Commercializing Open Science: Deep Space Communications as the Lead Market for Shannon Theory, 1960-1973

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Abstract: Recent research on the commercialization of scientific discoveries has emphasized the use of formal intellectual property rights (notably patents) as a mechanism for aligning the academic and entrepreneurial incentives for commercialization. Absent such explicit IPR and licensing, how is such open science commercialized?

This paper examines the commercialization of Claude Shannon's theory of communications, developed at and freely disseminated by Bell Telephone Laboratories. It analyzes the first 25 years of Shannon theory, the role of MIT in developing and extending that theory, and the importance of deep space communications as the initial market for commercialization. It contrasts the early paths of two MIT-related spinoffs that pursued this opportunity, including both key technical and business trajectories driven by information theory. From this, it offers observations about commercializing open science, particularly for engineering-related fields.

Keywords: academic entrepreneurs, information theory, open science, scientific paradigms, technology commercialization

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Industries typically enjoy long periods of relatively predictable incremental innovation, punctuated by irregular bursts of discontinuous technological innovation. Such discontinuities enable new, previously unexplored trajectories for technological innovation (Dosi, 1982; Nelson & Winter, 2002). From these new technological trajectories arise many opportunities for new products, new firms and new industries (Anderson & Tushman, 1990; Nelson, 1995).

In many cases, such technological breakthroughs can be traced back to basic research disseminated through the peer-reviewed process of open science, often from public research institutions such as universities. In some cases, the discontinuous improvement can be traced to a single discovery, whereas in other cases, it builds upon a stream of research in open science.

But how does such open science get commercialized? In particular, absent an explicit policy to align the interests of scientists and firms, how does the knowledge disseminated in open science become incorporated into the offerings of for-profit companies? And when the breakthrough reflects a new scientific paradigm, what is the co-evolutionary path of the nascent science, technology and commercial offering?

I examine the commercialization of the most influential new scientific paradigm in 20th century communications, Claude Shannon's 1948 comprehensive theory of information developed at (and openly disseminated by) AT&T's research laboratories. Beginning with that theory, I show its commercialization through follow-on scientific advances, and on to three MIT-trained engineers who applied that theory to deep space communications — the only significant application to communications in the first 25 years of information theory.

The paper begins with a brief literature review and a description of the data. I then trace the creation of information theory, the emergence of two distinct trajectories within the subfield of coding theory from 1948-1968, and the locus of basic research for each. I next show why coding theory was applied to space communications, and how specific MIT-trained individuals at two firms commercialized this technology to support NASA interplanetary missions from 1968-1977. From this, I propose a commercialization process more applicable to engineering-related scientific breakthroughs, and offer an extended framework for studying open science.

Data and Research Setting

An important source of technical knowledge since World War II has been the research university. In some cases, knowledge is codified and protected by formal intellectual property rights, and then licensed by universities to firms for some form of cash or equity payment (e.g. Zucker et al, 2002; Feldman et al, 2002, 2005; Litan et al, 2008).

This study focuses on a different process: knowledge spillovers from universities to industry. Such spillovers come through the dispersal of graduates into the workforce, and the dissemination of knowledge through the peer reviewed process that David (1998) terms “open science.” Based on the ethos of shared knowledge identified by Merton (1973), spillovers mean that research is a public good not readily appropriated for private gain, providing a crucial input for the cumulative invention of other researchers, and also as a key input for industrial R&D (David, 2002; Chesbrough, 2003: 191-194). However, the system has largely depended on the availability of public funding, which has declined in relative importance in the past 20 years (Fabrizio and Mowery, 2005). Another way of funding such knowledge flows is for universities to patent and license their knowledge, as with the 1980 Bayh-Dole Act in the U.S. (Mowery et al, 2004).

This study traces the knowledge spillovers between commercial R&D activities, universities and government agencies. It focuses on the largest breakthrough in communications theory in the postwar 20th century, the creation of information theory through the publication of Claude

Shannon (1948). Immediately recognized as a major breakthrough, Shannon's work created a new scientific paradigm (as defined by Kuhn 1970) for understanding the technology of telecommunications, but did not by itself specify how such technology would be developed.

Using an exploratory research design, I sought to explain the commercialization of Shannon's theory during its first quarter century, i.e. 1948-1973. When contrasted to other comparable breakthroughs, this commercialization was relatively slow. The Cohen-Boyer technique for recombinant DNA was published in 1973, brought the founding of Genentech in 1976, and was licensed in 1980 by four companies for six human therapeutics approved for sale by the FDA from 1982-1988 (Feldman et al, 2005). By comparison, error correcting codes were incorporated in only 14 of the 27 interplanetary spacecraft launched by NASA from 1960 through 1978, thirty years after Shannon's original publication.

When contrasted to the Cohen-Boyer patent and similar technologies, the case of information theory suggests two research questions: How does a major scientific breakthrough get commercialized when not protected by a patent or other formal appropriability mechanism, and when the relevant applications are not immediately obvious?

Histories of the information theory field identified the development of error-correcting codes as the most active area of theoretical research during the first 20 years of the field, with two distinct technological trajectories within the coding theory subfield (e.g., Berlekamp, 1974; "Information Theory Paper Award," 2006; "Claude E. Shannon Award," 2006). What proved to be the more fruitful of these trajectories was clearly identified with MIT during this period. Other histories identified NASA deep space missions as the first case where such coding theory delivered practical applications of error correcting codes and information theory, and one (e.g., Massey, 1992; Hagenauer, 1998).

In examining the decisions at MIT, NASA and elsewhere about potential applications within this new technological regime, I identified key differences in what Garud (1997) terms "know-why," "know-what," and "know-how." Particularly for the branch of coding theory that most directly reflected Shannon's theories, the know-why during the period 1950-1965 was concentrated among the faculty and alumni of MIT's electrical engineering department. Achieving know-what — finding a practical application for Shannon theory — would frustrate researchers across the field until the first successful applications to space coding. Meanwhile, the application know-how (the ability to implement the technology) was closely linked to know why when applications were yet unknown.

Here I use a rich combination of primary and secondary data sources to trace the development of Shannon theory, its application to deep space communications in unmanned NASA spacecraft, and its commercialization by two startup companies created to leverage the MIT-developed information theory. To measure the development of information theory, I examine the research of the information theory pioneers, as disseminated in academic journals, dissertations, university working papers and as consulting reports for clients. For measures of scientific capabilities I used the information theory field's own measures of the most influential researchers, and in particular the published recognition granted by the *IEEE Information Theory Society* and its predecessor organizations.

To trace the adoption of coding theory by NASA from 1960-1973, I compiled primary archival and secondary data on the communications systems used for all 27 interplanetary spacecraft successfully launched by NASA from 1960-1978. Additional primary data came from interviews with 11 engineers working in space communications during this period — of which 63% worked as NASA or JPL[1] employees, 55% worked as NASA (or JPL) contractors, and 63%

held graduate degrees from MIT. I supplemented this with oral histories available in the public domain or obtained via the Freedom of Information Act, as well as published research on NASA missions and communications systems.

Finally, I combined primary and secondary data on the two MIT spinoff companies, the only two companies with significant revenues from commercializing Shannon theory in deep space communications between 1960-1973.

Shannon's New Paradigm

Claude Shannon was an MIT graduate student from 1936-1940, supported by a fellowship, research, teaching and a graduate fellowship (Sloane & Wyner 1993). After earning a master's in electrical engineering and a Ph.D. in mathematics, he spent 15 years at AT&T's Bell Telephone Laboratories. During World War II Shannon mathematically proved the unbreakability of US codes: his 1945 monograph was both applied enough to be immediately classified as a military secret, and basic enough that upon publication in 1949, it "marked the transition of cryptography from art to science" (Massey, 2002: 14).

