Digital Analogs: Computing, Internet, and Spectrum Lessons for New Space Policy

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Entrepreneurs hoping for aggressive growth in space markets cite the commercialization of the Internet as a golden age of market dynamism and enlightened regulation. This study investigates the growth of commercial computing, a business-oriented Internet, and spectrum allocation as historical analogs guiding new space policy. These "digital analogs" share common threads of early military backing, high-value national security activities that developed many of the technological components, and a policy of encouraging the transfer of technology to the private sector. These digital case studies highlight the discovery of new markets, regulatory flexibility, and the power of venture capital financing to develop new technological platforms and stimulate economic growth. In addition, a large number of the emerging space entrepreneurs trace their early success to digital industries. Policy makers can learn valuable regulatory lessons from these digital analogs and anticipate some of the growth areas of the commercial space business.

1 Introduction

1.1 Overview

Commercializing the Internet was a signature United States policy success of the 1990s. Between 1990 and 1993 the Internet transformed from a controlled research environment to an open marketplace. An investment boom followed. By the end of the 1990s, the Internet was a vital center of economic growth. Despite the unraveling of the “dot com” venture wave in 2000–2001, worldwide growth of Internet users and Internet traffic continued at a rapid pace. Companies such as Amazon and Google are now central to economic and communication activity. Billions of users and millions of organizations rely on the Internet as an essential communication, entertainment, and productivity hub.

The Internet built upon an earlier information technology and policy success. The computer owes its origins and first decades of prosperity to governmental funding. The transition to commercial markets relied on technology built with public backing. It wasn’t until the late 1960s, nearly 25 years after the first computers, that commercial markets were the prime drivers of both research and demand. Computing progressed at a furious rate, moving to personal computing in the late 1970s. By the time of the Internet, computing was nearly ubiquitous in advanced economies.

Such success invites comparison. As the United States adopts a more commercial space orientation, some space industry participants are calling for a similar Internet regulatory approach. For example, Jeff Bezos commented that[1] "I want to see the kind of explosive growth (in space) that we've seen on the Internet with all of the entrepreneurialism and the dynamism – it's been kind of a gold age that you've seen over the last 20 years." Steve Jurvetson, a leading Internet and space venture capitalist, has advanced a similar theme.[2]

This study investigates the computing and Internet experience for insights applicable to space policy. At first it might appear that the space industry and information technology ("I.T.") are technologically too far apart for meaningful comparison. We believe this is incorrect. There are multiple connections between the I.T. experience and the move to commercial space, and the future of new space is closely tied to developments in the Internet and computing arena.

Economic historians distinguish between Smithian and Schumpeterian economic growth.[3] In Smithian growth, the same core set of products and applications benefit from efficiencies, higher quality inputs (such as a more educated labor force), and capital accumulation. In Schumpeterian growth, the major benefit arises through new products, new ways of doing business, and innovative applications. Computing and the Internet have been especially rich sources of Schumpeterian growth. Digital technology now pervades all consumer appliances and entertainment media. Online ecommerce reaches into almost all retail categories, with companies such as Amazon.com changing the face of retail. Online advertising has become the largest advertising venue, with companies such as Google displacing traditional advertising mediums such as newspapers and yellow pages. Streaming media has fundamentally changed the music and movie industry, and is threatening to do so for television. Some of the most important policy lessons from the Internet realm are in supporting Schumpeterian growth.

If we are fortunate enough to see dramatic launch cost reductions due to high levels of re-use, Schumpeterian insights from computing and the Internet realm may be especially valuable. With an order of magnitude fall in costs, many new products and services may become viable.

A second reason to look at the history of the Internet is the role of venture capital. Previous historical analog studies did not concentrate on industries relying on venture capital financing. Venture capital was critical to the growth and success of Internet commercialization and is showing increasing importance in commercial space. Venture-backed firms have different incentives and seek different payoffs than government or private debt funded firms.

A third reason to consider the history of I.T. is a shared concern regarding the regulation and use of spectrum. It was clear in the 1990s that the rapid growth in cellular telephony and mobile data would stress available commercial spectrum. Spectrum auctions pushed the creation of new capacity, encouraging the explosion of cell phone networks and usage. Similar actions may be necessary to procure the necessary spectrum for communication to and from space. The rapid growth in satellite constellations puts stress on the available spectrum for communications. Indeed, there is currently a pitched battle over future spectrum usage between new satellite constellation operators and next-generation mobile systems. This is perhaps the most important short-term commercial space policy decision.

Even without order-of-magnitude cost reductions in launch costs, Internet lessons are relevant to the new space community due to the impact of the Internet on the demand for commercial space services. A strong case can be made that many new space ventures are effectively digital spinoffs. Over the past two decades, the dominant share of commercial space demand has been digital entertainment and digital communication (primarily direct broadcast television and satellite radio).[4] Looking forward, SpaceX apparently anticipates space-based Internet services as providing a dominant revenue source, substantially exceeding its launch revenue.[5] While new space may provide important transportation, tourism, and even mining services, to date and in the medium term it is primarily a adjunct to the information technology sector.

1.2 Previous Analogs for Space Policy

Launius (2014) provides a recent look at historical analogs for new space policy.[6] Launius is especially concerned with funding justifications, but also discusses regulatory issues for the transcontinental railroad, early aviation and aerospace, the telephone industry, Antarctic science, large public works such as TVA, and the National

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[1] Jeff Bezos at the 32nd Annual Space Symposium, Colorado Springs, CO, April 12, 2016.

[2] Small Satellite Conference, Menlo Park CA, February 2016, and personal conversations.

[3] For example, Joel Mokyr, (2017), *A Culture of Growth: The Origins of the Modern Economy*, Princeton Press, Princeton.

[4] See Ward Hanson, (2015), "Embedded Space and Information Competition," Economist Corner's, *New Space*,, Vol. 3, No. 1.

[5] Rolfe Winkler and Andy Pasztor, (2017), "Exclusive Peek at SpaceX Data Shows Loss in 2015, Heavy Expectations for Nascent Internet Service," *Wall Street Journal,* January 13.

[6] Roger D. Launius, (2014), *Historical Analogs for the Stimulation of Space Commerce,* Monographs in Aerospace History, no. 54, National Aeronautics and Space Administration.

Park Service. As he states: "Each of the six cases covers meaningful lessons in political culture and circumstances, legal precedent, methods of execution, and change over time. Many are considered positive stories of successful public involvement in the private sector; some are cautionary tales of overreach and over-management; and some present lost opportunities that might have been more successful had circumstances been handled differently."

Launius considers whether a system of resource grants might work for some commercial space ventures. Like the alternating tracts given to the railroads, partial rights to develop the Moon, asteroids, or Mars could provide incentives for construction and valuable spill-over benefits to others. Two immediate problems arise. First, costs must fall dramatically for such ventures to make economic sense. Second, international law must change. The 1967 Outer Space Treaty currently forbids both national sovereignty and private ownership of astronomical bodies.[7] Unless the U.S. works to alter this treaty, or exits from its rules, no governmental body has the authority to assign property rights in outer space as an incentive.[8]

While government demand provided the bulk of early orders, U.S. policy has always relied on private firms to manufacture planes and provide aviation transport services. Militaries around the world spent heavily to transform the airplane from the Wright Flyer to a reliable craft and effective weapon. In World War I, the U.S. created the Army Air Service, U.S. manufacturers produced 11,950 planes during the war, and 69 military airfields with the United States. Following the war, airmail contracts with the U.S. postal service often provided the financial underpinnings of medium and low volume air routes and helped establish strong international routes.[9] During the Great Depression, airport construction was a natural project for the WPA.[10] Multiple regional airports provided large projects sharing similar designs and the need for many construction workers. New airports also spurred highway and bridge construction, also WPA favorites. In an ongoing effort to support new engines and airframe designs, the U.S. government created the National Advisory Committee for Aeronautics (NACA). NACA was a very important source of research and development for aviation for decades.

Developing aviation safety regulations provides lessons and context for the beginnings of space tourism. Following high-profile collisions, and many near misses, Congress created the Federal Aviation Administration. The FAA instituted air traffic controls over the most congested regions. The FAA also enforced a wide variety of safety measures, inspections, and post-accident reviews. Much of this regulatory infrastructure has been brought forward to commercial space.

Telecom provides one of the more cautionary of the Launius policy examples. For almost a century, AT&T dominated the telephone system in the United States. Most economists and regulators viewed telephony as a natural monopoly. This approach became engrained in Bell system practices. AT&T only permitted its own phones, modems, or faxes to connect to the system. While some Court and regulatory decisions loosened these restrictions somewhat beginning in the late 1960s,[11] it required the 1980s antitrust breakup of AT&T to set the stage for the telecommunication revolution of the 1990s.[12]

Launius's telecom example demonstrates the possible tension between innovation and competition. Competition policy is challenging when a monopoly arises due to patents, market forces that favor a winner-take-most result, or breakthroughs that allow one company to achieve a dominant market share. This may occur in the space market. For example, the first launch company to successfully deploy highly durable and easily reusable boosters may be in a position to dramatically underprice all rivals and deter potential rivals. Wise policy must balance both short run and long run efficiency concerns.

While the digital analogs share some of the Launius themes, there are important factors not present in the railroad, early aviation, or telecom examples. Digital technologies demonstrate the impact of dramatic and continuous declining costs, and also illustrate the role and incentives of venture capital financing. These digital industries are also technologically much closer to space markets, and enable many of the space systems. Policy makers can learn valuable regulatory lessons from these digital analogs and anticipate some of the growth areas of the commercial space business.

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[7] As stated in Article II of the treaty: "Outer space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means." "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies," U.S. Department of State. Signed January 27,1967, entered into force October 10, 1967.

[8] It is unlikely the United States would choose to exit the treaty entirely, as the treaty also has important and stabilizing restrictions on the placing of nuclear weapons in space.

[9] A fascinating discussion appears in T.A. Heppenheimer, (1995), *Turbulent Skies: The History of Commercial Aviation,*, Wiley, especially section 2.

[10] Ibid., pp. 119–120.

[11] See Federal Communications Commission. (1968) Use of the Carterfone Device in Message Toll Telephone Service, 13 FCC 2d 420, Docket No. 16942 and 17073, June 26. Also see Gregory Rosston and Michael Topper, (2009), "An Antitrust Analysis of the Case for Wireless Network Neutrality, SIEPR Discussion Paper No. 08–040, August.

[12] On this, see Shane Greenstein, (2015), *How the Internet Became Commercial,*, Princeton Press, especially section 2, "The White House Didn't Call."

2 Lessons From the Computer's Rise

2.1 Transistors, Technology Forecasting, and the Missing Communication Satellite Patent

A satellite orbiting 22,236 miles above the equator occupies a technically special and economically valuable position. Such a geosynchronous satellite's speed just matches the Earth's rotation rate. Geo satellites are a fixed spot in the sky for ground based antennas, with no tracking required. From such a vantage point, satellites also have a large footprint. A communication satellite in geo-orbit can rebroadcast television signals, relay phone calls, and transfer data to nearly 1/3 of the Earth's surface.

Geo-orbits are sometimes called the Clarke Belt, due to an October 1945 article published by science fiction writer Arthur C. Clarke.[13] In "Extraterrestrial Relays," Clarke sketched the feasibility of communication satellites, paying attention to the broadcast and receiving power requirements and the appropriateness of the system for television and FM radio. Had Clarke applied for a U.S. patent, he almost certainly would have received the fundamental patent on using geosynchronously-located communication satellites.

In later commentary, Clarke explained his lack of patent filing.[14] It was not an early commitment to open source systems, but rather Clarke's belief that a manned space station must accompany any long duration satellites. Satellites require on-board amplifiers to boost and re-broadcast signals. At the time of Clarke's article, amplifiers relied on vacuum tubes. Vacuum tubes are bulky, consume large amounts of power, and fail often. Even if they survive the voyage to space, vacuum tubes soon burn out with use. Clarke concluded that geo-satellites would require frequent maintenance visits from astronauts, requiring some form of orbiting space station. Clarke was keenly aware of the requirements of a manned space program, and correctly predicted that a manned station was at least two decades in the future.[15] Clarke anticipated that his patent would expire long before any such station, and any licensing revenue would be moot. Publication gave him credit for the insight, even if geo-satellites brought him no riches.

What Clarke failed to anticipate was the transistor. While Sputnik used vacuum tubes for its simple and short-lived radio beacon,[16] communication satellites have all relied on transistors. Transistors are far more durable than tubes, lasting years without repair. Digital innovation made communication satellites much closer to reality than Clarke's forecast, without the need for orbital repair stations. Syncom 3, launched in 1964, was the first geo-communications satellite and transmitted the Tokyo Olympics live to the U.S. market.[17] Many others followed soon after.

