How the Internet Became Commercial

Innovation, Privatization, and the Birth of a New Network

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The High Cost of a Cheap Lesson in Wireless Access

[Economic experiments] . . . include experimentation with new forms of economic organization as well as the better-known historical experiments that have been responsible for new products and new manufacturing technologies.

—*Nathan Rosenberg, 1992*[1]

In the late 1990s many industry developers were unsure whether any design for wireless Internet access would ever become embodied in a mass-market product. As it turned out, similar to other developments in the commercial Internet, the crucial decisions behind wireless local area networking—today called Wi-Fi—did not come to fruition by a simple or straightforward path. Its birth arose from a series of experiments, and these experiments involved decisions by several key industry executives, principally Steve Jobs and Michael Dell. Those decisions built upon several other experiments by a committee of engineers, and a set of policy makers at the Federal Communications Commission, which this chapter explains. Although it may not be apparent at first glance, the economic experiments that led to Wi-Fi contained many features found in other experiments that led to the commercial Internet.

The institutional details are generally underappreciated by all but insiders. The committee of engineers was sponsored by the IEEE (Institute of Electrical and Electronics Engineers), which helped form many com-

[1] Rosenberg (1992), 181.

FIGURE 14.1 Michael Marcus and Vic Hayes, helped develop rules and standards for Wi-Fi (Photo by Gail Marcus, 2008)

mittees that endorsed standards for interoperable products, and these designs helped coordinate designs from multiple suppliers. The standard for what later became Wi-Fi came from Subcommittee 802.11, the eleventh subcommittee to explore issues within the domain of Committee 802. Committee 802 was formed in 1980 and explored standards for local area networking, while subcommittee 11 was formed in 1990 and explored standards for wireless data communications. The subcommittee designed a standard for how to send data between both antennae and receivers, and that became crucial for the birth of mass-market wireless Internet access over short distances, such as a hundred feet. The crucial design emerged in 1999, when the committee published Standard 802.11b, which altered some features not found in Standard 802.11a (changing the frequency of electromagnetic spectrum it used, among other things).[2] The draft of 802.11b eventually caught on.[3]

How did Steve Jobs become involved? Jobs had just returned as Apple's CEO in 1997, and he initiated a meeting with executives at Lucent,

[2]The subcommittee first proposed a standard in 1997 that received many beta users, but also failed to resolve many interoperability issues (among many issues). Learning from this experience, and viewing its efforts as racing against those of a private consortium—called HomeRF—the subcommittee rewrote the standard over the next two years. What came to be known as standard 802.11a was ratified in early 2000, just after 802.11b was ratified.

[3]Standard 802.11a was licensed for usage in Europe and Asia as well as North America, while for some time 802.11a was only licensed in North America. Liu (2001), or Kharif (2003).

who had supplied many key engineers to Subcommittee 802.11, including its leader, Vic Hayes. Lucent's wireless LAN management welcomed the phone call and initially viewed it as payback for all of its investment of time and personnel in the subcommittee.

Lucent got more than they bargained for. Lucent's management anticipated bargaining hard to become the dominant equipment supplier of the hardware to make wireless LANs operate within laptop personal computers. Apple was still a fraction of Lucent's size, so Lucent expected a certain amount of deference from Apple, though, that is not how it played out. Cees Links, from Lucent, attended the meeting and in a memoir about the growth of Wi-Fi (written much later), and he describes how it began awkwardly.[4] One side showed up in suits and ties, while the West Coast engineers showed up in more relaxed wear. Jobs did not show up at first, and nobody would start without him. After some awkward small talk, Jobs finally walked in late. From thereon he did the majority of the talking. Links began a planned slide presentation, and described it this way:

> Then Steve asked, "Are there any questions?" I tried to show a few slides: key wins, market positioning, product offering, value creation, etc. Presenting slides with Steve Jobs is actually quite easy: you put up the slide, and he will do the talking, not necessarily related to the slide: then he asks for the next slides.

Links goes on to describe a short dialogue between Jobs and the senior management team from Lucent. This is where the management made their pitch and where they had planned to bargain hard. In response Jobs described what he wanted. Links's description of the end of the meeting is the most revealing:

> Turning the conversation back to wireless LANs, [Jobs declares,] "We need the radio card for $50 and I want to sell at $99." Then Steve apologized; he had to leave. Standing up, he said "Hi!" and went. The room fell silent.

The silence was understandable. Up until that point none of the wireless local area networking producers had ever achieved that price point, or anything near it. This price level was regarded as quite an ambitious

[4]Lemstra, Hayes, and Groenewegen (2010), 129–31.

target by Lucent, or any other equipment supplier.[5] Steve Jobs, on the other hand, acted as if he was delivering the simple hard truths about making mass-market products, and, as he did often with his unique managerial style, expressed impatience with anyone who did not see the vision he regarded as obvious.

Later events favored Jobs's point of view. NCR/Lucent eventually achieved that price point, albeit only after negotiations continued with Apple throughout production, as Apple changed the product requirements.[6]

The Apple Airport—the first mass-market Wi-Fi product—debuted in July 1999 at a MacWorld convention in New York. As far as the insiders in subcommittee 802.11 were concerned, there was nothing technically new about it; it merely embedded the 802.11b design in a functioning product that Apple sold. However, it did something no prior wireless product had done: it was aimed at the mass market. It came in a branded product from Apple, Apple distributed the entire system, and the price and functionality—such as the data throughput speed—were good enough for a typical PC user.