Bell Labs was the exemplar of a mid-20th century US corporate R&D lab, a list that also included labs owned by IBM, GE, DuPont and RCA (cf. Chesbrough, 2003a: 28). Protected by its telephone monopoly, Bell Labs believed in active dissemination of its research, including publishing its own journals and strong internal incentives for publishing in those journals. In many cases, its researchers spent more time publishing than their university counterparts.

In 1948, Shannon published his 25,000 word "A Mathematical Theory of Communication" in two successive issues of the *Bell System Technical Journal* (Shannon 1948). The paper reflected a combination of his MIT studies, wartime government-funded research, and his postwar work on AT&T communications problems. A February 1939 letter from MIT graduate student

Shannon to his mentor Vannevar Bush overlaps the initial themes of the 1948 paper, as does the 1949 paper on cryptography adapted from his classified 1945 report (see the compilation in Sloane & Wyner 1993).

Patents were a major goal for AT&T research in the postwar era, with AT&T delaying publication to enable patent filings for much of its electronics research.[2] As with other R&D labs, such patents provided firm-level appropriability for the research published in the open scientific literature. AT&T's failure to file a patent application for Shannon's breakthrough likely reflects either its basic nature or the lack of an obvious practical application.

Shannon's theory transformed communications engineering in the second half of the 20th century, for three reasons. First, it provided a common theoretical framework for analyzing communications across previously disjoint communication channels (such as telephone lines and radio waves) that had previously been treated as an *ad hoc* art rather than a science. Second, it postulated that arbitrary low error rates could be achieved across a noisy information channel; the science of how such results were obtained became the subfield of information theory known as coding theory. Finally, the paper provided both the theoretical and practical motivation for the eventual migration of all communications and information storage from an analog representation to a digital one.

An identity and sense of community for the information theory field quickly developed through the institution building, with an international symposium, a professional society and journal (later the IEEE Information Theory Society and the *IEEE Transactions on Information Theory*) established by 1954. The significance of the breakthrough was recognized immediately by leaders in the communications field, particularly at MIT, who accounted for 11 of the first 18 winners of the Information Theory Society's top prize, named for Shannon (Table 1).

Insert Table 1

Achieving the potential of information theory required communications engineers with both mathematical training and a grounding in a stochastic view of communications theory. The application of the new ideas was resisted by those who lacked such mathematical training or by those who were unable to accept the new paradigm that rendered obsolete their previous conceptions of communications engineering. In the 1950s, many felt the ideas of information theory were impractical given the price, size and performance of computing, but it was applied to military and aerospace communications in the 1960s and 1970s as computing power increased. The shrinking of computers from room-sized computers to thumb-sized microchips in the 1980s and 1990s enabled business and consumer applications such as telephone modems, DSL modems and digital cellular phones (Costello and Forney, 2007).

Research Within Shannon's Paradigm

Shannon provided a new scientific paradigm for communications engineering research, but did not explain how that paradigm could be applied. In the 1950s and 1960s, the scientific advances within the paradigm resulted from researchers applying the coding theorem to improve theoretical communications performance. This came through research both on error correcting codes (channel coding), and on source coding (compression), as well improved computing power obtained through advances in integrated circuits (Viterbi, 1973).

Within Shannon's scientific paradigm, the first area to develop was error-correcting codes, with major breakthroughs only a few years after Shannon's work (Hamming, 1950; Elias, 1955). Research within this subfield of information theory made it possible to reconstruct the original message without errors despite random perturbations of noise in the received signal. Research in coding theory focused both on mathematically optimal algorithms for coding and decoding messages, and also on matching those algorithms to particular problem domains and what was feasible to implement at the time. The only significant application of coding theory during the 1960s was in space communications (Viterbi, 1973).

Research within coding theory from 1950-1990 focused on two distinct technological trajectories: algebraic block codes and probabilistic convolutional codes (MacWilliams, 1968; Costello and Forney, 2007). The trajectories were separated by the cognitive mechanisms identified by Dosi (1982: 153), wherein “the efforts and the technological imagination of engineers and of the organizations they are in are focused in rather precise directions while they are, so to speak, ‘blind’ with respect to other technological possibilities.” The algebraic built upon the familiar paradigm of formal mathematical algebras, while the probabilistic worked within the new paradigm of Shannon’s statistical communications theory.

Each trajectory was associated with its own group of researchers and institutions. For algebraic coding, it was the invisible college of mathematicians trained in algebraic theory. For probabilistic codes, it was electrical engineers trained at MIT from 1950-1965, during its golden age of information theory. Each trajectory was extensively researched by its respective social group, and each reached a point of diminishing returns by 1975.[3]

Table 2 lists the most important coding technologies from each trajectory from 1950-1967, which in turn were applied by external contractors to NASA coding problems from 1965-1973, and deployed in spacecraft from 1968-2003. All of the listed papers were among most influential in the first 25 years of coding theory (as compiled by Berlekamp 1974), and (as reported in each paper’s acknowledgements) all but was one directly or indirectly funded by the military.

Insert Table 2

Trajectory #1: Algebraic Codes

Block codes were the first technological trajectory within the Shannon paradigm, beginning almost immediately after Shannon's paper (e.g. Golay, 1949; Hamming, 1950). These codes treated the coding of information as a reversible transform through operations within an algebraic field (Berlekamp 1968). This meant that the properties of the codes were quickly understood, because the inverse transform of algebraic decoding could be shown mathematically to exactly reconstruct the original despite certain number of transmission errors.

As such, the pioneers in algebraic coding worked within the paradigm of formal mathematical algebras, and thus the pioneers were mathematicians trained at elite schools such as Harvard, Caltech and MIT, as well as Shannon's former colleagues at AT&T's Bell Telephone Laboratories. Most of the key breakthroughs in block coding came during the period 1950-1960, including the development of Reed-Muller codes (1954), Reed-Solomon codes (1960) and Bose-Chaudhuri-Hocquenghem codes (1960) (cf. Berlekamp, 1974). The last major improvement of the 1960s came with an improved decoding scheme published by Berlekamp (1968).

During the first 20 years of information theory, such block codes were considered nearly synonymous with the study of error-correcting codes (e.g., MacWilliams, 1968). However, by the end of the 1960s they had reached a level of diminishing returns, such that a 1971 IEEE workshop famously (and inaccurately) declared that "coding is dead" (Costello and Forney, 2007).

Trajectory #2: MIT's Probabilistic Codes

Convolutional codes reflected an entirely different set of researcher skills and principles, ones more directly inspired by and consonant with the probabilistic view of information transmission developed by Shannon and others at MIT. The goal of convolutional decoding was not to reconstruct the original message if there were few enough errors, but instead find the most likely original message based on all available information. Instead of mathematically rigorous analytical solutions, they utilized the newly emerging process of computer simulation

As was clear by 1970, convolutional codes came much closer to realizing the promise of Shannon's theorem (Forney 1970b). The advantage of convolutional codes was that they used more information to delivery more accurate results and thus worked with a weaker signal (lower signal/noise ratio). Encoding convolutional codes also required only a few simple shift registers — well within the computing power of the era (e.g., Massey & Costello, 1971). However, the codes had serious computational problems on decoding, particularly when decoding weak signals, i.e. those that most benefit from coding to accurately recover the original data. Both computational cycles and memory were scarce in early computing systems, particularly when decoding real-time data streams.

The major breakthroughs of convolutional coding in the 1950s and 1960s — and their application to space communications — were largely synonymous with MIT-affiliated electrical engineers. The concept of creating convolutional codes came from MIT faculty member Peter Elias (Elias 1955). The first solution for decoding convolutional codes came with the discovery of sequential decoding in the Sc.D. dissertation of John Wozencraft (1957), and then the development of an efficient algorithm by his advisor, Robert Fano (1963). Thus, it is not surprising that in her chart of the evolution of coding theory, MacWilliams (1968) refers to this entire branch of coding as "MIT codes".