Clarke's "missing patent" illustrates two important phenomena. The first is the standard uncertainty that accompanies all innovation. Even someone as astute and imaginative as Clarke missed the *possibility* of an enabling invention just two years in the future.[18] Vacuum tubes were the critical barrier for Clarke, and their replacement was well on the way.

The second point shown by the Clarke example is the fundamental enabling role information technology plays for the space program. Commercial space is one of many industries, such as the Internet in the 1990s or autonomous vehicles today, that owe their existence to digital technology. The supply of modern semiconductors, integrated circuits, and powerful computers made the space program possible.[19]

2.2 From Weapons to Word Processing

2.2.1 The Military Years

The computer was invented with military funding. As Richard Rhodes comments: "The first problem assigned to the first working electronic digital computer in the world was the hydrogen bomb."[20] For the first decade of computing the design of atomic weapons provided the major source of computing demand. The U.S. military was the biggest funder of computing, as weapons projects were desperate for more powerful computing tools to analyze the complex design tradeoffs in both fission and

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[13] Arthur C. Clarke, (1945), "Extra-terrestrial Relays," *Wireless World,* October, pp. 305–308.

[14] Arthur C. Clarke, (1968), *The Promise of Space,* Harper & Row.

[15] The first manned flight by Yuri Gargarin was in 1962, but it would be a decade more before a space station would be in orbit. Even then, it would be in low earth orbit, far below the Clarke orbit.

[16] Jenny List, (2016), "Sputnik's Transmitter Beeps Again," Hackaday, February 23. Sputnik launched in 1957, 12 years after the Clarke article.

[17] Clarke, op. cit.

[18] William Brinkman, Douglas Haggan, and William Troutman, (1997), "A History of the Invention of the Transistor and Where It Will Lead Us," *IEEE Journal of Sold-State Circuits,* Vol. 32, No. 12, December. The first types of transistor were significantly more complex than the modern "planar" design that emerged in the late 1950s.

[19] For a fascinating discussion of emerging electronics and the Apollo program, see David Mindell,(2008), *Digital Apollo: Human and Machine in Spaceflight,* MIT Press, Cambridge. For example, the Apollo/ Saturn V systems used discrete transistors in most systems, but integrated circuits in the command ship's main computer.

[20] Richard Rhodes, (1995), *Dark Sun,* Simon & Schuster, p. 251). Futhermore:

"The ENIAC ran a first rough version of the thermonuclear calculations for six weeks in December 1945 and January 1946. Los Alamos prepared a half million punched cards of data, enough to keep a hundred people busy for a year at mechanical desktop machines."

fusion devices.[21]

As the Soviets acquired a fission bomb (1949), followed by a fusion bomb (1953), early warning systems capable of detecting Soviet bombers became a critical national priority. Such a system demanded far greater computing capabilities than existed, with sensors stretched over thousands of miles, and led to tens of billions of dollars invested in the SAGE radar and computing complex. The SAGE system drove many computing breakthroughs, fundamental to later timesharing and interactive commercial systems.

Memory was one of the biggest bottlenecks in computer performance and reliability. Early computers used cumbersome and unreliable display tubes as memory storage. Multiple failures per day, triggered by tube failures or even changes in the weather, were common. A real-time, high stakes system such as SAGE needed vastly better performance and much longer mean time between failure. The SAGE program, specifically MIT's Jay Forrester, made a breakthrough with the invention of magnetic core memory. SAGE also pioneered interactive displays, advanced methods of time-sharing, fault tolerant banks of computers, and other speed, usefulness, and reliability boosting approaches.[22]

The first computers worked on problems deemed essential to national security - atomic weapon design, tracking enemy bombers, and cracking enemy codes. The budget for these activities was secondary to mission success. Basic research and development under military contracts led to rapid improvement in almost all areas of computer hardware.

It was during the computer's military years that programming went from wiring diagrams to software compilers.[23] The early breakthrough general purpose machines - ENIAC, Von Neumann's IAS machine, Turing's Mark I, the IBM 701, and the SAGE Whirlwind, all used machine language. These multi-million dollar mainframes were difficult and expensive to program. It wasn't until April 1957 that FORTRAN finally was finished, and then only available on the IBM 704. Other machines, and other programming languages, followed soon after.[24] By 1960 most computers used recognizable programming languages, with high-level instructions compiled by the computer into its own required machine language.

The early wave of computers were almost exclusively government funded. Between 1949–1959 the government was the most important funder of research and development. By the end of the period the balance was shifting toward commercial self-financing, but all the major commercial systems could trace their R&D closely to military systems. Table (1) from Flamm highlights the split in R&D during the 1950s.

The military was also paramount in funding the development of the transistor. Although computers made great strides between 1945 and 1955, they still relied on bulky, unreliable, and power hungry vacuum tubes. Were this to continue, computers would remain high-cost specialty devices operated by only by the largest of organizations with the highest-value needs. What changed all of this, as well as our entire technological base, was the introduction of semiconductor transistors and integrated circuits. With semiconductor logic, computers became vastly more powerful. At the same time, they became much cheaper to build, own, and operate.

Each successive transistor inventions, such as the point contact transistor (1948), the junction transistor (1951), and the planar transistor (1958) was developed on government contract: As Riordan and Hoddeson put it:[25]

> "Fortunately, Bell Labs and Western Electric had four wealthy customers - the U.S. Army, Navy, and Air Force, plus AT&T itself - that were very interested. In the mid-1950s all of them were eager to send, receive, and manipulate electronic signals at the highest frequencies, where the greatest amounts of information could be transferred most rapidly. They were ready to foot the high up-front costs of making diffusion and silicon manufacturing technologies a reality."

Transistors were absolutely vital for the compact advanced avionics used in missiles, satellites, and manned spacecraft. By the end of the 1950s, transistors had replaced tubes in all new computer designs. Integrated circuits would soon follow, where multiple transistors and other circuit elements were combined on a single crystal of silicon.

2.2.2 IBM Goes Commercial, and Dominates the Mainframe Market

While IBM was not the earliest commercial computing firm,[26] it was the most successful in translating lessons

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[21] The history of support for the computer is well-covered in Kenneth Flamm, (1987), *Targeting the Computer: Government, Support and International Competition,* The Brookings Institution, Washington, D.C.

[22] See both Buderi and Stan Augarten, (1984), *Bit by Bit: An Illustrated History of Computers,* Ticknor & Fields, New York.

[23] Augarten, op. cit., especially pp. 195–223.

[24] Ibid, p. 216–217.

[25] Michael Riordan and Lillian Hoddeson, (1997), *Crystal Fire: The Invention of the Transistor and the birth of the Information Age,* Norton, p. 224.

[26] Eckart and Mauchly, inventors of the ENIAC, always aspired to serve the commercial market. As early as 1947 Prudential Insurance was investing in their company and developing a computer for actuarial uses. See Arthur Norberg, (2005), *Computers and Commerce: A Study of Technology and Management at Eckert-Mauchly Computer Company, Engineering Research Associates, and Remington Rand, 1946-1957,* MIT Press, Cambridge.

Table 1: *Government and Private Funding of Computer Research and Development of Selected Companies, 1949-59*

Company	Government Funding (Million Nominal $)	Private Funding (Million Nominal $)	Gov. Share
General Electric	$1,500	$1,370	52%
Sperry Rand	854	113	87%
Bell System	760	832	48%
IBM	397	184	68%
Raytheon	325	38	90%
RCA	275	324	46%
Computer Control Corp.	2.1	0.4	84%
Total	$4,113	$2,881	59%

Source: Flamm (1987), Table 4-1, p. 96.

learned on government contracts to the consumer marketplace. IBM's 1950s government contracts implementing SAGE for the Air Force, the Stretch computer for NSA, and the 7090 for the Ballistic Missile Early Warning System all created a technological base and manufacturing capacity that it could turn to creating a consumer computing market. "Well more than half" of IBM's research and development spending in the 1950s was paid for by U.S. government contract.[27] The government attached no royalties or residual payments for this backing, and it helped IBM become the world leader in computing. This is a pattern repeated throughout the decades in computing, where public R&D has been central to new computing capabilities.

Beginning in the 1960s, IBM invested heavily in consumer-oriented computing, leading to the breakthrough System/360. At the time, the System/360 was the largest private investment ever in a new product. IBM invested more than $5 billion in a four-year period, with $500 million on research and development and $4.5 billion for new plant and equipment.[28]

Compatibility was a breakthrough feature of the System/360. The same software could run on the largest or the smallest member of the family. This was a radical improvement in usability, and customer demand was extremely high. The System/360 moved IBM into a leadership position it held for several decades.

Even though integrated circuits were available in the early 1960s, the System/360 was transistor-based. IBM moved to integrated circuits in the 1970s, with the successor System/370. While this was several years after its competitors Control Data and NCR, IBM's combination of compatible software and sales force made it safe for IBM to delay its adoption of integrated circuits.

By the end of the 1970s the computer had existed for nearly forty years. IBM was the dominant computing firm, facing a modest challenge from the plug-compatible firms. Mini computer makers, such as Digital and Data General, had also carved out successful offerings by offering smaller systems tailored to mid-sized businesses and university departments. Computing appeared to be a stable oligopoly, with industry observers worrying about a lack of innovation and a potential threat from Japanese computer companies. All this would change rapidly. Once again, a semiconductor breakthrough transformed computing.

2.2.3 Personal Computing and Ubiquity

Computing historian Paul Ceruzzi states that "Second only to the airplane, the microprocessor was the greatest invention of the twentieth century."[29] This was not Intel's perception when it invented the microprocessor. Intel initially viewed the microprocessor as an industrial control device, and did not envision why anyone would want such an underpowered computer.[30] Intel originally developed its first microprocessor, the Intel 4004, under contract to calculator company Busicom.[31] In the next couple of years it released two more powerful versions, the 8008 and the 8080. Intel's 8080 and MOS Technology's 6502 would be the chips to launch the personal computer market.

The personal computer's development fell to hobbyists and startups, rather than established computing firms. The personal computer is a classic example of Clayton Chistensen's "entry from the bottom."[32] Hobbyists and startups create a new, inexpensive product that barely qualifies as a working computer. Being cheap, it captures the price sensitive market willing to live with limitations and partial functionality. Over time, as capabilities grow

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[27] Flamm, (1988), op. cit., p. 94.

[28] Augarten, op. cit., pp. 248–251.

[29] Ceruzzi, P., (2012), *Computing: A Concise History,* MIT Press, Cambridge.

[30] Ibid.. Also see Arnold Thackray, David Brock, and Rachel Jones, (2015), *Moore's Law: The Life of Gordon Moore, Silicon Valley's Quiet Revolutionary,* Basic Books.

[31] See Augarten, op.cit., pp. 253–281, for a history of the personal computer from 1970–1982.

[32] See, for example, Joseph Bower and Clayton Christensen, (1995), "Disruptive Technologies: Catching the Wave," *Harvard Business Review,* January-February.

while retaining the low price, the challenger wins more and more share from the incumbent (and expensive) providers.

The acknowledged first personal computer was the Altair 8800, announced in January 1975, and sold by a small company MITS in Albuquerque. It used the Intel 8080.[33] This is the machine that convinced Paul Allen to join MITS, and Bill Gates to leave Harvard and form Microsoft. A version of BASIC for the Altair was Microsoft's first product.

Microprocessors also stimulated the formation of the Homebrew Computer Club in Silicon Valley, which in turn became a hotbed of personal computing hobbyists. Homebrew's most famous alums, Steve Wozniak and Steve Jobs, launched the Apple I in 1975. By 1977, Apple had become a successful venture-backed startup with the Apple II.[34] Apple went public in December 1980.

The largest selling personal computer in the late 1970s was the TRS–80 from Radio Shack.[35] With a national retail presence, and a willingness to advertise the personal computer, Radio Shack was able to sell several hundred thousand TRS–80s per year from 1977 until the mid–1980s.[36]

IBM was much more proactive when confronting the personal computer market than it was when confronting the mini computer challenge. Teaming up with Microsoft, the IBM PC quickly became the leading business micro computer. Over time, PCs grew to dominate the home market as well. By 1990, IBM PCs and compatibles had nearly a 90% market share.

Personal computers transformed and expanded the computer industry. In 1974, fewer than 115,000 existed in the world.[37] By 1995 approximately 300 million units had been sold worldwide. Computing had become an every day part of business and society.