That is not the whole story, and that is where Michael Dell entered the events. Lucent's cards for Apple laptops and the Apple Airport system did not serve those who had PCs from suppliers other than Apple. That still left a large part of the PC industry uncovered. Most PCs used a Windows operating system from Microsoft. As it happened, that market became first addressed at Dell Computer.[7]

Michael Dell, founder and CEO of Dell Computer, by then one of the largest PC providers in the world, heard about the announcement of the Apple Airport and called Lucent. According to the account from Cees Links, Dell was "furious" with them because Dell was not first to experiment with

[5]A $100 retail price would have been anything from one-fifth to one-tenth the price of equipment in the first half of the decade. A cost of $50 would require economies of scale in production and extensive use of standard components, as the production cost of cards was higher than $100 at the time of the meeting between Apple and Lucent. As described in Lemstra, Hayes, and Groenewegen (2010), 131, it required Lucent to put into the initial price some of the learning curve benefits it anticipated, which was a departure from existing practice.

[6]See Lemstra, Hayes, and Groenewegen (2010), 130, which describes changes in product requirements linked to "all-or-nothing type of negotiations."

[7]For an account see Lemstra, Hayes, and Groenewegen (2010), 131–32.

a product release.[8] Lucent executives had to remind Michael Dell that he had an opportunity to be in on discussions as early as 1992. However, Dell had decided in 1993 to stop the discussions because he concluded (incorrectly, as it turned out) that there was no market for the technology.[9]

The two parties subsequently came to a deal. Making a version for Dell became a priority thereafter, and making it compatible with Windows XP was the main challenge for the team at Lucent. Eventually Lucent would succeed at that as well. To do that Lucent and Microsoft cooperated in changing the design of Windows XP, and a new version was released in 2001. It supported 802.11b in all Windows-based systems. Just as with Apple, Lucent made a hardware card for an external slot in a PC.

Those first two projects established the mass market for laptop use, pioneering the technical issues affiliated with the challenges of the Apple and Windows operating systems. Both were investments in product designs embedding 802.11b, aimed at fostering sales as part of either Apple's or Dell's portfolio of products. In both examples, one pioneering firm, Lucent, would gain considerable sales from its position, and (in retrospect) would retain the position as a leading provider of equipment for several years.

The importance of those two experiments for the market's development is more readily apparent in retrospect than it was at the time. After those two projects, the consumer-oriented mass market for wireless Internet access took off, with a large number of other firms also entering into production. Those two projects served as the bridge between years of experimentation with prototype designs and the design and distribution of products for mass markets, showing other equipment firms that real money could be made if oriented toward the demand the pioneering firms perceived.

Looking more deeply behind events, a complete explanation requires understanding both technology and market institutions. This chapter must go inside a committee that few nonengineers ever have heard of, IEEE Committee 802.11. This committee developed a new standard and made the design available without restriction. As this chapter describes, the subcommittee designed a standard around a set of flexible govern-

[8]Lemstra, Hayes, and Groenewegen (2010), 131. Links says Michael Dell "was furious about the fact that he had been beaten by Apple."

[9]Lemstra, Hayes, and Groenewegen (2010), 131.

ment rules for the electromagnetic spectrum, the electromagnetic wavelengths invisible to the eye. Those rules were themselves an experiment. Such flexible rules had never been deployed by any government, or by the Federal Communications Commission, and this chapter must explain the sense in which the rules were novel. The key insight seems too simple to be so profound: flexible rules would enable commercial firms to put many options in front of users, and users would choose which applications gave them the most value. User choice in this market determined something unprecedented: few of the original use cases for the spectrum remained popular. Instead, the vast majority of use migrated to an application they liked more—namely, wireless Internet access.

That last observation takes steps toward the deeper economic lesson of this episode. Flexible rules allowed spectrum to move from low-value to higher-value activities. That sentence may seem obtuse at this point in the chapter, but it represents a profound shift in government policy for the spectrum. Policy makers did not intend to foster innovation from the edges, at least not explicitly, but that is what they ended up doing nonetheless.

Adopting Rules for the Spectrum

The story of Wi-Fi begins in the early 1980s in the Federal Communications Commission, which is based in Washington, DC. As is typically the case in Washington, DC, a simple proposal does not get far until sensible voices of all ideological stripes see the wisdom in it, albeit each may see something different in it.

Like every other government, until the 1990s the United States government had a very restrictive system for allocating the spectrum. Governed by the 1934 Communication Act, the law gave the Federal Communications Commission (FCC) authority to license or bar companies from using the spectrum. Known as allocation through "command-and-control," the FCC allocated each unique wavelength to a particular firm for a specific purpose, such as radio, television, and mobile telephony. This system was first adopted in order to minimize one user interfering with another. At one time it was thought that interference was a primary concern in all uses of spectrum. Hence, a central government administration could allocate rights to use spectrum, as well as determine other technical details, such as power over frequencies, which prevented one user's activity from stepping on top of another.

To put it in very human terms, until the 1990s the owner and the purpose for the spectrum were determined far in advance by expert committees comprised of engineers, whose deliberations were approved of by the FCC. Spectrum was given to specific firms and for very specific purposes. These choices had the force of statute behind them and could not be undone except by the FCC. The choices committees made were rarely reversed, and only in exceptional circumstances.[10]

Circumscribing use eliminated many economic experiments before any ever got started. Why bother with an experiment if it would require moving spectrum from one use to another that command-and-control would not approve? For many years that begged a question: If market participants had had the ability to decide how to employ the spectrum for a range of economic experiments, would they come to a different conclusion about how to deploy it? If it were possible, would spectrum move from a use with low value to one with high value?

