a handful of large institutional operators (the PTTs) would provide all networking services. In the United States, networking was led by companies such as IBM and Digital Equipment Corporation, that sought to gain market share by providing proprietary network systems. In France, the videotex system Minitel, whose dumb terminals linked to mainframes via phone lines, became the world's first national public computer "network" in 1983.[25]

Ultimately, rather than the European PTTs, the seminal institution for the Internet was the U.S. Department of Defense. ARPA/DARPA enlisted think tanks, companies, academic institutions, and others to build the packet-switched network, known as the ARPANET, built on two networking protocols. One protocol, the Internet Protocol (IP), controlled how computers exchange data packets. The other, the TCP, managed network conversations. TCP/IP swept the world, becoming a standard for data networking in large part because of its integration into the popular Unix operating system—developed by AT&T but freely distributed due to AT&T's regulatory status as a telephone company not allowed to compete directly in the market for computing—and its adoption by military agencies.[7] It is fair to say that without institutional support and guidance, the Internet would not have emerged as it did.

THE ROLE OF THE NSF

The previous sections have focused on major projects in information technology history and on the role of institutions within those projects. This section focuses on one institution: NSF and its role in information technology from its inception in 1950 over many decades.[26] NSF was not the only institutional player in this space. As noted, in the United States, the military role was significant as were the roles of many academic institutions. Moreover, institutions in many countries outside the United States played roles. The focus on NSF is exemplary—an instance of how it happened—but not exhaustive.

At the end of World War II, analog computer designer and MIT professor Vannevar Bush, who had led the U.S. Office of Scientific Research and Development and advised President Roosevelt and President Truman, proposed the creation of a government-funded research agency to advance the sciences for public benefit.[27] Bush's agency, with modifications, became the NSF in 1950. From its inception, NSF was interested in the health of the United States' scientific enterprises, compiling data on the pipelines producing professional scientists and the work being done. With the military still playing the dominant role, NSF funding for computer research was limited to mathematics for the first few years, but in the mid-1950s, NSF began organizing workshops on information science. After the Soviet Union launched Sputnik (1957) and the National Defense Education Act (1958) was passed to promote science education, NSF became active in that area. Computers were also being more widely applied in education, and NSF became a key supporter of computer-aided instruction. As computational resources became more important to scientific research, NSF began funding such support. A major early beneficiary was the NSF-funded National Center for Atmospheric Research (founded in 1960)—one of a handful of (mostly military) government-funded laboratories to own and operate the most advanced supercomputers of the day, in this case for modeling weather, climate, and the physics of the sun and upper atmosphere.[28]

NSF's growing role in information technology research and development had three threads. One was experimental research, where computerized data analysis played an ever-larger role in the 1970s and early 1980s. Another was advanced scientific computing for mathematics, the physical sciences, the geosciences, and engineering. The third was to advance the availability and use of data networking beyond the limited number of academic institutions with access to the ARPANET. These threads came together in the mid-1980s with the formation of the NSF Directorate for Computer and Information Science and Engineering (CISE). Computer science was encouraged by dedicated support. The advanced scientific computing enterprise, which included the NSF-funded supercomputer centers, interacted closely with researchers in a variety of research fields and was instrumental in helping develop a computational paradigm for such research. NSF created a major spur to networking by requiring that eligible NSF researchers be able to access the supercomputers, even if they were located too far away to visit in person. That networking effort eventually led to the Computer Science Network (CSNET), a "network of networks" that linked computer scientists and stimulated network research.

The institutional role of NSF in the evolution of information technology took a major leap forward when the advanced scientific computing enterprise noted restrictions on getting adequate computational resources to researchers. A better data communication network was needed. At about the same time, the U.S. Department of Defense began repositioning itself with less emphasis on the varied institutional world that had created the ARPANET and more focus on military needs. This eventually led to the formation of the military network for military networking, while the other interests involved in the ARPANET faced an uncertain future. In part to fulfill the advanced network needs of advanced scientific computing and to exploit the "network of networks" philosophy behind CSNET, the NSF created NSFNET. NSF contracted build-out and operation of NSFNET to the Michigan Educational Research Information Triad, [(MERIT), now known as *the Merit Network*], created in 1966 by higher education institutions Michigan State University, Wayne State University, and the University of Michigan.