2.3 The Digital General Purpose Technology

> "Even after the early computers were developed, businesses continued to underestimate the demand for the new machines. Predicting demand when enormous cost declines have deposited a producer on a distant and entirely unfamiliar region of a demand curve is an uncertain proposition. The lesson, perhaps, is that with a sufficiently new and advanced concept, demand is created by a learning process. Users begin to understand how a radically new piece of technology can fit their needs only through experience with it. Certainly, this theme appears early and prevails throughout the history of information processing technology." - Flamm (1988)

The computer's rise is an example of the broader digital computing general purpose technology (GPT). GPTs are a economic concept highlighting that some innovations are so powerful they serve as the "engines of growth."[38] in the economy. The steam engine, the railroad, electrification, and the internal combustion engine all are acknowledged GPTs. Our era has been dominated by the digital GPT.[39]

There are three defining features of a GPT. First, a GPT is subject to major cost declines and quality improvements. The early manifestations of the technology are typically expensive and limited in function. Over time the cost/quality tradeoffs change dramatically. Second, GPTs yield many spinoff industries. Some of these spinoff industry can be sufficiently powerful to be considered GPTs in their own right. Third, GPTs have strong economic and technological complementarities. One the economic side, the fall in the price of the GPT drives up demand for complementary inputs. Systems of production are redesigned to take advantage of the input falling in price and growing in capabilities.

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[33] As Augarten points out, a much cruder kit called the Mark–8 appeared six months earlier form another individual (Jonathan Titus). Among other things, it lacked any durable ROM memory and even the operating system had to be laboriously entered in by toggle switch after every power on.

[34] Based on the MOS 6502 chip.

[35] Based on the Zilog Z80 chip, which remained the most popular microprocessor for personal computers into the early 1980s, supporting the CP/M operating system.

[36] Unable to compete with both Apple and the new IBM PC, Radio Shack exited the personal computer market by 1985

[37] Martin Campbell-Kelly, (2003), *From Airline Reservations to Sonic the Hedgehog: History of the Software Industry,* MIT Press, Cambridge, p. 90.

[38] See, for example, Timothy Bresnahan and Manual Trajtenberg, (1995), "General Purpose Technologies 'Engines of Growth'?, *Journal of Econometrics,* , Vol. 65, pp. 83–108 and Elhanan Helpman (editor), (1998), *General Purpose Technologies and Economic Growth.* MIT Press, Cambridge, see p. 43.

[39] Quote above from Kenneth Flamm, (1988), *Creating the Computer: Government, Industry, and High Technology,* The Brookings Institution, Washington, D.C., see especially "section 7: How Computer Firms Compete." The history of support for the computer is well-covered in Kenneth Flamm, (1987), *Targeting the Computer: Government, Support and International Competition,* The Brookings Institution, Washington, D.C. See also A very good popular treatment of this is James Gleick, (2011), *The information: a history, a theory, a flood.* Pantheon Books, New York.

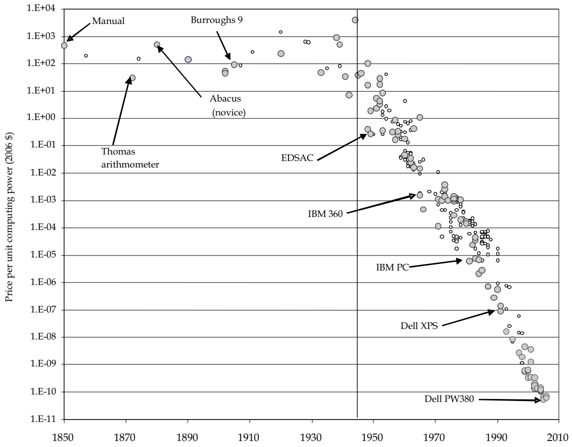

Figure 1: *Nordhaus (2007) finds exponential declines began with digital computing.*

2.3.1 Digital GPT Cost Reductions

Figure (1) demonstrates the astonishing rate of progress of the digital GPT, as measured by the declining cost of computation.[40] Modern computers are over a trillion times more powerful than those early models.

For hundreds of years, computing technology was a backwater. Decades might transpire between improvements. Yale economist William Nordhaus documents the very slow progress from 1850–1940 and the exponential improvements thereafter. A key limitation in this early period was the lack of sufficiently precise manufacturing tools. Charles Babbage provides a striking example. In the early and mid 1800s Babbage created plans for a “Difference Analyzer” and an “Analytical Engine.” His Difference Analyzer blueprints were sufficiently detailed that the British Museum of History used them in 2002 to produce two working devices. Babbage’s Analytical Engine was much more ambitious, and would have been a full fledged computer nearly 100 years earlier than actually occurred. Machining capabilities were too crude to build the machine, and mechanical switches too slow, for the computing device to be practical. While Babbage had developed many of the theories and core design principles, as he himself was forced to concede: “another age will have to be the judge.”

By World War II, electronics had developed to the point where computers were now feasible. War time needs in cryptography, radar systems, ballistics, and the Manhattan Project[41] provided high priority demands justifying the computer development efforts. The previous twenty years of electronics, especially vacuum tubes, created the necessary components for a digital computer.

Miniaturization is the driving force behind the cost declines reflected in the Nordhaus graph. The underlying physics were sketched out by Richard Feynman in a 1959 after-dinner speech entitled *There’s Plenty of Room at the Bottom*.[42] Feynman pointed out the multiple benefits when circuit elements become smaller. Signals travel shorter distances, current requirements drop, material costs fall, and the entire circuit runs faster. This is true regardless of whether the components are tube or transistor, discrete or integrated. As Feynman put it: “There is nothing that I can see in the physical laws that says the computer elements cannot be made enormously smaller than they are now. In fact, there may be certain advantages.” For the past 70 years computer technology has benefitted from the virtuous cycle of miniaturization. By the time of Feynman’s speech there had already been 15 years of exponential cost decline. This performance improvement has continued for another 55 years.

While Feynman provided the *direction* of the computing industry, a short 1965 essay by Gordon Moore of Intel that appeared in *Electronics* magazine came to be viewed as setting the *pace* of this miniaturization and cost reduction progress.[43] Asked to consider the evolution of the industry, Moore sketched his thoughts about cost improvements in the rapidly growing semiconductor industry. What is now known as Moore’s Law is the steady doubling of computing power and the rapid fall in computing cost. Engineers and business people struggle to maintain pace, and Moore’s Law became the focal point for these design objectives.

Innovation in the components underlying digital computing assisted in this race to smaller, faster, and cheaper. The earliest mainframes filled a room, consumed massive amounts of electricity, and failed often. By the late 1950s transistors replaced vacuum tubes, dramatically improving reliability, speed, and energy efficiency. The 1960s and 1970s saw the rise of integrated circuits, and their incorporation into computer memory and controls. By the 1980s integrated circuits were powerful enough to support consumer-oriented personal computers. By the end of the 1980s there were millions of computers capable of communicating and sharing information. At that point, an Internet was both feasible and highly desirable.

The digital GPT has been a central driver lowering the cost of space by reducing the weight needed to perform a task in space. Both the purchase price of satellites

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[40] William Nordhaus, (2007), “Two Centuries of Productivity Growth in Computing,” *Journal of Economic History,* Vol. 67, No. 1, pp. 128–159.

[41] For an in-depth yet accessible treatment, see George Dyson, (2012), *Turing’s Cathedral: The Origins of the Digital Universe,* Pantheon Books.

[42] Richard Feynman, at the annual meeting of the American Physical Society at the California Institute of Technology. First published in Caltech’s Engineering and Science, 1960. Feynman stressed that the eventual limits were quantum mechanical, and these were vastly smaller than the scale of circuits in 1960.

[43] Gordon Moore, (1965), “Cramming more components onto integrated circuits,” *Electronics*, Vol. 38, No. 8.

and the required mass for a given satellite function have fallen dramatically due to the digital GPT. The biggest difference between space possibilities now and the Apollo era is not in our rockets, but in our computers.

An extreme example of the interaction between space and the digital GPT is a highly ambitious effort by the Breakthrough Initiative to create deep space nanosatellite probes. Funded by Internet-entrepreneur Yuri Milner, the Initiative seeks to combine extraordinarily compact electronics, high efficiency solar sails, and Earth-based laser arrays into a deep space exploration system capable of near-relativistic speeds.[44]

Electronic miniaturization is at the heart of the approach. Table (2) illustrates estimates of satellite components available in the year 2000, 2016, and projected requirements for 2030. Consider just the first row of the table, the weight of a camera module. In pre-cell phone days, digital cameras were bulky and inefficient. Intense market competition, driven by a global cell phone market supply chain, has resulted in vastly smaller, more powerful, and much more energy efficient detector chips and lenses. The same is true of processors, opto-electronics, and other widely used commercial electronic components. The weight of satellite components has already fallen by more than –99% compared to 2000. The 2030 improvements needed are modest in comparison. Much more challenging is the propulsion system, utilizing high-power phased-array ground lasers to "push" the nanosatellite towards its target.

Other new space efforts benefit greatly from ongoing digital miniaturization. Companies such as Planet Labs use clusters of small satellite to provide commercial views of Earth for agriculture, mining, forestry, and other uses. Very large constellations of small but powerful Internet communication satellites are being developed for low-earth orbit. As discussed in Section 6, for the foreseeable future the new space market is in essence a digital spinoff.

2.3.2 Digital GPT Spinoffs and Complementarities

Input substitution is one of the most basic and powerful insights of economics. That is, when an input becomes more plentiful it is efficient to use more of it. This is true for both business and consumer uses. When a technology improves at the rate of the digital GPT, it leads to widespread substitution in an ever-growing number of industries. This is especially the case when new uses and new applications are possible, rather than just more of the same.

Delong and Summers (2001) point out that the digital GPT has been able to transform much of the economy by reinventing and expanding its uses. The first two decades of computing were dominated by "complicated and lengthy sets of arithmetic operations."[45] Scientific computing was central to the earliest usage of computing in weapons research and a national radar defense system. Both computing and the space program owe their early successes to the Cold War nuclear rivalry between the United States and the Soviet Union.

In the 1960s computing moved from primarily governmental to those funded by commercial demand. Corporate databases provided the second broad area of computing applications, with finance and insurance firms using mainframes to track customer accounts and stock market trades. By the mid–1960s these mainframes were powerful enough to handle real-time databases, such as airline reservation systems and manufacturing inventory control.[46]

Complementary assets are the third defining characteristic of GPTs. Technological complementarities are those "whose full benefit cannot be reaped until many of the other technologies that are linked to it are re-engineered, and the makeup of the capital goods that embody them are altered."[47] For computing the most important of these is software.

While software has always been essential to computing, the software industry was relatively slow to emerge. For the first few decades computing companies bundled their main packages with the hardware. Software expertise was valuable, and computer services companies emerged as one of the most important adjunct to hardware. Companies such as CSC and EDS were fundamental supports to large organizations' computing efforts, producing public companies and fortunes for their founders.[48] IBM announced plans to unbundle its computer systems in late 1968, apparently in response to a Justice Department antitrust investigation. Minicomputers and microprocessors always supported third party software.

The personal computer has been especially influential. Beginning in the 1970s, spreadsheets and word processors dramatically altered white collar work in small firms as well as the largest corporations. While it took until 1980 for the U.S. software market to reach $5 billion in sales, by 1990 it exceeded $44 billion and reached $138 billion in 2000.[49]

Not all third-party software was proprietary, in fact some of the most widespread and important software is open source. There is a long tradition of open source software, partly driven by AT&T's consent decree with the government restricting it from entering computer ser-

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[44] See material at https://breakthroughinitiatives.org.

[45] J. Bradford DeLong and Lawrence Summers, (2001), "The 'New Economy: Background, Historical Perspective, Questions, and Speculations," Federal Reserve Bank of Kansas City Fourth Quarter.

[46] Summers and DeLong, op.cit., p. 40. Flamm statistics.

[47] Helpman, op. cit. p.42.

[48] Martin Campbell-Kelly, (2003), *From Airline Reservations to Sonic the Hedgehog: History of the Software Industry,* MIT Press, Cambridge.

[49] Ibid., p. 175.

Table 2: *Solar Sailing Nano-satellite Mission Weight, by Year*

	Weight of Module, by Year, in milligrams		
Module	**2000**	**2016**	**2030 (Forecast)**
Cameras	24,000	40	20
Wiring	15	15	5
Radio-isotope battery	6,100	150	130
Processors	20,480	40	10
Navigation	10,240	20	20
Communication lasers and photon thrusters	24,000	60	20
Structure	100	25	10
Protective Coating	20	20	20
Total Mass in milligrams	84,955	370	220
(Percent of Year 2000)	100%	0.44%	
(Percent of Year 2016)		100%	59.5%

Source: Breakthrough Institute, 2016.

vices.[50] The Unix operating system and the C language emerged from Bell Labs, and became mainstays on university campuses. They would eventually become central to the Internet. The open source movement influenced World Wide Web development, with Tim Berners-Lee and CERN choosing an open source approach to these enabling technologies.[51]

2.4 Computing and Space: A Symbiotic Relationship

The space program and computing began at roughly the same time and for the same purpose. Both were military in nature, geared to winning World War II and the Cold War. Each was dominated by the specter of the atomic bomb. At the onset, each was impractical for commercial use, requiring major improvements and cost reduction.