Once again, it is possible to put a very human face on that question. In the early 1980s, one employee at the FCC, Michael Marcus, asked this question about the spectrum for short-range uses.[11] The question was rather pointed in the context of short-range uses, because one short-range application was less likely to interfere with another. Distance (or low power) prevented equipment in one location from interfering with another only a few dozen feet away. Moreover, in some of the primary short-range applications—for example, garage door openers, baby monitors, and wireless handsets—households used the spectrum infrequently, perhaps only a few times a day. Why would the FCC have to worry about interference if a user could transmit a signal no more than one hundred feet? Perhaps neighbors could work out the issues themselves, or perhaps simple technical solutions could be found (such as automated selection among multiple channels). The FCC could just leave market participants to find those solutions. Why would the FCC have to designate the licensee,

[10] Perhaps the best-known reversal occurred during the design of the broadcasting standard for color television. The Korean War delayed the deployment of the first approved design, and the after the war it was reconsidered, leading to deployment of a technically superior design from another designer.

[11] Marcus (2009).

an owner and designer, when plenty of firms could supply such equipment? More to the point, why would the FCC want the administrative burden of licensing hundreds of firms who made use of the spectrum in thousands of places?

Initially Marcus received a warm reception from those who had sympathy for free-market ideology. They saw an opportunity to make use of markets. The recent election of the Reagan administration had installed many commissioners with such sympathies. A task force was appointed and began to consider how such a system would work.

The initiative made it from blackboard to implementation in May 1985. FCC chairman Mark Fowler managed to pass the first civil use of unlicensed spectrum. Wireless telephone handsets were the first uses.[12] After that initial success, adherents to the established system raised many questions, momentum stalled, and only minor changes were made for many years. After many years another set of commissioners determined the priorities in the agency. Eventually backlash inside the FCC bureaucracy became powerful again, especially among those who did not see any merit to departing from command-and-control mechanisms. Marcus then became a target of deliberate efforts aimed to make him leave the FCC; he received terrible employee reviews and was hounded out of his job.[13]

After the 1992 election the Clinton administration installed commissioners who had a taste for reform. Giving the spectrum to users appealed to those who wanted to experiment with new forms of government, such as diffusing discretion to users and small manufacturers. Reed Hundt, the new chair of the FCC, felt he had a mandate for action, and he took it in many different areas, including spectrum policy. He foresaw information and communication technologies as a bridge toward a revolution in new services and productivity growth.[14]

The FCC took up Marcus's proposal again, and this time pushed through changes to enable new applications. By late April 1996 the FCC took the legal step to allow the change. The FCC initiated a "Notice for Proposed Rule Making" to make available a small amount of unlicensed spectrum for what became known as Unlicensed National Information Infrastructure (U-NII) devices. It was understood from the FCC's order that

[12] Marcus (2009).
[13] Marcus (2009).
[14] Hundt (2000).

the commission anticipated "short range, high-speed wireless digital communications" and devices that supported "the creation of new wireless local area networks ('LANs') and . . . facilitate wireless access to the National Information Infrastructure ('NII')."[15] Beyond that, however, little else was specified about the design or application of the spectrum. After deliberating over that summer, the commission made the spectrum available. The order that emerged on January 9, 1997, stated, "we are adopting the minimum technical rules necessary to prevent interference to other services and to ensure that the spectrum is used efficiently."[16]

Taking a minimal approach was, in fact, the key administrative innovation, though that was not apparent to all observers at the time. Traditional defenders of command-and-control regarded the allocation, known as the Part 15 rules, as "garbage spectrum," a throwaway to uses with low value, and a symbolic salvo in an ideological battle. The standard use cases used for reference—as mentioned, garage door openers, wireless handsets, and baby monitors—were also thought to be low value in comparison to radio, television, and mobile telephony. Perhaps a business case could be made for use in a warehouse, but this was not regarded as particularly valuable.[17] More to the point, forecasts about mass market wireless access to Internet data services did not play a central role in the design of these rules, or tip sides in the ideological fights in favor or against aspects of these rules. These rules issued as the commercial Internet began, and connection between these commercial events was distant. Use of euphemisms like the "National Information Infrastructure," as quoted above, was symptomatic of that distance.

Something crucial was embedded in the Part 15 rules, however. Consistent with Mike Marcus's original proposals, the spectrum did not have tight restrictions on its purpose—that is, the FCC did not control how the spectrum was used, or the purpose to which it was put. Any application was acceptable as long as it did not interfere with other activities outside the band. Even different applications could use the same spectrum.

[15]See the review of FCC policies found on http://www.cybertelecom.org/broadband/wifi.htm, accessed May 2007. Subsequent clarifications and rules aligned the spectrum in the United States with similar policies elsewhere.

[16]See the review found on http://www.cybertelecom.org/broadband/wifi.htm, accessed May 2007.

[17]See the discussion in Marcus (2009).

Related, the spectrum did not get designated to a single owner, and the FCC did not choose the equipment makers. Equipment makers were free to design their products in response to what they learned about its value from experimenting with its use. The spectrum was released with a few minor usage cases in mind, but the rules were made flexible enough to accommodate additional invention of new uses.