The MIT coding research during the period 1946-1970 was almost entirely funded through two MIT research labs. The 1946 Research Laboratory of Electronics (RLE) was located on campus, run and staffed by MIT faculty and students from the electrical engineering and physics departments — one of 12 university programs funded by the Defense Department and the only one that focused on communications (Shostak, 1985). Despite ongoing military funding, the RLE focus (particularly after 1951) was on more basic (and largely unclassified) basic research. Its research output was widely disseminated, through academic journal articles, RLE reports (monographs), and often published books.

In 1951-1952, MIT created a second research lab, Lincoln Laboratory and built a new facility 11 miles away. Lincoln was an Air Force sponsored Federally Funded Research & Development Center, with a culture similar to other federally funded labs such as the Los Alamos, Sandia and Lawrence Livermore nuclear weapons labs.

The military funding of basic (RLE) and applied (Lincoln) research supported MIT's key breakthroughs in information theory from 1950-1965. For example, the Berlekamp (1974) compilation of breakthrough papers in coding theory lists 11 journal papers with MIT (or RLE or Lincoln Lab) authors, all with military funding. Of the first 15 Shannon Award winners after Shannon (1974-1995), eight had graduate degrees from MIT (Fano, Elias, Gallager, Root, Massey, Viterbi, Berlekamp, Forney); all but Viterbi had earned their doctorate at MIT, and six were best known for their contributions to probabilistic coding theory, primarily in connection with convolutional codes. The MIT winners were also the only prize-winners in this period associated with convolutional codes.

During its rapid growth period during the golden age of information theory, MIT reinforced its lead by hiring its own graduates, who in turn mentored new graduates. This pool of MIT-developed knowledge of convolutional coding was carried by the MIT graduates to NASA during the late 1960s and early 1960s to solve its problems for deep space communications (Figure 1).

Insert Figure 1

Finding Applications in Space

While Shannon's theory excited and energized researchers for 20 years, it initially had little commercial impact. As a leading information theorist wrote in 1970:

> For many years after Shannon's announcement of the basic theorems of information theory in 1948, the absence of any actual realization of the exciting improvements promised by the theory was a source of some embarrassment to workers in the field (Forney, 1970b: 47).

Forney identified two sources of the problem. First, Shannon's paper was only an existence proof that predicted an improvement in communications performance, but did not explain how it would be achieved; delivering such performance proved to be the domain of coding theory. Second, "the channels of practical interest — telephone lines, cable, microwave, troposcatter, and HF radio — proved not to have anything like the statistical regularity assumed in the proof of the coding theorems" (Forney 1970a: 47). Fortunately, the space channel exactly corresponded to the random noise form assumed by Shannon (1948).

The first major application of Shannon's predictions regarding statistical communications theory thus occurred from 1964-1973 in a series of unclassified NASA-funded research and development projects, in which MIT-trained information theorists both solved NASA's communications problems and, in doing so, developed key breakthroughs in coding theory. As Hagenauer (1998: 6) concluded in a retrospective on the first 50 years of information theory in communications, “Deep Space Communications was the first area where engineers were led by information theory.”

However, when NASA was first considering coding in the early 1960s, few engineers believed in the promise of the probabilistic coding theory, and fewer still had the tacit knowledge to apply it to solve NASA’s problems. The eventual solution for improving the data rate for unmanned space combined all major breakthroughs in coding theory from 1954-1967, from three distinct areas: algebraic codes, probabilistic codes, and concatenating multiple codes (Figure 2). First launched into space from 1968-1977, these breakthroughs were brought to NASA by three of the leading MIT-trained information theorists of the 1960s.

Insert Figure 2

NASA’s Motivation for Coding

From Shannon’s theoretical limit, the effective signal strength determines the transmission throughput attainable for a given error rate. The application of coding theory could potentially provide a bit error rate of 10^{-5} (or 1:100,000) using a signal that was nearly 10 dB weaker than the uncoded case (McEliece 2005). For space communications, the effective power of the transmission (and thus the data rate) was a function of the transmitter power, effective antenna area (allowing for techniques that improve the effective size), and inversely proportionate to the square of the transmitting wavelength and distance.

NASA faced practical size limits for ground-based antennas (weight and cost) and spaceborne antennas (fitting in available boosters). The most demanding problem was receiving data from spacecraft, because the spacecraft transmitter had less power available for transmitting than the ground-based antennas operated for NASA. This problem was exacerbated for journeys beyond Mars to the outer planets, which required longer distances, were too far from the sun to use solar power, and involved long missions that would tax the space probe's power source.

From 1961 to 1981, the performance of ground-based receiving equipment was improved by an impressive 49 dB. However, most of this gain (37 dB) occurred in the first decade, as improvements became harder to achieve. In particular, by 1966 NASA had increased antenna diameter from 26 meters to 64 meters, and reduced receiver noise temperature from 1500° K to 50° K (Mudgway 2001). Most of the remaining improvements came from increasing transmission frequency, but the higher frequencies were more subject to atmospheric attenuation.

In the late 1960s and early 1970s, NASA project managers were planning the first missions to Jupiter and beyond. The 130 million miles of the 1964 Mars missions would become 500 million miles for the planned 1973 flyby of Jupiter or 1.9 billion miles for the 1986 visit to Uranus. Given the previous advances, transmitting images from those longer distances would require either increasing transmitter power (and thus available spacecraft power) or antenna size, but both were infeasible. Improving communications signal strength thus became a "reverse salient" in the sense of Hughes (1987). The entire point of unmanned probes was to transmit scientific data (and images) back to Earth, and the predictd signal strengths would be several decibels short of providing the data rates necessary to achieve mission goals.

Coding theory offered a solution to these problems. The proper encoding algorithm (implemented in spacecraft hardware) and decoding algorithm (in ground-based receiving equipment) could substitute for expensive improvements in antenna size or spacecraft power.

Early Efforts

While the first spacecraft used analog transmissions, digital transmissions were used beginning with Pioneer V (1960). However, no spacecraft used error correcting codes (beyond simple parity checks) for operational communications before 1968 (Table 3).

Insert Table 3

JPL employees were studying the use of block coding as early as 1960 (Viterbi 1960). In addition to the work of Viterbi (then a USC graduate student), major contributions were made by Solomon Golomb and Gustave Solomon (a co-inventor of the Reed-Solomon block codes), mathematicians trained at Harvard and MIT, respectively. These contributions were disseminated in a volume on digital communications by these JPL scientists (Golomb, 1964).

The block codes begun by Viterbi were intended to support transmissions for probes from as far away as Mars. The technology was first launched into space in 1969, when Mariner 6 and 7 transmitted telemetry more than 40 million miles from Mars. However, this provided only 3 dB of improvement, more than 6 dB away from the Shannon limit. The improvements necessary for missions to Jupiter and beyond would come from two different forms of convolutional coding, developed for NASA by MIT-trained engineers.

Codex: First Sequential Code in Space

Two companies used NASA as their lead customer for their convolutional coding business: Codex and Linkabit. The two companies were the principle coding companies of the 1960s, and thus the first to commercialize convolutional coding (Costello and Forney, 2007). Both companies had close ties to MIT, and both played similar roles in supplying technology for competing NASA agencies. However, coding theory played different roles in their eventual business strategies: one gave up, and one grew the business to a successful exit (Table 4).

Insert Table 4

The first company to exploit probabilistic coding was Codex, which was incorporated in Cambridge, Mass. in July 1962 to exploit the possibilities of coding theory. Cofounder Arthur Kohlenberg was well-connected to the MIT information theory group, a college classmate of MIT researcher (and then EE department chair) Peter Elias, and was the editor of the field's leading journal, the *IRE Transactions on Information Theor*y. The original "code" in Codex came from two early consultants and shareholders from MIT: Professor Robert Gallager and a 1962 graduate, James Massey. Codex hoped to market Gallager's coding technology for high-speed military communications, and Massey's for lower cost commercial applications.