The United States government wisely encouraged commercial adoption of the technologies it funded. By the 1960s computers were set to become primarily commercial. The IBM System/360 emphasized private sector demand. Military applications continued to drive many of the most advanced integrated circuits, which were then quickly applied in the commercial sector.

Both computing and space are dual use technologies. The balance between military and commercial shifted in computing decades ahead of space efforts. Part of this is technological. Computers are universal devices, and even the most primitive computers can (theoretically) attack almost any problem. Computers were able to evolve gradually from tubes to transistors and integrated circuits. As the digital GPT improved, computing use expanded. Performance improvements meant that the problems that justified computing could move from the existential threat category to more mundane tasks such as tracking insurance policies and scheduling warehouse shipments.

The U.S. computer market developed a dominant firm. While the U.S. government did eventually prosecute IBM for antitrust violations, the negotiated remedies were more important in the medium to long term. An end to "leasing only" IBM contracts created a market for the plug compatible firms, encouraging separate software, central processor, and peripheral markets. This unbundling helped set the stage for the eventual development of the minicomputer and microcomputer markets. These smaller and cheaper computers were necessary to extend the uses of computing, and maintain the momentum of Moore's Law. They were also fundamental in creating ubiquitous computing, a prerequisite for a widespread commercial Internet.

The laws of physics are much kinder to low-cost computing than to low-cost space flight. The physics of launch thrust, multi-stage rockets, and required orbital speeds have been well understood since the early days of rocketry.[52] There have been only modest rates of improvement in chemical fuels. While digital improvements in avionics and communications improved rocket accuracy and control, launch expenses stayed very high.

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[50] Steven Weber, (2004), *The Success of Open Source,* Harvard. See especially section 2, "The Early History of Open Source."

[51] Tim Berners-Lee, (1999), *Weaving the Web: The Original Design and Ultimate Destiny of the World Wide Web by Its Inventor,* Harper, San Francisco.

[52] For an especially interesting discussion of Tsiolkovsky's work and others, see Werner von Braun and Frederick Ordwy III, (1966), *History of Rocketry & Space Travel,* Crowell Company.

3 Learning From a Commercial Internet

3.1 Venture Capital and the Netscape Moment

For many investors, the Internet became real on August 9, 1995.[53] This is the day that Netscape went public. The stock launched at $28, tripled during the day and closed at $58.[54] A company that provided mostly free browser software was suddenly valued at more than $2 billion. Netscape was the first big Internet public offering, and it led to money pouring into venture-backed Internet startups.

Microsoft's Bill Gates famously downplayed the early commercial rise of the Internet and Web. Netscape's IPO startled Gates, and even more so the chance that an Internet browser provider might create an alternative operating system to the dominant Windows platform. By December 1995 things had changed, with Gates announcing that Microsoft would become Internet-centric.[55] Microsoft had already begun giving away its browser in August 1995, bundling it with Windows. It would aggressively push the use of Internet Explorer, making hardware manufacturers feature IE and creating difficulties for Netscape. Although Microsoft's aggressive attacks on Netscape would eventually be a leading factor cited in its antitrust violations, Microsoft's conviction came after Netscape found it necessary to become part of America Online.[56] Despite Netscape's head start and rapid growth, the power of a dominant incumbent willing to give away the same product as Netscape's main offering was too much.

Another feature of the Netscape moment was a flood of resources into a commercial Internet. Figure (2) shows the dramatic rise in U.S venture investing during the late 1990s, driven by the Internet.[57] No subsequent year has come close to the peak level reached in 2000. More than $100 billion of new funding flowed into venture capital during a single year. The Internet received the lion's share, with $20 billion for Internet software, $14 billion for fiber optics, $20 billion for Internet content, $3 billion for Internet services, and $15 billion for wireless telecommunications.[58] While many of these VC-funded companies would come to ruin, there were also huge successes.

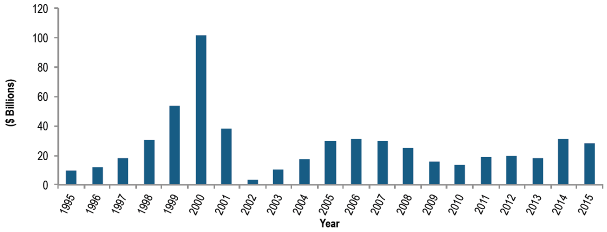

Figure 2: *The Internet Spike in the Venture Capital World (nominal value). Source: 2016 National Venture Capital Yearbook.*

Founders of some of the largest winners, such as Amazon, PayPal, and Google, are now active in new space ventures. Table (3), adapted from Startup Space, lists twenty-one billionaires with notable space affiliations. More than 2/3 of the participants made their fortunes in some version of information technology and software. The highest profile examples are Elon Musk and Jeff Bezos. Musk made his initial fortune as part of PayPal and risked it all on both SpaceX and Tesla. Blue Origin, founded by Jeff Bezos, has had success in landing and re-using its suborbital launcher. Planetary Resources is another space venture attracting investments from Internet veterans. Google is prominent with Larry Page, Eric Schmidt, and Kavitark Ram Shriram. Charles Simonyi, with a Microsoft background, is also a backer. Planetary Resources has asteroid mining as a long-term goal, with Earth observation as part of its shorter-term objectives.

These new space leaders bring a mindset and culture nurtured in the Internet world. They have called for an "Internet moment" for the commercial space program. In one sense this is ironic. Space has already had a decade exceeding the 1990s Internet.[59] Between 1960 and 1970 the "Apollo moment" poured money and talent into the race to the moon. Apollo funding came from the government, motivated by Cold War politics. The Internet alums and new space founders hope for is a critical private success that crystallizes investor perceptions that space is good business.

Venture capital operates differently than government contracting or debt-based financing. One of the challenges for effective regulation in commercial space is co-existing with the timescales, market needs, and culture common to venture-backed startups.

This section begins with the precursors to a commer-

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[53] Campbell, W. Joseph (2015). *1995: The Year the Future Began,* University of California Press.

[54] John Shinal, (2005), "Netscape: The IPO that Launched an Era," *Marketwatch,* August 5.

[55] Ken Auletta, (2001), *World War 3.0: Microsoft and Its Enemies*, Random House, Toronto.

[56] The acquisition occurred in November 1998, with the final decision on remedies in the MSFT case not occurring until April 2000. Ibid., p. 117 and 372.

[57] 2016 National Venture Capital Yearbook.

[58] Greenstein, op.cit., p. 261.

[59] While subject to some debate regarding the proper inflation indexing, the U.S. manned space program received more than $100 billion in funding (2017 dollars) during the 1960s.

Table 3: *The Well-Heeled Space Funders With Internet Backgrounds*

Name (2015 Net Worth)	**Source of Wealth**	**Notable Space Affiliation**
Bill Gates ($79.2 billion)	Microsoft	Kymeta
Jeff Bezos ($34.8 billion)	Amazon.com	Blue Origin
Larry Page ($29.7 billion)	Google	Planetary Resources
Chargles Ergen ($20.1 billion)	Satellite TV	DISH Network
Paul G. Allen ($17.5 billion)	Microsoft	Scaled Composites, Stratolaunch Systems, Vulcan Aerospace
Ma Huateng ($16.1 billion)	Tencent	Satellogic, Moon Express
Elon Musk ($12.0 billion)	PayPal, Tesla	SpaceX
Eric Schmidt ($9.1 billion)	Google	Planetary Resources
Yuri Milner ($3.2 billion)	Facebook	Planet Labs, SETI
Peter Thiel ($2.2 billion)	Facebook, Palantir	SpaceX
Kavitark Ram Shriram ($1.9 billion)	Venture capital, Google	Planetary Resources
Craig McCaw ($1.8 billion)	Telecommunications	Teledesic, ICO
Charles Simonyi ($1.4 billion)	Microsoft	Planetary Resources
Kenji Kasahara ($1.4 billion)	Social networking website	Astroscale
Morris Kahn ($1.0 billion)	Software	SpaceIL

Source: Forbes Billionaires, Tauri Group

cial Internet and quickly reviews the movement from propriety systems to an open Net. As with computing, ARPA and other agencies funded many of these Internet capabilities. Following deregulation, the venture-funded boom sealed the transition.

3.2 Setting the Stage

3.2.1 Proprietary Networks

Almost as soon as computers appeared in large organizations, researchers began experiments to remotely access these machines and share information. Bourne and Hahn document a wide variety of efforts in the 1960s and early 1970s, highlighting the many “firsts.”[60] Database search was a key theme, tapping into library catalogs and retrieving scientific journal abstracts.[61] By 1975 there were commercial firms such as DIALOG, LEXIS, and Dow Jones News/Retrieval providing online data access. These companies targeted large businesses with support staff, as the data services were both expensive and difficult to use.

Early U.S. consumer online services also faced numerous challenges. When CompuServe launched in 1976, the typical modem speed was a glacial 300 baud. Services had to maintain a very ”light“ page load. Services distributed CD-ROMs with graphics to augment the online textual content. Usage fees were $12.00 per hour during the day, and $5.00 an hour off-peak.[62] Despite their limitations, online providers The Source, CompuServe, DELPHI, MCImail, GEnie, The WELL, and AOL pioneered consumer online access during the 1980s. Features included online forums, messaging, online encyclopedias, financial services, e-commerce, email, special interest groups, and games.

There were parallel efforts in Europe, especially England and France. In 1981 travel agents could order online through Thomson Holidays. In 1984 a small ecommerce experiment let residents of Gateshead, England order groceries, prescriptions, and bakery items.[63] The French Minitel service was much more extensive, and demonstrated the power of rapidly available information, relatively ubiquity, and the tendency to create unexpected services.[64] Minitel utilized text-based information, and relied on specialized Minitel terminals. Eventually it would become something of a drag on French Internet adoption during the mid–1990s.[65]

By the late 1980s, dial-up speeds had increased by an order of magnitude. Costs also fell. The Prodigy online service was able to introduce a relatively low monthly flat rate price ($9.99 at service introduction) for its new service combined with online graphical advertising. The Prodigy Services Corporation was a household shopping

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[60] Charles P. Bourne and Trudi Bellardo Hahn, (2003), *A History of Online Services: 1963-1976,* MIT Press, Cambridge.

[61] Ibid, see timeline on pp. 415–418.

[62] Michael Banks, (2008), *On the Way To The Web: The Secret History of the Internet and its Founders,* APress, New York. See, especially section 3, “Making Contact with CompuServe."

[63] Michael Aldrich, (2011), “Online Shopping in the 1980s,” *IEEE Annals of the History of Computing,* October-December, pp. 57–61.

[64] William L. Cats-Baril and Tawfik Jelassi, (1994), “The French Videotex System Minitel: A Successful Implementation of a National Information Technology Infrastructure,” *MIS Quarterly,* Vol. 18, No. 1,March, , pp. 1–20.

[65] Eric Brousseau, (2003), “E-Commerce in France: Did Early Adoption Delay Its Development?,” *The Information Society,* Vol. 19, pp. 45–57.

and information service that connected home computers with an online network of servers configured to provide a multitude of education, information, and entertainment services. Prodigy was originally developed as part of a joint venture between CBS, IBM, and Sears, Roebuck and Company and launched in certain test markets in 1988 and nationally in 1990. Whereas CompuServe originally started to serve the business community and then branched out to serve home users, Prodigy followed the reverse course. The primary focus of Prodigy was the home user, only later in its history did Prodigy attempt to launch a business services division.[66]

These early consumer systems were a marketing revelation. Marketers realized that with the rise of personal computers, fax machines, and value-added online services they had a new and potentially much cheaper and more powerful method of directly interacting with customers. Computers allowed catalog and direct marketers to store individual transaction data cost effectively. The new online services suggested they could utilize this personal information to more effectively target and communicate with individual households. Peppers and Rogers pointed out that this had profound effects on the economics of direct marketing:[67]

> “For what it cost a 1950 marketer to keep track of all the individual purchases and transactions of a single customer, today’s marketer can track the individual purchases and transactions of several million individual customers, one at a time.”

The proprietary online services demonstrated latent demand for online capabilities. These limited and high-cost systems needed a more flexible, cheaper, and interconnected technological approach. As with the computer, the product of decades of research funding was ready to fill this need.