Standard Committees and Their Designs

The FCC has the force of law behind its actions. In contrast, any standard emerging from discussions at an IEEE committee was not legally binding on industry participants, and, accordingly, it was called a "voluntary standard." The committees did their work in the hope that such a design could act as a focal point for an interoperable design. In the best case, firms would embed the design in their products, such as wireless routers and receivers, and these would become interoperable as result. Firms could differentiate along other dimensions, such as other aspects of product design, brand, or distribution.

Committee 802 was formed in the early 1980s, before the privatization of the Internet was ever proposed. By the late 1980s the committee was well known among computing and electronics engineers because it had helped design and diffuse the Ethernet standard for local area networks.[18] By the late 1980s the 802 committee had become a victim of its success, and it had grown larger, establishing subcommittees for many areas, ostensibly to extend the range of uses for Ethernet.

Subcommittee 802.11 was established in 1990. Like all subcommittees of this broad family of committees, it concerned itself with a specific topic, in this case, designs for interoperability standards to enable wireless data traffic over short ranges—ostensibly doing with wireless technology what a local area network did with wires. A close look at the engineering suggests, however, that this label was mere window dressing for otherwise complex deliberations. For example, while "wireless local area networking" accurately described the aspirations for users, for suppliers the technical issues in this area hardly had any connection to the technical issues in

[18] See Burg (2001) for analysis of the growth of a local area network market and activities in Committee 802.

existing local area networking. As it would turn out, due to the very different error-correction issues, the software for a wireless local area network would end up bearing only a slight resemblance to that for a wired local area network, and contained many important technical differences.[19]

At first the committee did not get very far, lacking any clear direction. But then a new chair was appointed, Vic Hayes. Hayes was a technologist with a visionary outlook, a cheerful demeanor, and, more importantly, the patience to see his vision to realization. Hayes first developed prototypes of wireless technologies for National Cash Register, or NCR. At the time it was a subdivision of AT&T, which would later become Lucent (and later it was a division of Agere Systems). In that capacity Hayes first developed prototypes for wireless terminals for stockbrokers. Other applications for the technology were forecast, such as easy rearrangement of retail space.[20] From this experience he had a steady and flexible vision of the value of a standard that many component vendors could use to make interoperable equipment.

Other potential applications for this standard came up in the earliest meetings. One of the earliest prototypes had been a wireless local area network for a university campus.[21] Another was short-range wireless Ethernet in warehouses with complex logistical operations. Several firms had built expensive prototypes of these devices but had not found many buyers, or otherwise experienced very limited commercial response. Indeed, throughout the first half of the 1990s, as the 802.11 committee met and continued to do its work, pioneering firms continued their experiments with different uses and generated little interest among potential buyers, who regarded these prototypes as expensive in comparison to their usefulness.[22]

As with most such committees, Hayes tried to involve members who brought appropriate technical expertise and who represented the views of most of the major suppliers of equipment in which this standard would be embedded. At first, therefore, the group was comprised of enthusiastic designers focused on the needs of big users with potential warehousing applications (for example, FedEx, United Parcel Service, Wal-Mart, Sears, and Boeing), where the application's value did not seem specious. Al-

[19]See chapters 2, 3, and 4 of Lemstra, Hayes, and Groenewegen (2010).
[20]See Kharif (2003).
[21]See the description of Hills (2005), who began developing the equivalent of a Wi-Fi network for the Carnegie Mellon campus in Pittsburgh, starting in 1993.
[22]Also see chapters 2, 3, and 4 of Lemstra, Hayes, and Groenewegen (2010).

though it is obvious in retrospect, notably absent from the earliest meetings were representatives of many of the suppliers of valuable equipment a decade later, such as firms from electronics and computing.

Those firms would not be absent for too long. Several related efforts, such as HomeRF and Bluetooth, were founded in 1998. The former was organized by firms such as Motorola and Siemens, and at its peak involved over a hundred companies before it disbanded.[23] The latter was established by Ericsson, Sony-Ericsson, IBM, Intel, Toshiba, and Nokia, and currently still exists; today it involves thousands of firms. It focused on very short-range uses—under a few feet, and, as such, tended to have a set of applications distinct from Wi-Fi. Subsequent events would change the predominant use case, as economic experiments showed participants that high market value lay in a different configuration of technology, operations, and pricing than had originally been envisioned.[24]

Embedding the Design in Products

Wi-Fi did not emerge from a set of prespecified designs and classified stages. Economic experiments played a role in shaping that path, as pioneering firms took actions in response to the actions of the standard committee. As defined at the start of the chapter, economic experiments involved more than just new designs. They also involved new forms of economic organization and new products and new manufacturing technologies.

As it turned out, these experiments with Wi-Fi by Apple and Dell, described in the introduction, generated a response from many buyers, who also began to experiment. Users began deploying this equipment in a variety of settings, campuses, buildings, public parks, and coffee shops. Unsurprisingly, other vendors tried to meet this demand as well. Around the same time as the publication of 802.11b, firms that had helped pioneer the standard—including 3Com, Aironet (now a division of Cisco), Harris Semiconductor (now Intersil), Lucent (now Agere), Nokia, and Symbol Technologies—formed the Wireless Ethernet Compatibility Alliance (WECA). WECA

[23] HomeRF did not generate the enthusiastic sales that those who designed it predicted—even though the designers considered it technically superior to the alternatives. For speculation about why HomeRF failed, see, e.g., http://www.cazitech.com/HomeRF_Archives.htm, accessed in November 2010.

[24] See Rosenberg (1996).

branded the new technology "Wi-Fi," which was a marketing ploy for the mass market, since WECA's members believed that "802.11b" was a much less appealing label.[25] They aimed to nurture what enthusiasts were doing and broaden it into sales to a broader base of users.