NASA Work

In 1965, Codex hired Gallager's student, Dave Forney, only its second Ph.D. employee after Kohlenberg. He immediately went to work on helping NASA Ames Research Center improve the communications capabilities of its series of probes to the sun, the outer planets and Venus. The research & development of the communications systems for these probes was conducted from 1963-1971 by a group of five Ames communications engineers, who designed and built prototype systems based upon the research of three future Shannon award-winners.

The Codex work was done by Forney with advice from Gallager, who remained an MIT faculty member during this period. Codex performed two studies for Ames from 1965-1969, to evaluate alternatives and then to develop a sequential decoder based on the (public) research of

MIT colleagues (and future Shannon award-winners) Peter Elias and Robert Fano — the first commercialization of convolutional codes.

Forney emphasized the importance of having a single engineer simultaneously combining both the know-why (of deep theoretical knowledge) with the know-how (the specific steps necessary to implement the technology in hardware and software). Unlike larger organizations (such as Bell Labs) that separated the theoretical design from the technical implementation, as the sole Codex-employed coding engineer, he was able to advance the state-of-the-art in convolutional codes because "I could see what was important in codes — what made it good in practice or not good in practice."

The Codex-developed code was shipped on Pioneer 9, and required development of Fano sequential decoder software to run on the Ames computers (Forney, 1967). Instead of the 3 dB improvement required, the code delivered a 6 dB improvement over the uncoded case, nearly twice that provided by the JPL contemporaneous block code (Massey, 1992).

The communications requirements were more demanding for Pioneer 10 and 11 — the first space probes to the outer planets — due to greater distances and limited power. While the decoding was similar to Pioneer 9, NASA contracted with James Massey (an MIT alumnus then a faculty member at Notre Dame) to develop an improved convolutional code. Based on the dissertation of his student Daniel Costello, they identified a new type of code with an even lower error probability (Massey and Costello, 1971). The code was used for Pioneer 10 (launched 1972), which arrived at Jupiter in 1973, as well as Pioneer 11 (launched 1973), which became the first probe to visit Saturn in September 1979. This Ames-sponsored convolutional coding was also used in Pioneer 12 and 13 launched in 1978 towards Venus.

Exiting Coding

Coding was Codex's sole source of revenue in its first five years. In 1968, Codex shipped its first 9600 bit per second telephone modem. The growth rates for this commercial market segment were attractive, but the nature of the markets was entirely different than the government customers that had sustained its coding business.

Codex faced an unprecedented crisis in 1970 with the death of its two remaining founders, Jim Cryer and Kohlenberg. The company's directors appointed a new management team (with Forney as VP of R&D), raised an additional $1 million to keep the doors open, and decided to drop error-correcting codes entirely — referring future inquiries to Linkabit.

The single-minded focus on modems proved successful, as the demand for modems over time broadened from large firms to small ones, and eventually to individual consumers seeking dial-up network access. The company was acquired by Motorola in 1977.

Linkabit Creates NASA Standard

In 1968, after attending a workshop at NASA Ames, three former MIT students — Irwin Jacobs, Andrew Viterbi and Leonard Kleinrock — agreed to create a company to pool their respective consulting for government agencies and contractors. While Kleinrock soon dropped out, in 1971 Jacobs left his UCSD job to run the company full-time. Jacobs and Viterbi would use NASA as the first customer for a more than $10 million/year coding business.

Viterbi's New Decoding Algorithm

After completing his S.B. and S.M. degrees at MIT, Viterbi left Boston to take a job as a communications engineer at JPL While working full-time at JPL, he completed his Ph.D. at USC and then joined the UCLA faculty. Viterbi helped Jacobs spend the 1964-1965 academic year as a JPL communications researcher.

With a research stream dominated by the problems of space communications, Viterbi developed a new probabilistic algorithm for decoding convolutional codes that largely replaced the Fano sequential decoding algorithm. Viterbi initially underestimated the impact of his work in two ways. First, he believed it to be asymptotically optimum, but other researchers quickly realized that it was a maximum likelihood algorithm (Costello and Forney, 2007).

Secondly, as he said later, “I didn’t believe [it] was practical and most people I talked to didn’t believe it was practical either at the time” (Alonso 1992: 13). Three years after it was published, the first researcher to recognize the importance of the algorithm wrote that the algorithm “cannot achieve very low error rates efficiently” (Forney 1970a: 58).

Commercialization at NASA

As with the Codex application of coding for NASA Ames, the commercialization of Viterbi’s algorithm required a researcher who could combine both the know-why and know-how. The first breakthrough came from Jerry Heller, one of three doctoral students of Irwin Jacobs to do an MIT dissertation related to sequential decoding. After finishing his Ph.D. in 1967, Heller joined JPL’s communications research group, where he remained until joining Linkabit in 1969.

Heller’s know-why from MIT and the know-how required for his JPL job found a practical application with the Viterbi algorithm. While studying the Viterbi (1967) paper at JPL, Heller found that the algorithm was computationally superior to the Fano algorithm, and far simpler than anyone had imagined — quite feasible to implement with the simple shift register integrated circuits of the day. Viterbi was unequivocal about Heller’s role: “he was the first to recognize its practicality" (Alonso 1992: 15). The first use of a Viterbi decoder by NASA came with the Mariner 10 mission to Venus and Mercury (1973).

Another breakthrough came with the UCLA doctoral dissertation of Joseph Odenwalder, as supervised by Viterbi. Using the concatenation approach first proposed in Forney's (1965) MIT dissertation, Odenwalder combined a block code with a convolutional code to get the best of both algorithms. Odenwalder's 1970 dissertation was funded by a contract between UCLA and NASA Ames, as were the 1971 dissertations of two other Viterbi students. The final contract report submitted to NASA Ames summarized these three dissertations, and included excerpts from each (Viterbi, Odenwalder, Rosenberg & Zeoli, 1971) After completion of the UCLA studies, Odenwalder, Viterbi and others delivered two follow-on coding studies for NASA (Odenwalder et al 1972, 1973), but this time Viterbi contracted through Linkabit not UCLA.

JPL eventually adopted the scheme proposed by Linkabit, concatenating an outer block code and a Viterbi-decoded convolutional inner code. This combination was later designated the first NASA standard convolutional code, and was also adopted by the European Space Agency (Yuen et al 1983: 222). The Voyager 1 and 2 missions to Jupiter and the outer planets (1977) were the first to use Odenwalder's approach.

The research done by Codex, Notre Dame, UCLA and Linkabit was widely disseminated through journal articles and through contractor reports published by NASA. As of mid-2007, the Codex final report for NASA Ames (Forney 1967) had 19 citations in Google scholar, mainly in refereed IEEE journals. A 235-page report done by Linkabit summarizing the state of coding theory (Odenwalder 1976) is cited 29 times, and the author was still getting requests for the report after he moved to Qualcomm 20 years later (personal interview, Oct. 9, 2006).

Subsequent Commercialization

Unlike Codex, Linkabit believed in the future of coding. Jacobs was among the first to object to the aforementioned 1971 claim that "coding is dead," claiming (correctly) that increasing miniaturization of computing power would make coding practical (Costello & Forney, 2007).

In 1974, Linkabit began development of a specialized microprocessor for use in Viterbi decoding. It sold convolutional decoder products to government and military customers. Its advertising extolled the success of the Viterbi decoder hardware sold to NASA ground stations for processing the Voyager photographs from Jupiter, Saturn and Uranus. Linkabit used its coding expertise to develop secure communications terminals for the Army and Air Force, as well as more commercial forms of satellite communications.

With the increase in computing power and the diffusion of information theory training, coding eventually became commonplace in digital communications and storage. For example, a variant of the Reed-Solomon codes eventually adopted as part of NASA standard coding was incorporated in 1980 as the basis for encoding digital data in compact discs (Immink 1994).