3.2.2 DARPA Creates the Internet

The commercial Internet and World Wide Web grew out of decades of research, heavily sponsored by DARPA and other research agencies. The Internet was already 25 years old when it was deregulated. It was, and continues to be, an especially powerful and expandable set of technologies for general purpose online communication.[68]

The governmental origins of the Internet have been well-documented, and somewhat mirrors early efforts in graphical personal computing.[69] The role of the Defense Department’s Advanced Research Projects Agency (ARPA), especially the Information Processing Techniques Office (IPTO) is again central. ARPA funded the basic packet switching research of Paul Baran, the initial network deployment in 1969, the original IMP servers, and the operation of the early Internet nodes by the consulting company Bolt Beranek and Newman.[70]

Throughout the noncommercial era the research network continued to develop capabilities we now view as fundamental. Among the notable are email appearing in 1973, message groups in 1975, and TCP/IP in 1983. At each stage of this development researchers documented their efforts, reached consensus on core features, producing working code, and documented their work. An especially valuable innovation was the “Request For Comments.” RFCs began with the earliest stage, with RFC 1 published on April 7, 1969.[71] The full catalog of RFCs is online, continues to grow[72], and serves as “the principal means of open expression in the computer networking community.”[73] The success of the Internet approach has strongly influenced open source software generally, with many projects mimicking much of the governance approach.

3.2.3 The Internet Becomes Friendly

The World Wide Web originated outside of U.S. funding, but in a very similar setting and with active participation in the RFC process. Tim Berners-Lee was working at CERN in Switzerland in 1990 and was struggling with a method of sharing the huge and varied amount data that was emerging from the particle accelerator.[74] CERN researchers across the globe needed to share and annotate information, much of it including imagery. From these efforts came the concepts of URLs beginning with htttp,[75] web pages mixing text, images, and links, and many of the specifications so familiar and popular. Other users quickly realized this was a useful tool in many settings, far beyond particle physics. CERN also produced the first web server, with public demonstrations in 1991.

A final critical piece of enabling software was the

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[66] See Banks,op. cit. as well as Antonio Parham, (1990), Prodigy Business Services: An “Instructional Case” Study of Marketing Tactics For a Computerized Information Service, MIT Master’s Thesis.

[67] Don Peppers and Martha Rogers, *One-To-One Future.,* Currency Doubleday, p. 14.

[68] David C. Mowery and Timothy Simcoe, (2002), “Is the Internet a US invention?—an economic and technological history of computer networking,” *Research Policy,* 31, 1369–1387.

[69] See, especially Katie Hafner and Matthew Lyon, (1996), *Where Wizards Stay Up Late: The Origins of the Internet,* Simon and Schuster, New York. M. Mitchell Waldrop, (2002), *The Dream Machine: J.C.R. Licklider and the Revolution That Made Computing Personal,* Penguin. Tim Berners-Lee, op.cit.

[70] See Hafner and Lyon, op. cit., for details.

[71] Ibid., p. 144.

[72] https://www.rfc-editor.org/rfc-index.html

[73] Hafneer and Lyon, op. cit., p. 145.

[74] See Tim Berners-Lee, op. cit.,for a history of these efforts.

[75] See, for example, RFC 1945, https://www.rfc-editor.org/info/rfc1945.

browser, again emerging from a laboratory setting, this time the National Center for Supercomputing Applications in Urbana-Champaign. Programmers there made a "point and click" interface for the Web, releasing it in 1993, and making Internet use much easier for novices. It was many of these NCSA Mosaic programmers that relocated to California, and formed Netscape. Although there were some disputes regarding naming and rights to Mosaic, again the core of the Internet had been sponsored by public funds and transferred to the private sector.

By the end of 1993 the main software pieces for a friendly point and click interface to an efficient TCP/IP Internet were in place. What was also needed was access and transmission, which occurred with a modest regulatory change of great consequence.

3.3 Freeing the Internet

For much of the twentieth century the telecommunications system on the United States was a regulated monopoly. Had this remained the case, the Internet as we know it would not have happened. "Ma Bell" was very strict with allowable communications. It took a Federal Court decision in 1956 to permit users to attach a snap-on cup to a phone mouthpiece to make a call more private.[76] More devices were possible following the 1968 Carterfone decision, permitting an *acoustic* client-side link between the phone system and a radio call. AT&T actively worked against competition of any form in long-distance, even if transmission occurred over private microwave lines.

These actions and others led the U.S. government to prosecute AT&T on antitrust grounds.[77] The conclusion of the case was a consent decree breaking AT&T into a national carrier and seven regional Bell operating companies. While many of these companies have subsequently recombined, with AT&T and Verizon the main surviving companies,[78] during the 1980s and 1990s the United States telecommunication network was freer than it had been in a century. In particular, there was no legal presumption against entry or a dominant firm enforcing its choices on the network backbone. This competitive opportunity supported the next critical decision of the government, turning over the Internet backbone to private hands.

For the first 16 years of its existence, ARPA managed the Internet backbone. The first connection occurred in September 1969, linking UCLA and the Stanford Research Institute. By 1971, the network connected a number of the key computer science departments and information technology contractors. By 1980, the ARPANET incorporated most of the leading research universities and national laboratories.

In 1985, ARPA transferred control and operation of the non-military nodes of the ARPANET to the National Science Foundation. At first the NSF focused on improving operations of the (now) NSFNET.[79] The backbone speed was increased, although minuscule by modern standards.[80] It entered into a five-year managing contract with MCI and IBM/MERIT to run operations.

The NSF insisted that the Internet operate for non-commercial research purposes. The guiding document was the NSF Acceptable Use Policy. In particular, users of the NSFNET were not supposed to advertise or place commercial orders. [81]

> " The purpose of NSFNET is to support research and education in and among academic institutions in the U.S. by providing access to unique resources and the opportunity for collaborative work.
>
> This statement represents a guide to the acceptable use of the NSFNET backbone. It is only intended to address the issue of use of the backbone. It is expected that the various middle level networks will formulate their own use policies for traffic that will not traverse the backbone.
>
> 1. All use must be consistent with the purposed of NSFNET.
> 2. The intent of the use policy is to make clear certain cases which are consistent with the purposes of NSFNET, not to exhaustively enumerate all such possible uses.
> 3. The NSF NSFNET Project Office may at any time make determinations that particular uses are or are not consistent with the purposes of NSFNET. Such determinations will be reported to the NSFNET Policy Advisory Committee and to the user community.
> 4. If a use is consistent with the purposes of NSFNET, then activities in direct support of that use will be considered consistent with the purposes of NSFNET. For example, administrative communications

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[76] Hush-A-Phone v. United States, 238 F.2d 266 (D.C. Cir. 1956).

[77] See Shane Greenstein, (2015), *How the Internet Became Commercial,* Princeton. for a discussion of this and details on the transition briefly summarized here.

[78] See Thomas Gryta, Keach Hagey, Dana Cimilluca, and Amol Sharma, (2016), "AT&T Reaches Deal to Buy Time Warner for $85.4 Billion," *Wall Street Journal,* October 22. for the timing of these recombinations.

[79] Greenstein, op. cit., p. 25.

[80] The first *upgrade* was to 56K on the backbone! This was soon increased to 1.5MB/sec. Ibid., p. 51.

[81] National Science Foundation Annual Report 1988, Washington, D.C. (U.S. Government Printing Office)

for the support infrastructure needed for research and instruction are acceptable.

5. Use in support of research or instruction at not-for- profit institutions of research or instruction in the United States is acceptable.
6. Use for a project which is part of or supports a research or instruction activity for a not-for-profit institution of research or instruction in the United States is acceptable, even if any or all parties to the use are located or employed elsewhere. For example, communications directly between industrial affiliates engaged in support of a project for such an institution is acceptable.
7. Use for commercial activities by for-profit institutions is generally not acceptable unless it can be justified under (4) above. These should be reviewed on a case-by-case basis by the NSF Project Office.
8. Use for research or instruction at for-profit institutions may or may not be consistent with the purposes of NSFNET, and will be reviewed by the NSF Project Office on a case-by-case basis."

Under such a policy most of the modern Internet would be prohibited. There could be no ad-supported Google or Facebook, no ordering through Amazon, no ticket purchases at Expedia, or countless other activities.

Even with these restrictions, the utility and growth of the Internet continued. By 1990, there were approximately 1 million Internet hosts. Capacity growth was needed, and the NSF increasingly felt the demands of network operation would conflict with its support of basic science. At the same time, political leaders were pushing to open up the Internet to additional uses.

Greenstein (2015) details the NSF handoff to private industry. After some initial jockeying by lead contractors for a preferential position, NSF reached a final plan for the handover in May 1993. MCI and IBM continued to operate the backbone, but without a requirement for enforcing the Acceptable Use Policy. Various networks were strongly encouraged to interconnect, and firms developed a method of traffic interchange. Several of the core assets of the Internet, such as the DNS registry, were transferred to private hands in a manner eliciting complaints of cronyism. While possibly true, these transfers happened quickly and smoothly. By 1994, the Internet was open for business, able to carry both research and commercial traffic. One of the largest bursts of innovation investing was about to occur.

3.4 A Commercial Internet

3.4.1 Venture Funded Innovation

Following privatization, entrepreneurs needed backing for their new ventures. To an unprecedented degree this was provided by venture capital. As discussed in Hanson (2000), there was a positive feedback loop involving investors, users, and entrepreneurs. Or, as Mowery and Simcoe put it:[82]

> "Although antitrust and deregulatory telecommunications policies remained influential, defense R&D spending was overshadowed by private sector R&D investment by the 1990s. And one of the most important mechanisms for Internet commercialization was the US VC industry, which assumed a larger role in the commercial exploitation of the Internet than had been true during the formative years of other postwar US high-technology industries."

Large pools of capital, such as pension funds, insurance companies, and other large investors, manage portfolios worth hundreds of billions of dollars. Finance theory shows that efficient and diversified portfolios should devote a (small) portion of their assets to high risk, high return investments.[83] Over the last few decades, the preferred method for this risky investment share is early stage investments in high technology startups. Some of the largest global corporations, such as Apple, Cisco, Google, and Facebook, trace their origins to this form of risky investing.

Most pension and life insurance companies lack the experience to invest in startups. Instead, they outsource this fraction of their portfolio to venture capital firms. VCs gain skill in identifying startup teams with both good ideas and the ability to transform these new approaches into successful companies. The various venture capital firms organize funds stressing particular areas of emerging technology, such as the Internet, clean tech, or life sciences.

Venture capital firms do not lend money. Rather, VCs buy an ownership share in a startup. The size of the equity share is in proportion to the funds invested, as well as the current startup valuation. The earliest investments in a new company can be the most lucrative, but they are also the most likely to fail.[84]

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[82] D. Mowery, D. and T. Simcoe, (2002), “Is the Internet a US invention?—an economic and technological history of computer networking,” *Research Policy,* 31, 1369–1387.

[83] Modern portfolio theory demonstrates that risk averse investors should construct their portfolio along the efficient frontier. The higher the risk of an asset class, the higher must be the return.

[84] For example, the earliest investors in Google were able to purchase shares at approximately 4 cents a share. These were worth $85 at IPO, or more than $800 per share in 2017. One of these early investors was

As a startup does not repay a venture investment, which it would with a loan, a venture firm must eventually be able to sell its shares to recoup their original investment and make a profit. Some form of "exit event" is required. For major successes, such as Netscape or Google, this is an initial public offering. More commonly, an acquisition by a more established firm provides the mechanism for selling shares.

Venture investing is a game of averages. In the majority of cases, the venture-backed startup fails to go public and receives only lukewarm acquisition interest. For a venture fund to make money, the few big wins must offset these more numerous failures or modest successes.

The venture capital system is a key reason for the importance and continuing success of Silicon Valley. VCs and startups have long co-existed in the Bay Area,[85] with veterans of successful companies occasionally starting their own venture operations or joining established venture firms. Proximity increases the chances of discovering the next big thing, meeting the best entrepreneurs, and bringing in additional investing partners to lower the exposure to any one investment.

Silicon Valley has had the good fortune of operating with the power of the digital GPT at its back. For more than six decades information technology has been central to the Valley's economy. Moore's Law created an ongoing stream of new computing opportunities. Engineers substitute digital technology into more industrial devices, production processes, and final goods. This sequence includes such broad areas as mainframe computing, avionics, mini-computing, personal computing, the rise of the Internet, social media, and mobile computing. Perhaps no other technological area has been so rich in the potential for continual improvements and spinoffs, and the association of IT with venture capital has been very close. Successful venture capitalists became quite good at extrapolating from current possibilities as new price points emerged. Table (4) highlights just how widespread the importance of the Internet still is among venture-backed startups.

Space investments do not appear separately in Table (4). If they did, the Internet's influence would be large as well. Startup Space reports \$1.8 billion in space-related venture investments in 2015.[86] Of this, \$500 million went to OneWeb and \$900 million from Google to SpaceX. OneWeb is entirely Internet-related. While neither Google nor SpaceX confirms the exact arrangements for their agreement, their agreement appears to be targeting the Internet-related constellation being planned by the firms. This would total \$1.4 billion of the \$1.8 billion for just those two firms alone.