The NSFNET was renamed the *Internet*, opened to commercial use, and the governance mechanisms now used were created [for example, the Internet Engineering Task Force (IEFT)]. The Internet evolved into a global phenomenon much larger than NSF. During this period, a research institution in Switzerland, the Conseil Européen pour la Recherche Nucléaire (or the European Organization for Nuclear Research), created the World Wide Web for the exchange of documents and images. An NSF-supported "supercomputing" center, the National Center for Supercomputing Applications, affiliated with a higher education institution, the University of Illinois, Urbana-Champaign, pioneered the Mosaic web browser. Mosaic soon became the basis of commercial web browsers, most notably Netscape, and the Internet age began in earnest. Since the creation of the CISE Directorate and the launch of the Internet, NSF has continued to take an institutional lead on information technology, funding the lion's share of basic research in the field.

SPOTTING WHERE INSTITUTIONS WILL BE IMPORTANT

In summary, many of the advances in information technology, around which today's massive IT markets are centered, originally emerged from research and development mobilized and sustained by institutional action. Researchers who study institutions and infrastructures take a deep interest in how they both generate and sometimes inhibit innovation. For most who work in innovation, this deep focus is unnecessary. Yet it is helpful to have a perspective on when and how institutions and infrastructures may become important in any innovative activity. The following checklist may provide some guidance:

- *Multi-institutional compatibility and embedding*: Whenever the establishment or sustainability of a technology requires acceptance by or support from more than one institution, one of them or a new one will have to push hard to achieve the right compatibility and embedding. For example, the value of the ARPANET was far from obvious, even to many of its developers who worked at multiple institutions, each with its own goals, culture, and technology, including computers made by different manufacturers and using different operating systems. Only after ARPA forced its clients to use the network did its interest start to become clear.[7,29] It is essentially impossible to coordinate across multiple institutions without the backing of an institution.
- *Scale and scope*: As a general rule, the larger the scale (number of things involved, regardless of diversity) or the larger the scope (diversity of things involved), the more institutional influence will matter. As an example, when an infrastructure grows large enough to cross political boundaries (for example, state or national borders), institutional coordination is needed. Here, standard-setting, standard-certifying, and coordinating institutions, such as the ISO, the (IETF), and the Internet Corporation for Assigned Names and Numbers, may play essential roles.
- *Sustained support lasting long enough for proof of concept*: Some technologies require time to become diffused, adopted, and routinized. Funding and political support for such technologies is usually easier with institutional backing.
- *Regulatory issues*: Regulation of health, safety, privacy, honesty, competition, ethics, and so on is usually reserved to institutional actors, such as the legislative and legal systems and professional associations.
- *Red tape reduction and opposition interference*: Institutional influence is often required to reduce or remove red tape necessary to pursue development or establish new technologies. Even when such actions have a clear and obvious rationale, such as the exigencies of war or a pandemic, institutional authority is needed to invoke them. In addition, most proposals have one or more opponent coalition(s) working to hinder or stop them. An institutional agency can keep the opposition at bay long enough for the innovation to take hold.
- *Workable mechanisms for the long run*: The question of whether or not an innovation is manifestly better, improves value, or enables things not previously possible is often entirely debatable early in its trajectory. The graveyard of better technologies that died out for nontechnical reasons is depressingly large. Long-run success requires workable mechanisms for both proving and improving benefits and reducing harm to people and existing institutions and infrastructures. Creating these mechanisms often requires institutional action by government, professions, risk management trend-setters (for example, insurance), and others.
- *Cultivate infrastructural growth*: Creating plug-and-socket arrangements (such as application programming interfaces and routers) that allow existing technologies to interoperate with new ones, instead of displacing them (leading to battles with the institutions committed to them), is a key principle in cultivating infrastructure, which typically emerges organically from a background of existing systems and routines as connections grow among new innovations, entities, and institutions. This cultivation is more like an ecological or agricultural process than an engineering problem. Legal and political arrangements that promote or deny such connections may be at least as important to their fate as technological innovation. Institutional involvement can be complicated, as when diverse ownership of required patents for an innovation (a patent thicket) necessitates a patent pool.[30] This can involve formally constituted institutions (for example, governmental patent offices), professions (for example, patent lawyers), and academic institutions whose members (for