Despite its technical achievements, Linkabit achieved only modest financial success, in part due to undercapitalization. Seeking capital and legitimacy to fund manufacturing of its first consumer product (HBO's first video descrambler), Jacobs and Viterbi sold Linkabit to M/A-COM, effective August 1980. In its final year as an independent company, Linkabit earned more than $20 million/year, and four years later it accounted for some $95 million of the parent company revenues.

In 1985, Jacobs and Viterbi left Linkabit and founded Qualcomm.[4] Its first semiconductor product was a single-chip implementation of the Viterbi decoder first commercialized in JPL's 1973 mission to Mars. The Viterbi algorithm is now a standard part of every digital cell phone, with more than one billion served, and is also used to decode direct broadcast digital satellites (Forney, 2005).

Discussion

This study traced the initial commercialization of a new scientific paradigm disseminated through open science. It showed how commercialization was delayed by scarcity of “know-why” among the paradigm’s top researchers, and the search for a real-world problem that matched the theory’s assumptions. It identified the first commercial application within that paradigm, and the most important technical advances along two trajectories towards servicing that application. Finally, it showed how the scientific research elaborating the superior trajectory within that paradigm was publicly funded, concentrated at one institution, and (despite open dissemination) was initially commercialized by researchers with strong ties to that university.

The commercialization of Shannon’s scientific breakthrough has many similarities to commercialization of other university-developed knowledge, notably the commercialization of recombinant DNA studied by Zucker, Darby and colleagues (e.g. Zucker and Darby, 1996; Zucker, Darby & Armstrong, 2002). However, I identify two important differences between these two breakthroughs: the role of tacit knowledge in finding applications for scientific breakthroughs, and a more direct process for commercializing such breakthroughs. From this, I suggest a broader conception of the “open science” process.

Applying Tacit Knowledge to Discover Applications

A new scientific breakthrough creates knowledge that is both tacit and scarce, and thus provides for potential excludability with or without formal intellectual property rights. The greatest knowledge of breakthrough discoveries resides in those scientists making them, and the acquisition of the new knowledge is most difficult when the technological discontinuity is greatest (Zucker et al, 2002: 141).[5] During this period, such knowledge flows through the mobility of those skilled researchers (David, 2002: 41).

The existence of a real world problem is a commercial opportunity for a firm, and thus the “know-what” of such potential applications is a crucial antecedent to commercializing an innovation (Hsieh et al, 2007; Garud 1997). However, unlike with recombinant DNA, the commercial application of Shannon’s theory was not immediately obvious. As such, the incentive to acquire this tacit knowledge remained lower and the technical advantage conveyed by tacit knowledge remained for more than two decades after Shannon’s discovery, with that knowledge mainly localized to those affiliated with MIT’s electrical engineering department. Linked by their shared knowledge — as well as education and friendship ties, these researchers formed a community of practice (cf. Brown & Duguid, 2001).

Commercialization is impaired not only by barriers to flows of tacit and other ambiguous knowledge between organizations, but also within organizations through the separation of basic research, applied research and development (cf. van Wijk et al, 2008; Chesbrough, 2003: 31-34). We would expect these barriers to have a more severe impact on engineering-based commercialization than those for commercializing pure sciences, given the inherent linkages between theory and practice in the engineering fields.

While a brilliant theoretical researcher, Shannon’s breakthrough was clearly informed by an interest in communications problems — whether as a hobbyist during his childhood, in his college studies of engineering, or his work in World War II on communications secrecy. However, in developing and applying Shannon’s theory, MIT’s engineering faculty worked on campus on basic research, while applied research and development took place at MIT’s off-campus Lincoln Lab. Similarly, within AT&T and even within Bell Labs, the Communication

Theory Department (where Shannon once worked) reported through a different management chain than did the development-oriented engineers.

The first commercialization of Shannon's ideas came from engineers who had the "know why" of Garud (1997) that allowed them to both extend and apply information theory. Interviews with engineers involved in application of Shannon's theory to space communications emphasized that a prerequisite to success was making the trade-offs involved in the joint optimization of various performance goals — power, range, speed, reliability, cost — meeting certain goals while optimizing on others. Such engineering proficiency required an intimate knowledge of both the theoretical and the practical, and thus was a source of competitive advantage.[6]

This inextricable link in engineering between research and development may be one reason why startup formation is relative common among engineering professors, at least at some elite universities (e.g., Roberts, 1991; Kenney & Goe, 2004). Another possible explanation is that — unlike the more typical professors identified by Ambos et al (2008) — many engineering professors are comfortable in both a research and industrial setting. Of the four central researchers in NASA coding, two (Jacobs, Viterbi) shifted from academia to industry, one (Forney) eventually shifted from industry to academia, while the fourth (Massey) licensed his technology to start two companies while remaining an academic.

A More Direct Commercialization Process

Prior studies of technology commercialization have emphasized the importance of managing the difficult process of transferring scientific knowledge from the inventor of basic scientific knowledge to the commercial scientist or engineer that will do the applied research. Such models have assumed these are distinct individuals and organizations, both because of the divergent technical skills required, but also because commercialization requires both incentives and productization assets not found in the university setting (e.g. Shane, 2002; Zucker et al, 2002). At the same time, research on knowledge transfer has shown the difficulty of transferring technology between organizations, particularly when the knowledge is ambiguous or the sending and receiving organization are dissimilar in culture or structure (van Wijk et al, 2008).

The commercialization of information theory in deep space coding during the 1960s and 1970s suggests an alternate process model[7] for commercializing university innovations:

- *Have Star Scientists Commercialize Their Own Knowledge.* Three of those directly involved in deep space coding theory (Massey, Viterbi, Forney) were among the first 16 winners of the Shannon Award — information theory's equivalent to the Zucker et al (2002) "star scientists." Prior to or during their NASA work, they also studied under or co-authored with six of the remaining 13 initial winners.
- *Directly Link Basic Research, Applied Research and Development.* These three MIT-trained "star" engineers produced basic research, did applied research for space communications, and also were involved in either the design or (in Forney's case) the actual implementation of the communications system that used the technology. Similarly, the dissertation research of Odenwalder (under Viterbi) and Costello (under Massey) was later developed by both men into technology used in NASA communications.
- *Maximize the Codification and Dissemination of Knowledge.* Both to satisfy the customer and to advertise their innovation competencies, the contract R&D performed for NASA and JPL was widely disseminated, both as journal articles and working papers (i.e. NASA technical reports).

The first two points emphasize transferring knowledge within people rather than between people, consistent with the study of Song et al (2003) of knowledge transferred in the semiconductor industry through hiring experienced engineers. The third point reflect an effort to maximize the "open science" spillover effects of the knowledge creation activities.

In seeking to apply this model, one limitation — as in any study of a single innovation — is defining the boundary conditions for generalizability. Below are testable propositions that suggest the conditions that separate this direct commercialization process from the indirect commercialization model (as captured by Zucker and others) used in the life sciences:

- *Engineering Rather than Science.* The advantages of direct commercialization are likely much lower for the sciences than for engineering, where (as noted earlier) there is an inherent interdependence of basic research and applications and where engineers appear to be more likely to have a mix of academic and industrial skills.[8]
- *Minimize the Assets Needed to Commercialize.* Commercializing a biotech invention requires numerous marketing, distribution, manufacturing and regulatory compliance assets not available to university scientists. In contrast, doing R&D studies for one government agency is well within the capabilities of individual scientists: NASA convolutional coding studies were done by Massey and Viterbi as college professors, and by Codex and Linkabit early in their respective corporate histories.
- *Early in a Paradigm.* The commercialization through space communications occurred very early in the Shannon paradigm, when few applications were known, and there were few suppliers and customers. Thus, it is not surprising that there was less incentive to monetize spillovers through patents and licensing when compared to the Cohen-Boyer patent, for which commercial products appeared in less than a decade.