3.4.2 E-commerce Pioneered the Commercial Internet, but Advertising Pays the Bills

E-commerce was at the core of the first wave of Internet startups. The "dot com" revolution sought to transform both business to business and consumer sales, and attracted a burst of venture capital funding. Several factors accounted for this emphasis. Facing challenges for Walmart and other "big box" stores and a lack of expertise, existing retailers were slow to adoption online sales.[87] This lack of response created a perceived opportunity for startups, especially in consumer categories such as books, music, consumer electronics, and computers. Business marketplaces hoped to challenge existing supply chains in a wide array of industries. A wave of IPOs seemed to validate these entrants, with investors willing to fund retail startups with very little track record and negative cash flow. Many of these startups came to ruin in the 2000–2001 shakeout, never able to effectively reach profitability. Existing businesses, especially in the B-to-B market, woke up to the power of the Internet and used their existing supply chains and marketing expertise to thwart the startups.

Despite the failure of many speculative ventures, there were notable successes. Amazon.com expanded its product lines from books to almost everything, and has managed to expand its sales substantially every year. It is now a retailing powerhouse. EBay serves as the order-taking interface to tens of thousands of small retailers. Dell and other computer makers pioneered direct sales to consumer and build-to-order systems. Music retail pioneer CDNow expanded the available range of titles dramatically over physical stores, and early digital download sites such as Napster showed the power of purely digital delivery to transform the music business. Thousands of other online retailers, both hybrid and online only, expand their reach to a national (and occasionally international) market using the Internet. Consumer e-commerce is still less than 10% of retail sales, approximately \$500 billion in 2016. The e-commerce retail share has followed a (seasonally adjusted) steady upward trend since the Census Bureau began tracking it in 1999.[88]

Jeff Bezos, who invested \$250,000 in 1998. If Bezos held on to his Google shares they would be worth approximately \$2.7 billion. Kara Swisher, (2009), All Things Digital, October 5.

[85] Tax and policy changes in the 1980s are often credited with allowing pension funds to invest more freely in risky assets, providing a crucial boost to the venture industry.

[86] Tauri Group, (2016), "Start-up Space: Rising Investment in Commercial Space Ventures," January, p.13.

[87] See Ward Hanson, "section 7: Discovering a Role Online: Brick-and-mortar Retailers and the Internet," in William Aspray and Paul Ceruzzi, editors, (2008), *The Internet and American Business,* MIT Press, pp. 233–258.

[88] U.S. Census Bureau, (2017), "Quarterly Retail E-Commerce Sales, 1st Quarter 2017."

Table 4: *The Widespread Influence of the Internet on 2013 Venture Investments ($ Millions*

Industry	Internet Related	Non-Internet Related
Biotechnology	16.2	4,565.7
Business Products and Services	53.8	164.2
Computers and Peripherals	222.2	295.0
Electronics/Instrumentation	1074.0	171.5
Financial Services	324.0	212.4
Healthcare Services	107.1	179.0
Industrial/Energy	22.5	1,484.0
IT Services	1,967.0	25.9
Media and Entertainment	2,771.4	164.1
Medical Devices and Equipment	15.6	2,114.5
Networking and Equipment	669.6	-
Other	5.6	93.0
Retailing/Distribution	228.4	12.0
Semiconductors	132.5	464.9
Software	10,821.3	198.7
Telecommunications	572.4	71.2
Total	19,009.3	10,514.8

Source: 2014 National Venture Capital Association Yearbook

While e-commerce has been a notable commercialization success, the Internet's impact on the advertising market has been profound. As seen earlier, the NSF Acceptable Use policy prohibited advertising. The commonly acknowledged first advertisement using the Web, a banner ad paid for by AT&T, appeared on the hotwired.com web site in October 1994.[89] It ran on the top of the page and when clicked led the user to the advertiser's web site. This simple format would remain the dominant method for the first decade of online advertising.[90]

Advertising revenues have long been central to the commercial Internet. During the early years, it funded the rise of online portals Yahoo!, InfoSeek, Excite, and America Online.[91] Much of the money spent by the dot com retail startups went to marketing expenses, especially online advertising, driving the development of many of the online portals, search engines, and access providers. Thus, the early growth of online advertising was closely tied to the dot com wave.

The first wave of Web advertising had none of the current capabilities, lacking even the ability to reliably measure impressions. Early online approaches emphasized sponsorship of particular web site sections, especially on leading Internet portal sites Yahoo! and America Online. In addition to exclusivity, a key feature of sponsorship is duration-based payment. Advertising sites specify pricing by time interval, such as cost per month, rather than by viewership levels or user actions. Sponsorship became less common, and performance based methods more important, as Internet companies developed suitable measurement and appropriate metrics. Online advertising has strongly tilted toward the informational advertising of the print media rather than the persuasive brand advertising of television and radio.[92] The dominant form of online advertising is a "call to action" to visit an advertiser product page rather than a self-contained branding experience.

Search engines, most notably Google, provided a second wave of advertising growth. Search engine advertising reached beyond online retailers and tapped into thousands of small and medium sized traditional businesses. Advertising format simplicity, combined with strong measurement tools, made it possible for these advertisers to shift their advertising dollars from newspaper and Yellow Pages to search spending. For example, Google AdWords generate billions of dollars of revenue using a few lines of text with links to advertisers' landing pages.[93] More recently, social media and video content have grown to be important advertising venues.

Time usage and relevancy have been two of the keys to online advertising success. Advertising dollars tend to follow consumer time usage, and the many online applications increasingly attracted viewership. Relevancy, especially for search, has made online advertising very

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[89] For a description of the early years on online advertising, see Ward Hanson, (2000), *Principles of Internet Marketing,* Thomson South-Western, Mason.

[90] Ibid., p. 278.

[91] Yahoo! was almost entirely advertising supported, while AOL also relied on monthly fees for its Internet service business.

[92] This is also reflected in the business difficulties of the print media, such as newspapers and magazines, as they lost customers' dollars to the Internet. Television and radio advertising have been less affected to date.

[93] Google AdWords thrive primarily due to the high relevance of the connected information.

effective. Even primitive ads can be highly effective if they reach the right consumer at the right time. Combining advertising reach with advertising effectiveness has made online advertising a powerful economic force.

From its humble beginnings in 1994, online advertising revenue is now larger than newspapers, magazines, radio, and even television. In 2016, U.S. online advertising revenues grew more than 21% and exceeded $72 billion. Some of the most sophisticated technologies in Silicon Valley, such as massive clusters of servers, big data analytics, machine learning algorithms, and artificial intelligence, are devoted to achieving slight improvements in online advertising effectiveness.

Figure (3) shows the rapid growth in U.S. online advertising revenue, with no obvious plateau.[94] This is striking for at least two reasons. First, early participants did not view the Internet as a major advertising venue. Deregulators were familiar with some of the most popular services on the Internet, such as email, chat groups, and bulletin boards, and expected them to be popular outside of the research community. Web pages also looked promising for sharing commercial material. There was little discussion during the early 1990s that the Internet would be a major advertising venue, and except for modest success by online services such as Prodigy, little historical basis for optimism. Indeed, a best-selling business and marketing book published in 1993 stressed the interactive potential of faxes rather than the Internet.[95] There was also an antipathy to advertising by many early Internet entrepreneurs, including Brin and Page, who did not initially plan to utilize advertising as part of Google's approach.

The economics of advertising is a second reason why Figure (3) is so surprising. Aggregate advertising spending is primarily a zero-sum game between advertising venues.[96] For decades, U.S. advertising spending has been approximately 2% of GDP. Advertising grows along with the general economy, splitting between advertising venues. Internet advertising's growth rate far exceeds the growth in the economy, coming at the expense of other advertising approaches.

As with the computer, there is a strong element of Schumpeterian surprise in the business applications of the Internet. It is highly unlikely a committee sitting in 1992 could have foreseen the dot com boom or the dramatic rise in Internet advertising. Yet by permitting these activities, policy makers allowed a creative wave that has altered many aspects of the retail and advertising industries.

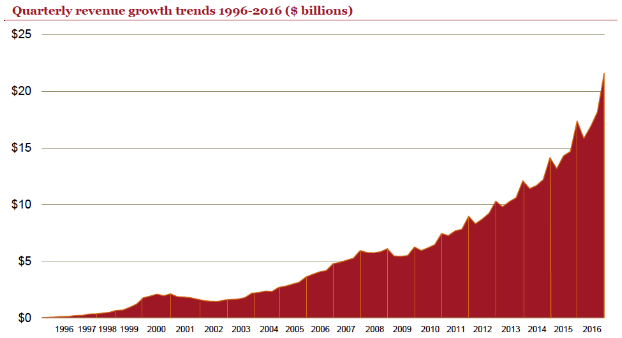

Figure 3: *U.S. Online Quarterly Advertising Revenue. Source: Internet Advertising Bureau*

3.5 Venture-Backed Space Startups and Regulation

Startups are risky and prone to failure. A startup can fail due to technological risk, mismatches with the marketplace, the entry decision of a dominant firm, execution mistakes, and a host of other factors. Successful venture firms learn how to distinguish "good failures," and reinvest in an individual or team with a promising idea, even if they had a previously failed startup. Startups can take big chances, knowing that a failure isn't fatal to their entrepreneurial career. One of Silicon Valley's strengths is the recycling of personnel.

Venture funds are structured to allow time for startups to succeed, and to weather any macroeconomic downturns. Venture funds have protections against early withdrawals of funds, as well as provisions that may require additional investments when market conditions are unusually challenging. As long as the long-term expected return is high, this risk fits into the diversification strategy of the ultimate investors. Venture capital's patience and tolerance for failure is much higher than the political or bureaucratic systems.

Industries where venture capital is important reward behaviors that (occasionally) generate unusually high returns. Examples include rapid prototyping, multiple product releases with incremental improvements, and aggressive timetables for new products. Researchers and industry participants note that changes in the I.T. ecosystem over the last decade have substantially lowered the entry costs of software-based entrepreneurs. Due to previous innovation, an entrepreneurial team can develop a software product, ship it globally, and serve a market of millions without much less capital, a major change from even a decade ago. When Facebook experienced its extraordinary growth in 2004–2006, it struggled mightily to provide enough server capacity to meet demand.

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[94] IAB, (2017), "IAB Internet Advertising Revenue Report: 2016 Full Year Results," Internet Advertising Bureau, April.

[95] Peppers and Rogers, op. cit..

[96] The precise mechanism for this magnitude is not fully explained in the marketing or economics literature, but is strongly suggested by the Dorfman Steiner result and its extensions. On this, see the excellent review of the economics of advertising by Bagwell (2007).

Server capacity was much less of a problem for companies such as SnapChat or WhatsApp. Just a few years later, these startups were able to scale to hundreds of millions of users by relying on cloud providers for both the hardware and the network management skills. Cloud services transform fixed costs to as-needed variable costs.

While venture culture has much to commend as an engine of rapid innovation, there are some common biases and social challenges. As the venture mentality spreads more broadly into space activities, regulators should anticipate areas where regulatory invention might be required. However, regulatory forbearance may be even more important. A key distinction is between business and physical risks. By and large, business risks should be tolerated. Physical risks are much more the province of regulation. Even here, there should be a distinction between participant risk versus risk to third parties.

As seen in the late 1990s Internet boom, venture enthusiasm in particular fields can overheat. In retrospect, certain investments will seem wasteful or even foolish. This is inevitable, and is the cost of achieving breakthroughs and exploring the technological and economic potential of innovations. While it is easy to find examples of unwise investments and excessive entry, regulators should avoid the temptation to dampen this competitive dynamic. Handling business risk is one of the competitive advantages of the venture industry and one of the biggest weaknesses of the political process.

Regulators should especially resist the temptation to be an equalizer between incumbent providers and disruptive entrants. A classic setting is price competition. If a new venture is able to undercharge an incumbent service provider, regulators should be very cautious about blunting this competitive pressure. Christensen and others have stressed the power of "entry from the bottom." Market entrants may get a foothold by providing a low-cost, limited feature service. Over time, the entrant's capabilities grow while still retaining a cost advantage. Faced with a threat to market share and profits, incumbents often resort to lobbying and the political system rather than a market response. It can be politically tempting for regulators to carve out demand segments isolated from competitive forces. This is rarely beneficial to society as a whole.[97]

Venture backing may overemphasize blockbusters and ignore small but necessary improvements. Space projects may require collaborative or public solutions to provide certain necessary but unglamorous innovations. Technological roadmaps and collaborative standards can be valuable aids to an otherwise venture-oriented commercial sector.

4 Supporting Innovation With Spectrum Auctions

4.1 The Internet In Your Pocket

There are a handful of computing product announcements memorable enough to revisit years after they occur. Some come to us through print, like Bell Lab's 1948 transistor announcement and IBM's 1964 System/360 introduction. Some we are fortunate to have on video, such as Douglas Engelbart's 1968 demo of what a computer could be, Steve Job's 1984 introduction of the Mac that made much of Engelbart's vision a reality, or again with Steve Jobs introducing the iPhone in 2007. Each of these announcements changed the path of technology, and eventually changed modern life.