WECA also arranged to perform testing for conformance to the standard, such as certifying interoperability of antennae and receivers made by different firms. This is valuable when the set of vendors becomes large and heterogeneous, as it helps maintain maximum service for users with little effort on their part. In brief, while the IEEE committee designed the standard, a different body (of similar firms) performed conformance testing.

Events then took on a momentum of their own. Technical successes became widely publicized. Numerous businesses became users of Wi-Fi and began directed experiments supporting what became known as *hot spots*, which was an innovative business idea. A hot spot is a data transmission mediated by a third party for local use in a public space or on a retail premise. A hot spot in a public space could be free, it could be installed by a homeowner, or it could be maintained by a building association for all building residences. It could be supported by the café or by a restaurant or by a library trying to serve its local user base. Or, it could be subscription based, with short-term or long-term contracts between users and providers. The latter became common at Starbucks, for example, which subcontracted with T-Mobile to provide the service throughout its cafés.

Hot spots were similar to, but outside of, the original set of use-cases for the standard. Since nothing precluded this unanticipated use from growing, grow it did. It grew in business buildings, in homes, in public parks, and in a wide variety of settings, eventually causing the firms behind HomeRF to give up. The growing use of Wi-Fi raised numerous unexpected issues about interference, privacy, and appropriation of the signals of neighbors. Nevertheless, these issues did not slow Wi-Fi's growing popularity.[26] Websites sprouted up to give users, especially travelers,

[25]The choice of the label "Wi-Fi" resembled "Hi-Fi" or high fidelity, a term commonly used to describe high quality and expensive musical components. The label was meant to signal high quality transmission. Yet 802.11b actually has little to do with music or fidelity, and "Wi-Fi" is a made-up phrase.

[26]In high-density settings it was possible for there to be interference among the channels, or interference with other users of the unlicensed spectrum reserved by the FCC, such as cordless telephones. The diffusion of so many devices also raised questions about norms for paying for access in apartment buildings, from neighbors, and others. See Sandvig (2004).

directions to the nearest hot spot. As demand grew, suppliers gladly met it. As in a classic network bandwagon, the growing number of users attracted more suppliers and vice versa.

Collective invention played its familiar role. Economic experiments among a community of participants led to many new insights that accumulated over time. While several pioneering firms took important steps in initiating market development, no single firm was responsible for all the economic experiments that eventually altered the state of knowledge about how to best operate equipment using IEEE Standard 802.11b. Rather, many firms responded to user demand, demonstrations of new applications with tangible market experience, and the lessons accumulated.

In this way, Wi-Fi became an industry-wide platform. All participants took actions using standards that invited activity from complementary component providers. In this instance of Wi-Fi equipment, the presence of a standard, related institutions for conformance, and the universal participation of virtually all the industry, encouraged experiments in antennae and receiver design, as well as in deployment of final equipment in new operational modes (such as a hot spot). Because Wi-Fi deployed at an industry-wide level, experimenters could presume (safely) that other complements would make use of the same design, which led each experiment to specialize on narrow issues and specific issues of interest to the experimenter.

Interplay

Later events in the development of Wi-Fi illustrate how a firm can invest in building on an economic experiment. Reacting to the experiment that generated Wi-Fi, Intel created Centrino, a large program that would install wireless capability in its notebook computers. It was officially launched in March 2003.

As with many aspects of growth in wireless access, the Centrino program is easy to misunderstand. Centrino was much less obvious to Intel in advance than it was in retrospect. It too was an experiment, just on a very large scale.

At the turn of the millennium Intel's strategic plans were responding to multiple market forces. While demand for desktop and notebook computers had grown along with the Internet in the 1990s, Intel's marketing department forecast an imminent slowdown in the share of desktop sales, as well as increasing engineering challenges supplying faster chips. More worrisome, Intel had branded itself as a firm that always marketed better and faster microchips, while it was no longer clear that demand for bigger and faster would arise across all segments of computing. Notebook users valued mobility, for example, and that placed value on distinct attributes, such as longer battery life, less energy-intensive chips, physically smaller storage, more compact designs, less weight, and less heat. Even by the late 1990s many mobile users had shown a willingness to give up improvements in bigger and faster microprocessors in order to get improvements on these other attributes.

In 2001, in response to a number of initiatives and studies, Intel's management decided it was time to change priorities. Labeling this a "left turn," the company chose to embed a Wi-Fi connection in all notebooks that used Intel microprocessors.[27] This was easier said than done. The choice *not only* involved redesigning the Intel microprocessor, Intel's core product, stressing lower power and lower processing speeds, but it also involved redesigning the motherboard for desktop PCs and notebooks, adding antennae and supporting chips. Intel made a number of reference designs and made them widely available at low cost.

Intel's management hoped that its endorsement would increase demand for wireless capabilities within notebooks by, among other things, reducing weight and size while offering users simplicity and technical assurances in a standardized function. The firm also anticipated that its branding would help sell notebooks using Intel chips and motherboard designs instead of using microchips from Advanced Micro Devices (AMD). Furthermore, antenna and router equipment makers anticipated that a standardized format for wireless notebooks might help raise demand for their goods.

The redesign brought one concrete benefit to users—namely, it eliminated the need for an external card for the notebook, which was usually supplied by a firm other than Intel and installed by users or original equipment manufacturers (OEMs) in an expansion slot. Intel hoped for additional benefits for users, such as more reliability in wireless functionality, fewer set-up difficulties, longer-lived batteries due to less need for heat reduction, and thinner notebook designs due to smaller cooling units.