Other related factors may also be involved. Commercialization assets of pharmaceutical research provide entry barriers due to economies of scale, and the sizable specialized up front costs raise the magnitude of stranding risk for investing in an unproven technology. However, pay-as-you-go revenue models (such as consulting) provide an entrée for new firms (such as Linkabit) to create a viable business from unproven technologies. After entering without commercialization assets, both Codex and Linkabit built the necessary assets as they transitioned from a study-oriented business models to one based on building products.

Additionally, the period studied was not only early in the Shannon paradigm, but it only had one customer with miniscule revenues — not enough to attract a large supply of new entrants or support the entry of large incumbents. Thus, the ability for new firms to survive without complementary assets may reflect the small market size (and lack of competition) as much as the revenue model.

Unpacking the Dimensions of Open Science

From Newton's 17th century observation about "standing on the shoulders of giants," both the practice and study of scientific discovery has emphasized the importance of openness as enabling knowledge flows and cumulative discovery (e.g., Merton, 1973; David, 1998). Important antecedents to such openness have included professional norms, the location of research activities (university or government vs. industry) and the source of funding.

In response to recent policy shifts from public to private funding of university research, some research has emphasized a narrow definition of "open science," which David (1998: 15) defines as being "supported by state funding and the patronage of private foundations, and carried on in universities and public (not-for-profit) institutes." Collapsing and bifurcating the dimensions of openness may be useful in making policies for public research support. However, the commercialization of information theory provides an example of confounding the openness of knowledge dissemination with its presumed antecedents overlooks other paths for commercializing scientific knowledge.

At its most basic, “open” science would be defined by the availability, flows and ability to apply forms of tacit and explicit knowledge — as has been done for other forms of openness such as open innovation, open source software and open standards (Chesbrough, 2003; Rosen, 2004; West, 2006). Rather than a strict bifurcation, such definitions also allow for degrees of openness, such as the differences among open source license in the rights and responsibilities granted (Rosen, 2004) or the differences in open standards in the rights of access to technical information, rights to commercialize that information, and the costs for such access and commercialization (West, 2006).

For firms (or universities or individuals) seeking to profit from discoveries, the degree of openness dictates the appropriability strategy. In some cases, firms may achieve greater appropriability through secrecy than the patent system (e.g. Cohen et al, 2000). In other cases, neither mechanism may be available to firms, but even without formal IP rights (as Zucker & Darby note) tacit knowledge can still provide competitive advantage.

At the same time, the location of such scientific discovery has important impact on both the knowledge flows and commercialization. This suggests that the study of commercialization of basic science would consider both how open is the scientific process, as well as differences due to the actor performing the research. Such a two-dimensional classification is shown in Table 5.[9]

At opposite corners of this classification are the two archetypes of David’s (1998) classification: corporate actors pursuing research that is undeniably closed (#6), and university research that has previously been termed “open science” (#1). To avoid confusion, the latter can be referred to as “public science,” a term used by Narin et al (1997) that appears synonymous with the subsequent use of “open science”.

The value of the new classification approach is instead seen in the remaining cells, i.e.., more closed science in universities and more open science in companies.[10] The case of the former — privatizing university science (#5) — has been the subject of considerable research and criticism. The use of confidentiality in contract university research is common in academic consultation going back to at least the 1930s (Etzkowitz, 2002), but its recent use in medical research has been decried due to potential conflicts of interest (e.g. Baird et al, 2002).

Less controversial is the publication in open science of scientific breakthroughs that are protected by patents and then exclusively licensed to private interests (#3), which is at the center of most recent conceptions of commercializing university knowledge (e.g., Litan et al, 2008). Such patent licensing was an explicit goal of the US Bayh-Dole Act, which helped encourage a shift in the pattern of commercializing university research from free spillovers of public science (Mowery et al, 2001, 2004). However, such increased university patenting has both decreased the utilization of public science by some companies and also delayed the commercialization of such science in private inventions (Fabrizio, 2006, 2007).

This study examines the opposite case — more open research strategies pursued by for-profit actors — in this case, Bell Labs, Codex and Linkabit. Claude Shannon published his greatest scientific contribution in an open journal article and later a book. While publication was customary, Bell Labs normally encouraged it in parallel with patent applications (#4), and thus its decision not to patent Shannon’s work was atypical for its electronics research in that era.

The contract R&D performed for NASA and JPL had a fundamentally different character, as the government funding meant that researchers were required to disseminate their work widely without right to formal appropriability (#2). Here the locus of research does not appear to be a factor: it is impossible to distinguish between the spillovers of Viterbi & Odenwalder at UCLA or the same men while at Linkabit, or between the coding research done for NASA Ames by Codex and that led by Massey of Notre Dame.

Open dissemination by Linkabit and Codex are consistent with the earlier characterization of another MIT spinoff, BBN, the commercial firm that played the greatest role in building the ARPAnet (and thus the Internet) during the 1960s and 1970s. Mowery and Simcoe (2002: 1372) describe BBN as a "quasi-academic" environment based on its close links to MIT and its culture. Interviews with more than a dozen Linkabit alumni suggest that this moniker would also apply to this company, at least through the mid-1970s and possibly as late as its 1980 acquisition.[11]

Suggestions for Future Research

The limitations of this single-industry study suggest opportunities for future research. The study focused on those who commercialized information theory, and thus cannot draw inferences about the motivations of those who did not — whether through lack of training, limited proficiency or (in retrospect accurate) skepticism about its initially limited commercial potential. Without a counterfactual, questions remain about the government's allocation of rights from funded research. Open dissemination was a condition of NASA funding, and yet neither Codex nor Linkabit would have pursued these studies if they did not think it would lead to other areas where they could gain advantage such as through trade secrets or patents.

The classification of open science given by Table 5 offers opportunities for refinement and elaboration. Is openness of knowledge spillovers a discrete scale (as suggested), or a continuous variable? Is the source of funding a more relevant dimension than the location of research, i.e., is all publicly funded research (done by industry, university or government) fundamentally different from privately funded research?

Finally, this study hints at the opportunities for studying the differences in commercialization of the sciences (especially life sciences) and engineering fields. Prior research has looked at the entrepreneurship (but not the technology commercialization steps) of engineering researchers (e.g., Rindova and Kotha, 2001; Kenney & Goe, 2004). Nelson (2005) considers the licensing of a significant electronics breakthrough — FM music synthesis — but from the standpoint of the internal university imperatives, rather than the decisions by external actors to commercialize the university technology, which would be another opportunity for future research.