When Jobs introduced the iPhone ten years ago, he began with a bit of a tease, claiming to be announcing three breakthrough products that day. The first seems quaint today, a multi-touch iPod, but at the time the iPod was Apple's biggest moneymaker. The second was a new category for Apple, a smartphone with phone and data capability. The third was a mobile Internet communicator. Of course, these were not three separate products, but the first iPhone.

The iPhone would propel Apple to the highest valuation of any company in the world. Google followed with the Android mobile system, utilizing a multi-vendor approach that helped broaden its reach and lower its price. In 2016 alone, 1.5 billion smartphones were sold globally.[98] This is an amazingly fast diffusion of such an expensive product.

Smartphone data usage has caused congestion of existing networks and high demand for additional radio spectrum. Smartphones use a variety of radio bands. The first generation iPhone released in June 2007 incorporated quad-band GSM, Edge, WiFi, and Bluetooth radios. The second generation iPhone added 3G for faster data transfer and satellite GPS for location services. By 2011, the iPhone incorporated a world phone with GSM, HSPA, and CDMA radios. High-speed 4G LTE data services appeared in 2012. Apple added short range NFC capabilities for secure payment systems in 2014. Android phones have followed a similar path. Apple and Google now operate platforms with millions of apps available through their online stores, allowing users worldwide to hail a ride, book a room, engage in banking, post messages to friends, or thousands of other activities.[99]

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[97] There is a long debate in industrial organization about the need for regulatory intervention in certain "natural monopoly" settings. Most economists find the cure worse than the disease, with regulatory capture much more common than enlightened regulatory intervention.

[98] Gartner Research, (2017), "Gartner Says Worldwide Sales of Smartphones Grew 7 Percent in the Fourth Quarter of 2016," February 15.

[99] See, for example, Bresnahan, T., Davis, J., and Yin, P., (2013), "Economic Value Creation in Mobile Applications," in *The Changing Frontier: Rethinking Science and Innovation Policy,* Jaffe, A. and Jones, B. editors, University of Chicago Press.

Even before the smartphone, the rapid spread of cellular phones was affecting the commercial space market. A notable example was Iridium, the pioneering commercial low-earth orbit constellation creating a global satellite phone system.[100] The buildout of the terrestrial cellular network and the spread of the Internet were two of the most important reasons for Iridium's commercial failure and bankruptcy. By the time Motorola was able to bring Iridium online in 1998, a global traveler could already email back to the home office or use a roaming signal on a cellular network in most major cities in the world. The Internet and cell phone dramatically lowered the rate of Iridium adoption as well as the willingness to pay for the Iridium handsets and usage plans.

Neither of these two competitors were significant market forces when Iridium was designed and funded, and supplanted much of Iridium's forecasted demand. The essential market need was still present, as the Internet and cellular systems showed the value of global communications. After much political wrangling, Iridium was saved from de-orbiting by the U.S. military. Iridium was especially valuable to Special Forces, Marines, and drones going into distant battlefields. Iridium's global ubiquity could justify its limited data rates and high prices.

The smartphone is also the main force in the coming battle brewing between terrestrial networks and new space ventures. 5G networks are the next step for high speed mobile data transfer. These 5G networks hope to rapidly transmit even the highest resolution image and video. There is a serious problem however. Some of the spectrum that is most promising for 5G terrestrial networks is also highly desirable for LEO-based satellite Internet. Current international agreements also tilt toward a space usage for many of these bands. Lobbyists on both sides are pushing both in the U.S. and globally to secure more spectrum for their respective systems. Spectrum may well be the biggest limiting factor for either 5G or LEO Internet reaching its technical and market potential.

Efficient spectrum allocation was a policy success of the 1990s and 2000s, and it that helped the Internet make a smooth transition from desktop to pocket. This section reviews that process, its economic logic, and lessons going forward in the coming spectrum battles.

4.2 Spectrum Markets

4.2.1 Allocating Spectrum

A wide variety of wireless services use spectrum, including broadcast radio, television, point-to-point microwave, satellite, radar and many others. Markets for most non-governmental spectrum licenses and spectrum-based services have existed for nearly 100 years in the United States. The Commerce Department governed the early days of radio broadcast, generally under a "first come, first served" regime and Court adjudication of disputes rather than in a regulatory proceeding. With the introduction of the 1927 Radio Act, the Federal government asserted more control in assigning licenses to specific operators, designating specific bands for specific uses, and mandating the use of specific technologies.

Leo Herzel[101] in 1951 and Ronald Coase[102] in 1959 set forth the intellectual underpinnings that such licenses could (and should) be awarded by markets rather than by a governmental process. The key insight of Herzel and Coase was that the FCC process added no value to the allocation/assignment process as licenses would end up in the hands of those who valued them most highly on the secondary market and the FCC process simply hindered such ultimate allocations.

Using auctions to award licenses for specific services subject to specific Federal Communications Commission (FCC) technical rules would have been a small step forward (assignment). However, much bigger and complementary steps were to set up a framework that would allow a competitive market for wireless services and to minimize the role of the FCC in determining the technical and service requirements for licensees (allocation). By allowing more flexibility for licensees to change technology and service, operators could attack markets where prices were too high and respond to changes in consumer demand without having to get Commission approval.

The 1934 Communications Act assigned to the Federal Communications Commission ("FCC") responsibility for managing non-Federal spectrum us "in the public interest." The FCC has historically determined what services and technologies can make use of specific frequencies of the electromagnetic spectrum through an administrative rule making process. Typically, the FCC put different services in different parts of the spectrum (bands), although there are many exceptions where two or more uses share bands. This entire planning process, from the earliest stage through rule making and licensing, can take many years. The National Telecommunications Information Agency (NTIA), part of the Department of Commerce is responsible for Federal uses of spectrum.

Despite whatever success these agencies might have had at determining an optimal combination of service and technology at any point in time, continuing changes in consumer preferences and technology eventually cause that combination to become suboptimal. As the diver-

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[100] An excellent account of the Iridium story appears in John Bloom, (2016), *Eccentric Orbits*, Grove Atlantic Press, New York.

[101] Leo Herzel, (1951), Comment, "Public Interest and the Market in Color Television Regulation," *U. CHI. L. REV.*

[102] Ronald Coase, (1959), "The Federal Communications Commission," *Journal of Law and Economics,* Vol. 3, pp. 1–40. Coase received the Nobel prize in economics for his work on regulation and market mechanisms.

gence between the value in the current service and in potential new uses increases so do the gains from reallocation. In other words, the overall allocation process should strive to be both statically and dynamically efficient.

As new mobile wireless devices have become available, demand for mobile wireless services by consumers and government agencies has increased dramatically. In just the past six years, more than one-quarter of households have given up wired home phone service entirely leading to nearly half of all U.S. household apparently relying instead on phone service from their wireless provider. Consumers are also increasingly accessing the Internet over mobile devices for a variety of applications, including streaming video. The FCC reports that between 2009 and 2013, the number of wireless connections capable of 3 Mbps downstream went from under 2 million to more than 133 million. As of March 2015, the NTIA reported that cell phone providers offer LTE coverage to more than 98 percent of the population.[103]

Advances in wireless capabilities have built on complementary assets, including much more powerful processor enabling smartphones, the development of "apps" and services such as mobile video have let to a virtuous circle of increasing demand, lower prices, increased quality and subsequently more advance inputs and complements to wireless service. Innovation at the edges[104] happened in large part due to the ability for firms to experiment with different products and business models and to have many firms fail or lose money along the way. The combination of technological advances and changes in demand and supply provided motivation for the movement of spectrum from initial allocations to more valuable uses over time. The FCC's increasing reliance on market-based spectrum policies has facilitated the movement.

4.2.2 Cellular Service

One of the many complaints about the old bureaucratically controlled system of license allocation is that it took a long time to respond to market changes and opportunities for new services. The original concept of low-power cellular systems emerged in the 1940s, and rudimentary cellular systems could have been available in the 1970s.[105] The FCC did not award the first experimental cellular license until 1982, and more pervasive licensing not complete until the later 1980s. The FCC awarded two licenses per market, first using the comparative hearing approach and then using lotteries.

In 1982 it was not clear that the licenses were extremely valuable.[106] By 1984 the licenses started to reflect much higher value. In part, the increased expectation of the value of cellular licenses came from the advances in technology due to the microprocessor revolution. Moore's Law created capabilities that led to hand-held phones. The increased value of wireless service manifested itself in prices for the resale of the licenses and the increased number of applications for the remaining available licenses.[107]

The high value of the cellular licenses made clear the inefficiency and inequity of the comparative hearing process.[108] After abandoning the lengthy and arbitrary comparative hearing process, the FCC moved to award licenses by lottery. Lotteries led to hundreds of thousands of applications. According to McMillan, "In one not atypical case, some dentists won the right to run cellular-telephone service on Cape Cod; they immediately sold their license to a real telephone company Southwestern Bell, for $41 million."[109]

One of the key early decisions in the cellular licensing process was the initial market structure. At first, the FCC decided to have a single license and to award that license to the incumbent wireline telephone provider because it thought that the wireline provider would be best technically able to set up and run a wireless telephone system. The Antitrust Division of the Department of Justice pushed the FCC to allocate licenses to at least two providers so there would be competition to provide service. Ultimately, the FCC agreed and assigned one of the two 20 MHz licenses to the incumbent wireline telephone company and one to a new entrant. The FCC mandated the use of the Advanced Mobile Phone Service (AMPS) analog technology and banned dispatch service on the cellular frequencies.

Initial prices for cellular service were relatively high. Despite the high prices, demand for wireless service was also high and there was a push to allocate more spectrum for wireless service. The FCC's first action was to grant an additional 5 MHz to each of the cellular licensees, compounding any original windfall. Even after this in-

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[103] White House Office of the Press Secretary, (2015), "FACT SHEET: Next Steps in Delivering Fast, Affordable Broadband," March 23.

[104] Much as Greenstein describes in the commercialization of the Internet.

[105] Rohlfs, J., Jackson, C. and Kelley, T., (1991), "Estimate of the Loss to the United States Caused by the FCC's Delay in Licensing Cellular Telecommunications." National Economic Research Associates, Washington, D.C.

[106] McKinsey initially thought that there would be 1 million subscribers across the country by 2000, and in the discussions about the division of assets under the AT& T break-up the negotiators did not care about the placement of the cellular assets.

[107] Gregory Rosston, (1994), "An Economic Analysis of the Effects of FCC Regulation on Land Mobile Radio." Ph.D. Dissertation, Stanford University.

[108] For example, the FCC awarded a Los Angeles cellular license on the basis of one additional cell site in the plans on Catalina Island despite the fact that the rest of the systems were identical and ultimately bore no relation to the system that was initially constructed nor to the long-run performance of the system.

[109] John McMillan, (2002), *Reinventing the Bazaar: A Natural History of Markets,* Norton, New York.

crease, it was clear that both carriers and consumers highly valued more spectrum for mobile wireless. As a result, in 1989 the FCC began a proceeding for a new allocation of spectrum for "Personal Communication Service" (PCS). Around the same time, the FCC began to investigate the introduction of digital technologies to provide more capacity and higher quality service on the same spectrum.

4.2.3 The Move to Auction

Proposals for auctioning spectrum had circulated for many years, even being included annually in budget proposals from Presidents Reagan and Bush in the 1980s and early 1990s, but had never been adopted. Congressman and senators with significant influence on the commerce committees that oversaw the FCC routinely spoke against the use of auctions. For example, in 1987, Senator Daniel Inouye (D-HI), Chairman, Senate Subcommittee on Communications, wrote to Senator Lawton Chiles (D-FL), Chairman, Senate Budget Committee, that a proposal to collect $600 million from a spectrum auction "undercuts the fundamental tenet in communications policy that the airwaves are a limited public resource," and "it is inappropriate to sell such a resource to the highest bidder." In 1989 Rep. John Dingell (D-MI), Chair of the House Energy and Commerce Committee, introduced legislation that contained the following provision:

> "PROHIBITION OF SPECTRUM AUCTION—REASSIGNED FREQUENCIES .—No frequency reassigned by the President under section 4 of this Act shall be allocated or assigned by the Commission by means of any system using any auction or comparable device or practice."

One factor pushing toward auctions was the PAYGO provision of the Budget Enforcement Act of 1990 that required any new spending to be "paid for" by revenue increases or spending cuts elsewhere. The projected billions of dollars from selling spectrum became very attractive to the new Clinton Administration, who wanted to increase spending in some areas without cutting spending elsewhere.