example, editors and reviewers) control the archival literature related to primacy claims. Depending on the political salience of the issue, this might involve institutions such as legislatures and courts.

- *Account for different paces of change*: Another challenge is differential speed among occupations in their embrace of new technology and when technological innovation occurs quickly but institutional change is slow.[31,32] Different occupations embrace new technology at different rates, compounding the already significant variance in adoption speed among individuals. Moreover, not all institutions are slow. Financial institutions (for example, the money markets) sometimes move even faster than technological innovations, anticipating success or failure. However, regulating competition, health, safety, and other concerns can take a long time.

Problems with systems involving computers and humans can be so complicated and involve so many issues that it takes time simply to sort everything out. Institutions and infrastructure take the long view, providing time at the beginning and at the end. ◼

REFERENCES

1. J. Abate, *Inventing the Internet*. Cambridge, MA: MIT Press, 1999.
2. B. Allyn, "'COBOL Cowboys' aim to rescue sluggish state unemployment systems." National Public Radio. https://www.npr.org/2020/04/22/841682627/cobol-cowboys-aim-to-rescue-sluggish-state-unemployment-systems (accessed: Oct. 2020).
3. J. Angwin, J. Larson, S. Mattu, and L. Kirchner. "Machine bias: Risk assessments in criminal sentencing." ProPublica. https://www.propublica.org/article/machine-bias-risk-assessments-in-criminal-sentencing (accessed Oct. 2020).
4. D. E. Bailey and P. M. Leonardi, *Technology Choices: Why Occupations Differ in Their Embrace of New Technology*. Cambridge, MA: MIT Press, 2017.
5. G. C. Bowker and S. L. Star, *Sorting Things Out: Classification and Its Consequences*. Cambridge, MA: MIT Press, 1999.
6. J. Buolamwini and T. Gebru, "Gender shades: Intersectional accuracy disparities in commercial gender classification," in *Proc. Conf. Fairness, Account. Transparency, Mach. Learn. Res.*, vol. 81, 2018, pp. 77–91.
7. V. Bush, *Science the Endless Frontier: A Report to the President*. Washington, D.C.: United States Government Printing Office, 1945.
8. M. Castells, *The Rise of the Network Society*. Cambridge: Blackwell Publishers, 2000.
9. R. N. Charette. "Inside the hidden world of legacy IT systems: How and why we spend trillions to keep old software going." IEEE. https://spectrum.ieee.org/computing/it/inside-hidden-world-legacy-it-systems (accessed: Oct. 2020).
10. P. David, "Why are institutions the 'carriers of history'?: Path dependence and the evolution of conventions, organizations and institutions," *Struct. Change Econ. Dynam.*, vol. 5, no. 2, pp. 205–220, 1994. doi: 10.1016/0954-349X(94)90002-7.
11. P. N. Edwards, *The Closed World: Computers and the Politics of Discourse in Cold War America*. Cambridge, MA: MIT Press, 1996.
12. P. N. Edwards, "Y2K: Millennial reflections on computers as infrastructure," *History Technol.*, vol. 15, nos. 1–2, pp. 7–29, 1998. doi: 10.1080/07341519808581939.
13. P. N. Edwards, S. J. Jackson, G. C. Bowker, and C. P. Knobel, *Understanding Infrastructure: Dynamics, Tensions, and Design*. Ann Arbor, MI: Deep Blue, 2007.
14. P. N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming*. Cambridge, MA: MIT Press, 2010a.
15. P. N. Edwards, "Some say the internet should never have happened," in *Media, Technology and Society: Theories of Media Evolution*, W. Russell Neuman, Ed. Ann Arbor, MI: Univ. of Michigan Press, 2010b, 141–160.
16. K. Flamm, *Targeting the Computer: Government Support and International Competition*. Washington, D.C.: Brookings Institution, 1987.
17. K. Flamm, *Creating the Computer: Government, Industry, and High Technology*. Washington, D.C.: Brookings Institution, 1988.
18. P. A. Freeman, W. R. Adrion, and W. Aspray, *Computing and the National Science Foundation, 1950-2016*. New York: The Association for Computing Machinery, 2019.
19. T. Haigh, "Actually, Turing did not invent the computer," *Commun. ACM*, vol. 57, no. 1, pp. 36–41, 2014. doi: 10.1145/2542504.
20. M. Hicks, *Programmed Inequality: How Britain Discarded Women Technologists and Lost Its Edge in Computing*. Cambridge, MA: MIT Press, 2017.
21. T. P. Hughes, *Networks of Power: Electrification in Western Society, 1880-1930*. Baltimore: Johns Hopkins Univ. Press, 1983.
22. V. Insinna, "The US nuclear forces' Dr. Strangelove-era messaging system finally got rid of its floppy disks." C4ISRNET. https://www.c4isrnet.com/air/2019/10/17/the-us-nuclear-forces-dr-strangelove-era-messaging-system-finally-got-rid-of-its-floppy-disks/ (accessed Oct. 2020).
23. B. Kahin and J. Abbate, Eds., *Standards Policy for Information Infrastructure*. Cambridge, MA: MIT Press, 1995.
24. B. Kahin and E. J.Wilson, Eds. *National Information Infrastructure Initiatives: Vision and Policy Design*. Cambridge, MA: MIT Press, 1997.