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Tables and Figures

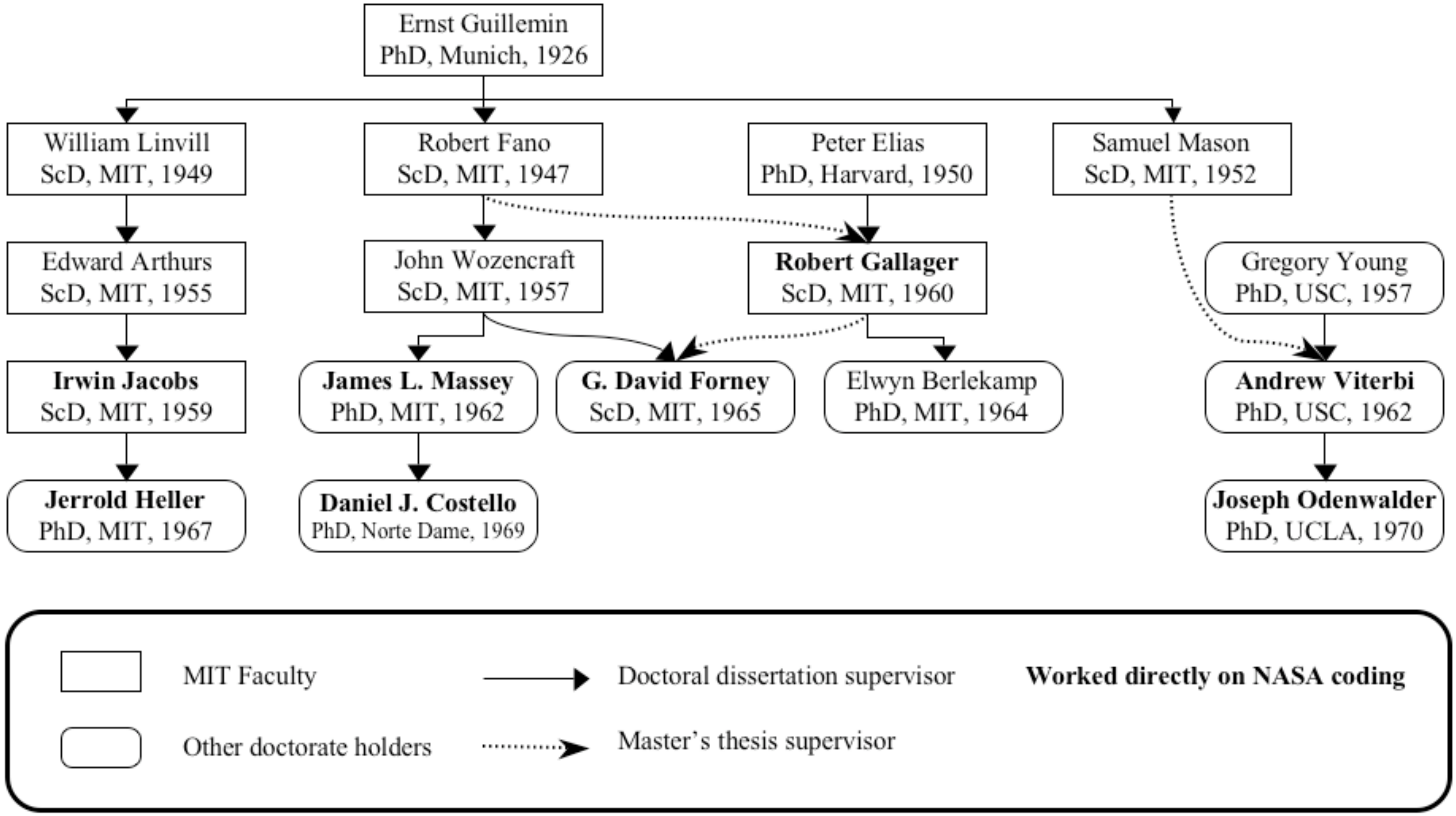

Figure 1: Academic genealogy for key researchers on NASA convolutional coding, 1966-1973

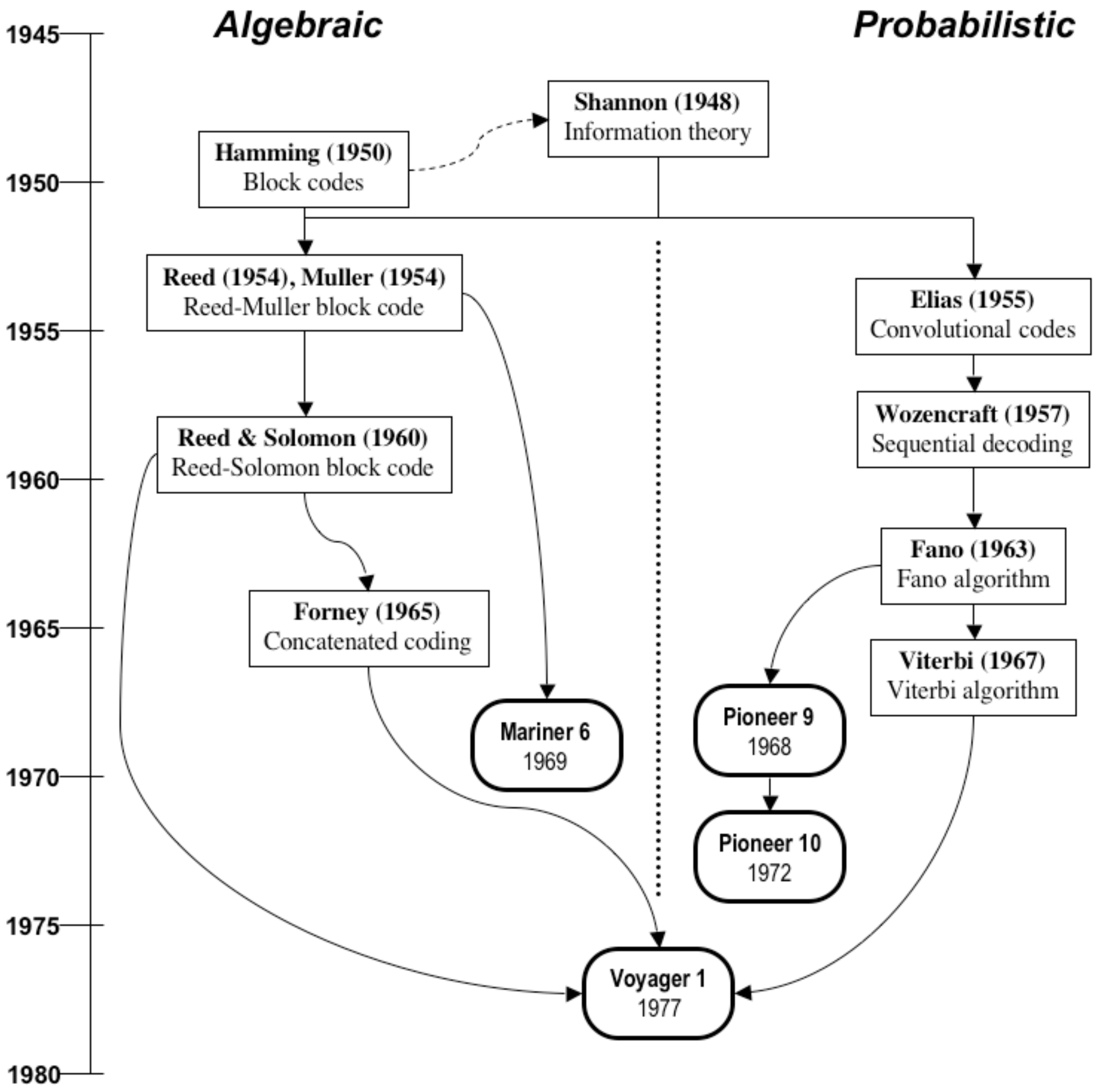

Figure 2: Evolution of coding theory applied to NASA deep space probes

Award Date	Name	Major Contribution	MIT Ties
1973	Claude E. Shannon	Creating information theory	S.M., EE, 1940; Ph.D., Math 1940; faculty, 1958-1978
1976	Robert M. Fano	Information theory textbook; sequential decoding algorithm	S.B., EE, 1941; Sc.D., EE, 1947; EE faculty, 1947-84
1977	Peter Elias	Convolutional codes	S.B., EE, 1944; EE faculty 1953-91; dept. chair 1960-66
1982	Irving S. Reed	Reed-Muller and Reed-Solomon codes	MIT Lincoln Lab researcher, 1951-1960
1983	Robert G. Gallager	Low-density parity check codes	S.M., EE, 1957; Sc.D., EE, 1960; faculty, 1960-2001
1986	William L Root	Signal detection	S.M., EE, 1943; Ph.D., math, 1952; MIT Lincoln Lab researcher, 1952-1961
1988	James L. Massey	Algebraic decoding	S.M., EE, 1960; Ph.D., EE, 1962
1991	Andrew J. Viterbi	Optimal decoding of sequential codes	S.B., EE, 1957; S.M., EE, 1957
1993	Elwyn R. Berlekamp	Theory of algebraic codes	S.B., EE, 1962; S.M., EE, 1962; Ph.D., EE, 1964
1995	G. David Forney	Concatenated codes	S.M., EE, 1963; Sc.D., EE, 1965; adjunct professor, 1996-present
1997	Jacob Ziv	Source compression	Sc.D., EE, 1962