[27] For a full account see Burgelman (2007).

Seeking to inform users about all those changes, Intel adopted "Centrino" as a label, and it initiated a program to certify compliance.

Intel's management further worried that wireless notebooks would not be used widely enough to merit their investment in Centrino, so Intel's management considered exploring activities far outside of its core product, microprocessors. These exploratory actions were not far outside its philosophical approach to managing the demand for microprocessors. Intel long ago made a distinction between managing its first job, making microprocessors, and managing anything that helped it sell more microprocessors, which was often given the label "Job 2."[28] For example, the company launched a program to change the demand for the wireless feature of notebooks. As part of Job 2, Intel eventually certified fifteen thousand additional hot spots in hotels, airports, and other public places by the time Centrino launched.[29]

As another example of Job 2, Intel made motherboard designs available to others. The firm had crept into the motherboard business slowly over the prior decade as it initiated a variety of improvements to the designs of computers using its microprocessors. Years earlier, the firm had designed prototypes of these motherboards and by the time it announced the Centrino program, it was making some motherboards, branding them, and encouraging many of its business partners to make similar designs. The wireless capabilities of a notebook had not been the focus on these earlier programs, so the announcement of the Centrino program represented a shift in strategic aims and direction for the Intel programs affiliated with motherboards.[30]

This latter program illustrates one of the interesting conflicts that emerged in Wi-Fi's development. Intel's motherboard designs could increase the efficiencies of computers, but that benefit was not welcomed by every OEM that assembled PCs or other industry players. Firms such as Texas Instruments and Intersil had lobbied earlier for different designs for the 802.11g upgrade, investing heavily in the efforts at Committee 802.11. Neither of them had intended to help Intel's business, and neither of them

[28] Gawer and Cusumano (2002).

[29] Burgelman (2007).

[30] For history and analysis of why management chose to invest heavily in some complementary technologies and not others, see, e.g., Gawer and Cusumano (2002), and Gawer and Henderson (2007).

wanted to see Intel increase its influence over the designs that were deployed to most users.

Moreover, Intel's designs eliminated some differences between OEMs and other component providers. Many of these firms resented both losing control over their designs and losing the ability to strategically differentiate their own designs. At the same time, other OEMs liked the Intel design, since it allowed the firms to concentrate on other facets of their business. That competitive rivalry eventually generated cooperation from every small OEM, especially after Intel initiated marketing programs for Centrino. These programs were especially necessary to induce cooperation from many big OEMs.

Intel ran into several unanticipated crises, such as insufficient parts for the preferred design and a trademark dispute over the use of its preferred symbol for the program. However, the biggest and most important resistance came from the largest distributor of PCs, Dell Computer, one of the earliest firms to get the market started. Dell insisted on selling its own branded Wi-Fi products, buying internal cards from others that handled Wi-Fi, bypassing Intel altogether. Dell branded its solution and had grown a good side business from its pioneering efforts. It did not want to give that away to Intel.

Despite Dell's resistance, the cooperation from antenna makers and (importantly) users helped Intel reach its goals. By embedding the standards in its products, Intel made Wi-Fi, or rather Centrino, easy to use, which proved popular with many users. (Indeed, eventually this success would induce reluctant cooperation from Dell.)

The Centrino example illustrates the array of deliberate firm activities taken during a short period that built on top of learning from an earlier undirected economic experiment. The activities in IEEE Committee 802.11 ended up affecting the activities of many other firms, such as equipment manufacturers, laptop makers, chip makers, and coffee shops, which then shaped new activities in Committee 802.11 as well.

This example also illustrates that economic experiments can—and do—happen in spite of overt conflict between firms. Those firms may be either direct competitors or participants in a value chain with diverging interests. Conflict arises, as it did here, when all can forecast that the success of one firm's experiment adversely affects the business fortunes of another.

Experiments and Creating Value

What do we learn from the evolution of Wi-Fi? The growth of wireless access illustrates many of the elements underlying economic experiments, and, interestingly, these elements were present with the experiments that took place in dial-up access. It also illustrates the errors of many economic myths, and we start with those.

First consider the myth that new market opportunities evolved organically, independently generated by market incentives. Market incentives eventually played a role, but the historical facts suggest a nuanced reading of their role. In this instance a committee of engineers, many employed at industry suppliers, and not all of them participating with the same motive, met for years and designed a standard for a market in which products designed around proprietary standards had not appealed to many users. That involved collaborative ideation and iteration. Only after the emergence of a standard did recognizable profit-making activity emerge. Incentives worked indirectly, creating the shadow of future market events on collective action.

Second, incentives also did shape market actions, but not all innovative outcomes. There was a potential disconnect between those who incurred the costs of experimentation and those who learned from it. The disconnection occurred as an unintended by-product of deliberate experiments.

Where did incentives matter directly? By helping market participants learn about the nature of demand in quickly evolving environments, companies tried to position their offerings and pricing structures. Such lessons increased value for the experimenter by generating more revenue through improvement of an existing service, enhancing profits from lowering operation costs or avoiding higher investment expenses, or enhancing pricing power through targeting services to customers better than rivals. In general, many of these benefits could not be measured. If they could be measured—even partially—the private value could be measured in terms of the additional revenue contributed to a firm's business and/or the additional cost savings it generated.[31]

[31] Filtering between noise and cause is a key challenge in such experiments. See Thomke (2003a) for approaches for designing experiments so they can be measured in settings where firms control many of the key aspects of the experiment.