25. J. L. King, "Project SAGE, half a century on," *ACM Interfaces*, vol. 17, no. 5, pp. 53–55, 2010. doi: 10.1145/1836216.1836230.
26. J. L. King, V. Gurbaxani, K. L. Kraemer, F. W. McFarlan, K. S. Raman, and C. S. Yap, "Institutional factors in information technology innovation," *Inform. Syst. Res.*, vol. 5, no. 2, pp. 139–169, 1994. doi: 10.1287/isre.5.2.139.
27. A. L. Norberg, J. E. O'Neill, and K. J. Freedman, *Transforming Computer Technology: Information Processing for the Pentagon, 1962-1986*. Baltimore, MD: Johns Hopkins Univ. Press, 2000.
28. S. Ornstein, *Computing in the Middle Ages: A View from the Trenches 1955 1983*. New York: 1st Books Library, 2002.
29. J. L. Perry, K. L. Kraemer, J. L. King, and D. Dunkle, "The institutionalization of computing in complex organizations," *Informatiz. Public Sector*, vol. 2, no. 1, pp. 47–73, 1992.
30. C. Perez, *Technological Revolutions and Financial Capital: The Dynamics of Bubbles and Golden Ages*. London: Elgar, 2002.
31. J. Roebke. "Scoundrels, saints, and the fiction of individual genius." Undark. https://undark.org/2020/10/22/the-fiction-of-individual-genius/ (accessed Oct. 2020).
32. C. Shapiro, "Navigating the patent thicket: Cross licenses, patent pools, and standard-setting," in *Innovation Policy and the Economy*, A. B. Jaffe, J. Lerner, and S. Scott, Eds. Cambridge, MA: MIT Press, 2001, pp. 119–150.

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Digital Object Identifier 10.1109/MC.2020.3045254