Source: "Claude E. Shannon Award" (2006), MIT library (dissertation dates); personal CVs, biographies. Award is normally announced one year before formal presentation

Table 1: Shannon Lecturers with strong MIT affiliations, 1973-1997

Trajectory	**Technology**	**Paper**	**Author**	**Doctorate**	**Employer**	**Reported Funding**
Information theory	n/a	Shannon (1948)	Claude Shannon†	Math, MIT, 1940§	Bell Telephone Laboratories	*See text*
Algebraic block codes	Golay codes	Golay (1949)	Marcel Golay	EE, ETH Zurich, 1924	Army Signal Corps	US Army
	Hamming codes	Hamming (1950)	Richard Hamming	Math, Illinois, 1942	Bell Telephone Laboratories	Unspecified
	Reed-Muller codes	Reed (1954); Muller (1954)	Irving Reed;† David Muller	Math, Caltech, 1949; Physics, Caltech, 1951	MIT Lincoln Lab; U. Illinois	Unspecified¶; US Army, US Navy, US Air Force
	Reed-Solomon codes	Reed & Solomon (1960)	Irving Reed;† Gustave Solomon	Math, Caltech, 1949; Math, MIT, 1956	MIT Lincoln Lab; MIT Lincoln Lab	US Air Force
Probabilistic convolutional codes	Convolutional codes	Elias (1955)	Peter Elias†	Math, Harvard, 1950	MIT	US Army, US Navy, US Air Force
	Sequential decoding of convolutional codes	Wozencraft (1957)	John Wozencraft	EE, MIT, 1957§	*MIT doctoral dissertation*	US Army, US Navy, US Air Force
	Fano algorithm for sequential decoding	Fano (1963)	Robert Fano†	EE, MIT, 1947§	MIT	US Army, US Navy, US Air Force
	Viterbi decoding of convolutional codes	Viterbi (1967)	Andrew Viterbi†	EE, USC, 1962§	UCLA	US Air Force
Coding theory	Forney concatenated codes	Forney (1965)	G. David Forney†	EE, MIT, 1965§	*MIT doctoral dissertation*	US Army, US Navy, US Air Force

† Awarded Claude E. Shannon Award by IEEE Information Theory Society

§Holds an S.M. degree in E.E. from MIT

¶ MIT Lincoln Lab was created and funded in the 1950s by the US Air Force.

Table 2: Major scientific breakthroughs in coding theory from 1948-1967

Approach	**First Use**	**Launch**	**Destination**	**Coding Developed by**	**Outer (Block) Code**	**Inner Code**	**Decoder**	**Increase†**
Uncoded analog	Explorer I	Jan. 1958	Earth orbit	-	-	-	-	-
Uncoded digital	Pioneer V	Mar. 1960	Solar orbit	-				
Convolutional Code	Pioneer 9	Nov. 1968	Solar orbit	Codex, NASA Ames	-	Convolutional R=1/2, K=25	Fano sequential	+6.1 dB
Block code	Mariner 6	Feb. 1969	Mars	JPL	Reed-Muller (32,6)	-	"Green Machine"	+3.2 dB
Convolutional Code	Pioneer 10	Mar. 1972	Jupiter	Notre Dame, NASA Ames	-	Convolutional R=1/2, K=32	Fano sequential	+6.9 dB
Concatenated block & convolutional codes	Mariner 10	Nov. 1973	Venus	JPL	Golay (24,12)	Convolutional R=1/2, K=7	Viterbi maximum likelihood	n.r.
Concatenated block & convolutional codes	Voyager 1,2	Aug. 1977	Jupiter	JPL, Linkabit	Reed-Solomon (255,223)	Convolutional R=1/2, K=7	Viterbi maximum likelihood	+7.1 dB
Concatenated block & convolutional codes	Galileo	Oct. 1989	Jupiter	JPL, Caltech	Reed-Solomon (255,223)	Convolutional R=1/4, K=15	"Big Viterbi Decoder"	+8.7 dB

Source: Probe dates from NASA.gov; coding information from NASA archives and published research
† Effective gain in signal/noise over uncoded transmission, for a bit error rate of 10^{-5}, as reported by McEliece (2005)

Table 3: Evolution of space probe error-correcting codes, 1958-1989

Company	**Codex**	**Linkabit**
Founded	1962	1968
Location	Cambridge, Mass. later Newton, Mass.	Los Angeles, Calif. later San Diego, Calif.
Founders	Jim Cryer Arthur Kohlenberg Joe van Horn	Irwin Jacobs Andrew Viterbi Leonard Kleinrock
Previous employer	Melpar, Inc.	UCSD & UCLA
Space client	NASA Ames	Jet Propulsion Laboratory
Military client	Air Force and Army	Air Force and Army
Coding business	1965-1970	1968-1990s
IPO	1968 IPO raises $2.3 million	n/a
Exit	In 1977, bought by Motorola for $89 million	In 1980, bought by M/A-COM for $40 million
Line of business at time of exit	Telephone modems	Orbital and deep space communications modems

Table 4: Firms selling coding theory in space, 1968-1973

		Openness of Scientific Process		
		Open	**Intermediate**	**Closed**
Locus of Research Activity	**Nonprofit**	1. Traditional public science	3. Licensing of university research	5. Confidential contract research
	For profit	2. Quasi-academic contractors	4. Industrial research labs	6. Traditional private R&D
	Dissemination	Open	Open	Closed
	Appropriability	Tacit knowledge	Patent	Trade secret

Table 5: Dimensions of openness in scientific discovery

End Notes

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[1] JPL (the Jet Propulsion Laboratory) has been NASA's primary research lab for unmanned interplanetary exploration, but is operated by Caltech under contract to NASA.

[2] For example, Hamming's work on coding was mentioned by Shannon in his 1948 paper, but Hamming (1950) was not published until April 1950, three months after AT&T filed for a patent (issued as #2,552,629). Sloane & Wyner (1993: xxxv) report that while at Bell Labs, Shannon co-authored three granted patents (all with AT&T colleagues), of which two led to articles published in the *Proceedings of the Institute of Radio Engineers*. To file for patents, Bell Labs also delayed publication of the Dec. 1947 invention of the transistor.

[3] After that, significant improvements in coding theory came with the creation of two new trajectories: turbo codes introduced in 1993, as well as the low-density parity check codes discovered by Gallager in 1960 but not computationally practical until nearly 40 years later (Costello and Forney, 2007).

[4] Qualcomm later developed an extensive business model based on the licensing of CDMA-related communications patents, which is described by Mock (2005).

[5] I am grateful to an anonymous reviewer for noting the importance of tacit knowledge in this study.

[6] In this case, prior depth of technical understanding is a prerequisite to firm success in a new technological domain. This is a possible alternate explanation for the significant findings of George et al (2008), who attribute such depth as a consequence of repeated invention for a given patent technology class.

[7] Here I use "process model" in the sense of Mohr (1982: 37): one that "is the sort that consists of ingredients plus the receipe that strings them together in such a way as to tell the story of how Y occurs whenever it does occur."

[8] Based on a study of MIT, Agrawal and Henderson (2002) also suggest that patenting plays a relatively unimportant role in commercializing university engineering research.

[9] I am grateful to a second anonymous reviewer for suggesting the use of this two-dimensional categorization.

[10] The existence of closed (such as classified) government research is acknowledged, but analyzing the institutions and incentives of such research is beyond the scope of this paper. See, for example, Weswick (2000).

[11] Forney recalled Codex as being less academic than nearby BBN, but more academic than a typical industrial research department.