Revenue might have increased through altering pricing practices. For example, the acceptable pricing norm for hourly caps changed over time, as ISPs learned about the reaction of different customer segments to distinct menus of choices. Similarly, Wi-Fi prices in many hot spots reflected carrier perception about what the market demand could support.

Pricing experiments often coincided with experiments regarding the range of services offered. During the mid- to late 1990s, for example, virtually all ISPs experimented with changes to the standard bundle offered, such as default e-mail memory, instant messaging support, and hosting services in which the ISP maintained web pages for clients. Most Wi-Fi hot spots, in contrast, did not alter the standard bundle much, restricting access to one simple function. While ISPs experimented with performing services complementary to access, such as hosting services, networking services, and web design consultations, most Wi-Fi hot spots retained their status as stand-alone services.

Learning oriented toward cost reduction resembled learning oriented toward enhanced revenue. For instance, as dial-up ISPs learned from one another about the efficient deployment of 56K modems, those who deployed it found they could charge a modest price premium for faster service (approximately five dollars), but that that premium disappeared in less than a year, after the modems became more common.[32] Similarly, many Wi-Fi hot-spot providers initially charged for access but later found competition reducing their ability to price the service. Instead, Wi-Fi merely became an element of service for a location, often at no charge at all. While that might have led to better customer retention for a café, and eventually manifest as greater sales or higher firm prices, it would have been difficult to attribute a specific change in price or volume to only that investment in Wi-Fi.

More broadly, events in wireless access illustrate that incentives generate action, but others benefit. Pioneers reacted to incentives and expended costly resources on economic experiments. Those costs involved personnel taking time and effort. They also could involve real resources to build prototypes. In some circumstances, however, learning was cheap to an entrepreneur when others took pioneering action. In most circumstances

[32]See Stranger and Greenstein (2007).

an inexpensive lesson to a later beneficiary came at a high expense to a pioneer, such as a failed business. Succinctly, accounting for industry-wide costs, cheap lessons came at a high cost.

Industry-Wide Benefits

Events in Wi-Fi can be understood with reference to a traditional economic concept called a "learning externality." A learning externality arises when one party learns from the experiment of another but does not take part in the experiment and does not compensate those who incurred the costs from the experiment. Learning externalities were pervasive during the growth of the commercial Internet, and this example illustrates a widely pervasive phenomenon.

Looking back on the experiment in Wi-Fi and other access markets, at least two externalities shaped the experience with learning. There was an information externality *between* firms, as when one firm's directed experiment taught another firm a lesson, or a set of actions interacted in an experiment and taught every industry participant a lesson. There were also information externalities *over time*, as when the lessons of prior experiments generated lessons on which further experiments were built. The example of Wi-Fi shows that these two externalities were pervasive, as well as difficult to distinguish from one another.

Many of these learning externalities were *positive*, that is, one market participant benefited from the actions of another.[33] These positive externalities took one of two forms. In one case, what worked for one firm became known and imitated by others. For example, success from an experiment at one hot spot in one location in 2001 implied it might be profitable in another location with similar features. Alternatively, what did not work for one firm becomes known and, therefore, avoided. For example, the difficulties with the first design for 802.11 become known from experiences in 1997, leading equipment firms to save money by delaying building plans until a more suitable design emerged.

[33]In standard economic parlance, if it were possible to anticipate the benefit and to write a contract over its measured levels, the beneficiary would have *paid* for the benefit.

Intertemporal externalities also were common. For example, lessons about how to avoid commercial failure could be as valuable to observers as those who employed them. These valuable lessons often emerged this way, and it is easy to see why. The firm whose failure illustrated the lesson for others rarely, if ever, did so for the purpose of teaching others, and almost never under contract with the others who (later) gained the benefit of the lessons learned from the failure. For example, AOL learned from the experiments of many prior ISPs who altered their pricing or product lines, but did not arrange the rest of their product offerings in an appealing fashion. Similarly, many hot-spot developers of Wi-Fi learned from the pricing experience of others who did not get their pricing right.

Which externalities operated quickly and which operated slowly? The answer emerges by distinguishing among four distinct types of lessons that led to positive externalities. The first were *market lessons.* These pertained to norms and patterns of market-based actions, such as how to write a contract that users found acceptable, and how to price services, and so on. Second, *technical lessons* pertained to the design of a piece of equipment—for example, knowing how to configure Wi-Fi so that it worked in the type of space/location at all times that fit the supplier's needs. Third, *heuristic lessons* combined technical knowledge with either market or operational knowledge about how employees behaved in firms and how customers reacted to firm behavior. For example, knowing how to deploy Wi-Fi for a maximal set of users was such a heuristic lesson. Fourth, *complex lessons* were marketing and operational lessons that involved many functions inside an organization—for example, knowing how to integrate the use of Wi-Fi into a wide variety of other offerings. These four types of lessons spread at different rates.

Consider market and technical lessons. In 1999 the market and technical lessons about Wi-Fi were often rather trivial for an ISP to learn. Generally, these technical skills were common among those who operated bulletin boards, computers, ISPs, or related equipment. Most local and national ISPs already had procedures in place to, for example, implement billing, publicize their services to local users, or address user service calls. Doing so for Wi-Fi in a coffee shop or restaurant was easy. Although the market actions changed, these were relatively easy to execute within existing organizational procedures, and the contracts were easy to draw up.