Economists also strongly supported auctions, but primarily for efficiency reasons. The only reason that spectrum would fetch high prices is that it was scarce and useful in providing a valuable service. While it would be best for there to be no scarcity and a low or zero price for spectrum licenses, economics is concerned with the efficient allocation of scarce resources. Reed Hundt, the Chairman of the FCC from 1993 - 1997, paraphrasing Winston Churchill said, "Auctions are the worst way to assign spectrum license except for all the others." Congress, swayed by the potential revenue and the obvious inefficiencies of the existing system, included a mandate for using spectrum auctions in the Omnibus Budget Reconciliation Act of 1993. Not only did the Act mandate the use of auctions, but required that auctions commence within eleven months of the passage of the Act.

4.2.4 Auction Implementation

While the congressional pressure against auctions had abated, there was still congressional influence on the Commission in relation to how it would auction the highly valuable PCS licenses. Section 309(j) of the Act required that the Commission consider how to promote the interests of small businesses, businesses owned by women and minorities, and rural telephone companies ("designated entities") in the award of spectrum licenses. The Act told the FCC to consider using set-asides, bidding credits, and installment payments to promote the interests of the designated entities. Congress saw need for such measures because the designated entities were not likely to be successful in acquiring licenses in an auction with purely monetary goals. The FCC utilized all three mechanisms in the second broadband PCS auction in December 1995 (the "C Block" auction).[110]

The FCC used the Rand McNally designations of Major Trading Areas (MTAs) for the first major broadband auction and smaller Basic Trading Areas (BTAs) for the C Block set aside auction. Because the first auction had two licenses in each geographic area and because bidders had different business plans, licenses available in the auction could be substitutes or complements. The A and B licenses were nearly identical in each area, so functioned as substitutes as no party could buy both. In addition, some parties wanted a foothold in wireless service so could trade off different geographic areas. At the same time, some bidders valued licenses in contiguous geographic areas more highly than either alone, or needed to have a minimal amount of population coverage for their business plan. In these cases, licenses would be complements with a higher value for the bundle of licenses than the sum of the value of the individual licenses.

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[110] Had the FCC simply auctioned two or three nationwide licenses, a straightforward traditional auction run by a cattle auctioneer would likely not have been much different than running a more sophisticated electronic auction. However, the FCC chose not to allocate nationwide licenses for two reasons: smaller bidders would have difficulty acquiring such large licenses at the auction even if they could band together for the bidding and then sell of the undesired portions in their own private auction. The risk would be very high for them about the unknown price of the parts they would want to sell after the auction. The second issue was that the existing cellular providers did not have nationwide coverage with their licenses and systems. Either they would be excluded from bidding across the country or there would be a reduction in the additional competition in areas where they won one of the new PCS licenses. Neither of these outcomes was politically acceptable.

The FCC issued a Notice of Proposed Rulemaking soon after the passage of OBRA '93 discussing several possible auction mechanisms that would be more efficient than a simple sequential auction for the licenses. The responses to the NPRM, and an academic conference convened to discuss the auctions, led economists inside the FCC to push for a novel design for spectrum auctions. This was a simultaneous multi-round ascending auction (SMR).

There was significant risk in adopting the novel design. It had never been tried before, and the broadband PCS auction was expected to have companies bidding billions of dollars. Failure of the auction design would put spectrum auctions overall at risk, not just risk jettisoning the novel design. Chairman Hundt pushed hard to see if there was a safer auction design, but then took a major political risk and agreed that the SMR would be the way to go. The risk of failure was mitigated by running two narrowband PCS auctions in the summer and fall of 1994, partially testing the approach and the software, before the first major broadband PCS auction.

As a result of the two successful tests, the FCC went forward with the broadband PCS auction using the complex SMR design. Evaluations of the auction were that it allowed bidders to express preferences between substitute licenses and also to aggregate complementary licenses. [111] The success of the SMR format led to governments around the world using it for spectrum auctions.

4.2.5 Auction Concerns

It is important for auction design to be in line with the potential uses of the spectrum. If there is no economically viable use for 1 MHz blocks of spectrum compared to 10 MHz blocks, it would unnecessarily complicate the auction to slice the spectrum into 1 MHz blocks. In a similar way, dividing geographic areas into inefficiently small areas would make aggregating the necessary parts more difficult. The auction design should reflect the most likely use of the spectrum. However, it should also allow companies to subdivide or aggregate the spectrum both in terms of frequency and geography.

One issue with the standard SMR format is the risk of "exposure." When a bidder values the combination of two licenses much more highly than either one alone, it is possible that the bidder could pay too high a price if it were to win only one of the two, or to overpay for the combination. This problem occurs predominantly when bidders have different preferences. One solution to the problem of exposure is to allow combinatorial or package bidding.[112]

Auctions allocate licenses to those who value them most highly. However, private value for an asset is not necessarily the same as social value. Social value is the sum of producer surplus and consumer surplus, whereas bidders will only consider producer surplus. A license for a very socially useful service may not be the allocation in the auction because the potential provider cannot appropriate enough of the gains to outbid other uses. A bidder may also try to prevent competition for the exact same service that it is providing. It is quite likely that the private benefit to a monopoly provider of a service is greater than the rents that a second provider of the same service could generate. As a result, the incumbent can often justify a higher bid for spectrum licenses than new competitive entrants. Therefore, it is important for auction designers to think about competition policy when setting up auctions.

4.3 The Flexibility of Auctions

Auctions serve an important function in allocating a scarce resource efficiently. However, a much more important offshoot has been the influence that auctions have had on incorporating more of a market orientation in the governance of spectrum use. The ability to get more money in auctions with flexible-use licenses may have influenced some regulators and politicians to advocate (or at least not to oppose) more technical and service flexibility for new licensees.

With more flexibility, licensees have transitioned rapidly to digital data services, changing the nature of wireless services dramatically over the past 25 years. As a result, a robust market for complementary products has developed, allowing control to flow away from the network and toward the edges with uncontrolled innovation. Ultimately, the demand for spectrum is an input to a desire for a huge variety of communications. Allowing firms to experiment with different technologies and services, some of which have succeeded and many more of which have failed, have led to a significant increase in consumer benefits from wireless services. For example, over the past twenty years there have been at least four generations of wireless technology. Cellular providers have moved from primarily voice to primarily data services. No further governmental approvals were required for this evolution of services and technology.

The flexibility of auctions is important to commercial space, especially with the emergence of high-speed LEO Internet constellations. Spectrum is a battleground between existing GEO systems, emerging LEO providers,

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[111] See Ausubel, L., Cramton, P., McAfee, P. and McMillan, J., (1997) "Synergies in Wireless Telephony: Evidence from the Broadband PCS Auctions," *Journal of Economics and Management Strategy,* Vol. 6, No. 3, pp. 497–527. and Paul Milgrom, (2004), *Putting Auction Theory to Work,* Cambridge Press.

[112] See Levin, J. and Skrzypacz, A., (2014), "Are Dynamic Vickrey Auctions Practical?: Properties of the Combinatorial Clock Auction," Stanford University Working Paper.

and future terrestrial wireless approaches. Each alternative communication provider will no doubt claim advantages for its approach. Regulators world-wide must accommodate competing global systems, and consider the possibilities of license exposure.

Auctions may be helpful in mitigating the conflict between "horizontal" traditional air traffic and "vertical" space launches. To date this has not been a serious concern, as launch activity is modest. However, building out multiple satellite constellations as well as creating a space tourism industry would require a much higher launch frequency. Governing bodies could allocate air traffic passage more effectively if congested rights are subject to auction. While it is unlikely that the exact mechanism will be the same as for spectrum allocation, the "flexibility insight" is especially relevant. It is also likely that a careful analysis of transaction costs between launch providers and air carriers will be important to an optimal result.

5 Summary

Historical analogs are a partial guide to policy in the emerging commercial space market. Earlier studies have pointed out the role of loan guarantees to lower risk, almost self-financing land grants to provide financial incentives, and the benefits of prizes to focus investments. Important negative lessons include the potential for speculative over-enthusiasm, a potential breakdown of competition, and the difficulty of avoiding bureaucratic capture by the industry being promoted.

This study contributes two additional industries, early computing and the rise of the Internet. We also consider spectrum allocation, a critical input to modern communication. These "digital analogs" provide three more recent historical lessons, and are all closely connected to the success of new space ventures.

Computing and the space program share many founding features. Both developed out of military needs and prospered through military funding. The computing industry broke away from government funding much earlier than commercial space. In part this was a gift of physics - computing enjoyed an unparalleled technological opportunity. Nature allowed massive amounts of miniaturization, with each step along the way producing more powerful devices that were both cheaper to build and operate. Commercial markets were eventually much larger than military needs. Technical improvements created computers that eventually businesses and then consumers could afford. Had Moore's Law stalled in the 1970s, computing would be a back-office business service with little consumer appeal.

One of the main lessons of the computing revolution is the uncertainty of emerging demand when sharply lower input prices are achieved. Each step of the computer revolution created surprising new markets. Exclusively military calculations and scientific work was followed by large scale record-keeping and databases. New markets emerged with manufacturing, design tasks, business logistics, and "what-if" business simulations.

By the late 1980s computers in all shapes - mainframes, minis, and personal - had become sufficiently ubiquitous in advanced economies that they could serve as communication devices. Early proprietary networks, such as CompuServe and Prodigy, suggested a commercial market was possible. In the early 1990s, the U.S. government deregulated a much more open and powerful system, the Internet, triggering a wildfire of entrepreneurial activity that has dramatically altered a variety of industries and business practices. Freeing up the Internet was a huge policy success.

The computing revolution has already been responsible for lowering the costs of space. While launch costs per pound have not fallen much over the past few decades, the computing cost per pound has fallen exponentially along with Moore's Law. Much more powerful satellites and space craft can be designed with less mass. Reusable rockets, made possible in part by much improved computing capabilities, will finally lower the cost per pound as well.

Several Internet policy lessons are valuable for the new space setting. The commercial Internet demonstrated the power of a venture capital financed innovation system. Venture capital investments create different incentives and biases than government contract or debt financing. Understanding the venture cycle can better promote innovative space startups. It is also important for policy makers to understand the culture of venture-backed firms. Many of the most consequential new space firms owe their backing to alumni of the venture-backed Internet. This is a very different heritage than traditional aerospace contractors.

The U.S. Government freed up resources that helped the Internet grow. Communication spectrum is another policy success. Without the spectrum auctions of the 1990s and 2000s and granting flexibility to licensees, the wireless growth of the Internet would have been severely hindered. Spectrum policy is still an important area, with conflicts between space and terrestrial users. Market mechanisms are likely to be some of the most efficient means of balancing these conflicting uses.

Self-generating innovation was present both in the computer and Internet experience. Rosenberg often stressed the importance of both "learning by using" and the interaction between commercial activity and science.[113] Commercial Internet markets encouraged the development of new Internet features, and stimulated engineers to create new Internet capabilities. Promising commercial space markets will do the same, encouraging material scientists to develop new materials, roboticists to create new automated capabilities, and more. Renewed basic science efforts, spurred by a commercial space sector, always carry with them the potential for major breakthroughs in unexpected directions.

Some of the most relevant policy lessons of the Internet are what the government did not do. Government officials wisely avoided "worst case" scenario planning and allowed the Internet to develop without a complete specification or set of safeguards. For example, government planners might have held onto Internet control until more secure Internet protocols existed. Such precautionary actions would almost surely would have stalled the commercial Internet, hindered venture investing, and stretched out its adoption by decades. Cyber security is indeed a real issue, but the benefits of a global Internet far surpass its costs. Failures were allowed, even encouraged, and new capabilities stimulated by a much more open and organic growth path.

Government officials mostly avoided picking winners and losers. Surprises have shown the wisdom of this restraint. It was far from obvious that the Internet would be a major advertising venue, or that most online services would be free because of it. Yet, neither Google or Facebook charge users for their highly valuable services.

All three analogs demonstrate the power of flexibility and technological re-use. The general purpose nature of computing made it possible to move from specialized military uses to commercial applications as costs fell. Companies could adapt the general tools of an easy-to-use yet powerful Internet to almost all industries and multiple access devices. Spectrum could be repurposed from voice to data without additional licensing or regulatory hurdles. When fundamental new applications are possible, the essence of Schumpeterian economic growth, policies supporting flexibility are highly desirable. As space commerce blossoms, technological and regulatory flexibility will be highly valuable as well.

Commercial space activity over the next decade may well be dominated by LEO satellite constellations providing high speed consumer Internet. This continues a pattern of commercial space as an information technology offshoot. Digital communication and entertainment is the dominant customer for commercial space. If the planned LEO constellations of high speed Internet satellites become a reality, the Internet industry will be paying for the majority of launches in the next decade. The Internet may well be the "anchor tenant" that permits the perfection of highly reusable launchers. This commercial activity may set the stage for many more ambitious commercial space ventures, and extend commercial space far beyond satellites in Earth's orbit.

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[113] See, for example, Nathan Rosenberg, (1982), *Inside the Black Box: Technology and Economics,* Cambridge, especially pp. 120–159.