Technical and market lessons tended to spread easily for another reason: they tended to become codified quickly.[34] For example, most equipment suppliers in competitive markets would not consider selling equipment if information about it were not codified because most buyers demanded it in contracts as a condition of purchase. Related, vendors of equipment also would have developed a set of marketing parameters for their buyers, which guided them toward best-practice deployment.

Others lessons pertained to heuristic knowledge about how to operate that equipment efficiently, and these too spread comparatively quickly. For example, lessons about how to manage a Wi-Fi router at peak usage levels was not known initially after a new piece of equipment became available for use, but such lessons would be learned through trial and error. As it turned out, those lessons spread to different coffee shops through a variety of mechanisms—administrators in key locations coordinated it (for example, at Starbucks), franchises communicated with one another (for example, at McDonalds), bulletin boards emerged to support different types of user groups, and the Wi-Fi association invested in support activities as well.

Several factors affected the speed at which heuristic lessons spread, and, as a result, these could spread quickly or slowly. On the one hand, some heuristic lessons spread slowly because, as sources of potential competitive advantage, the firms that first discovered them guarded them. For example, firms guarded their strategies for how to deploy equipment efficiently, and they may also have guarded information that indicated details about their future designs. On the other hand, some firms, such as equipment providers, had strong incentives to spread lessons, since their spread contributed to further sales. Such tension was inherent in the diffusion of Wi-Fi, for example. Intel's program to further fund development of certification of hot spots is another illustration.

The similarity between vendor organizations also shaped spreading of lessons. Most dial-up ISPs used similar software tools for monitoring users, particularly after these showed up in the discussion boards at an

[34]In this context, "codified" refers to an idea put in a structured format that another technically trained individual can understand without having the author present—e.g., words, mathematical formulas, plans, pictures, or professional drawings. See, e.g., the discussion in Nelson (2007).

open source project, such as Apache, the most popular web server. The community effectively coordinated many innovative efforts for dial-up ISPs in the mid- to late 1990s, by sharing multiple upgrades and fixes to the source code among ISPs. By supporting similar technology, operations, and heuristics, the designs embedded in standards in many organizations also contributed to sharing of lessons. For instance, organizations, such as the Internet Engineering Task Force (IETF) and the World Wide Web Consortium (W3C) facilitated the movement of lessons. Seen from this perspective, the 802.11 committee for Wi-Fi and WECA helped the lessons spread quickly.

The other side of the same coin is variance in idiosyncratic factors, which could slow the codification of such heuristic lessons. One community of users may differ from another. For example, though peak ISP usage occurs around the same time of day in different locations, surfing behavior varied according to gender, family status, age, education, and income of the members of the household. The sum of these varied across cities, and even from one vendor to another within the same city. Such variety interfered with finding commonalities in, for example, marketing strategies for a new feature across locations or vendors.

Complex lessons spread slowly. In part this was due to the lengthy investigations by firms seeking to lower cost or generate extra revenue. They often were interdependent, where one operational goal reinforced the other, or associated with unique firm features, such as scale. Almost by definition, these lessons resisted immediate codification and moved slowly from firm to firm. For example, management at one hotel chain would not lightly discuss with other hotel chains which type of customer showed a willingness to pay for Wi-Fi. This is not surprising, since firms often hesitated to share information about what sort of costly activities built customer retention most effectively—for example, did users have greater willingness to pay incrementally for access or as a standard part of their contract?

That does not means complex business lessons never spread. Rather, they spread with more effort and at greater cost. In general, they spread more slowly. Even while technical information and market lessons moved quickly between locations and firms, the ability of a firm to prevent direct rivals from imitating its business actions immediately slowed others. Some complex lessons also did not tend to spread to others, at least for a short time.

Economic Experiments in a Complex World

Stepping back from events, it is possible to see that policy makers did not foresee—indeed, could not have foreseen—the consequences of their flexible spectrum policies. Flexibility unleashed two complementary economic processes: movement of value and learning from experimentation.

The spectrum moved from low-value to higher-value activities as it became embedded in different products. Users bought Wi-Fi products instead of garage door openers and baby monitors. In comparison with the old command-and-control rules for allocating spectrum, which often fixed the application, the movement between uses occurred quickly. Users made their choices, and suppliers followed demand. More to the point, it occurred much more quickly than it would have occurred if government managers had retained the right to approve of a change in application.

Flexibility also enabled the firms to learn from experimentation. There were few restrictions on how accumulated lessons got used and by whom. Technical, operational, and heuristic lessons spread quickly, while some complex lessons did not spread at all. That allowed the spectrum to move between different users for Wi-Fi, such as between users who deployed Wi-Fi in business spaces and homes and those who deployed it in public spaces, such as café's and airports. Suppliers learned from one another's experiments, and moved to supply Wi-Fi wherever they could capture some of the created value. In comparison with the old command-and-control rules for allocating spectrum, which often fixed the identity of the seller who embedded the spectrum in products, this movement between uses occurred quickly.

Said simply, the flexible rules allowed lessons from experience in the market to spread quickly and widely. Accumulated lessons were built on the experience of other mistakes and triumphs. Almost by definition, the knowledge pool contained more lessons than any single firm could have learned on its own.

Accumulated knowledge also exhibited a mismatch between cost and benefit. Those who paid for lessons were not necessarily those who used them most profitably. As it typically turned out, many firms taught others lessons, and that had little to do with the original motives. Pioneers conducted the earliest experiments, and the timing of investment was determined by concerns that later participants did not—indeed, could not—influence. Only later, the most important lessons for value became known, creating the potential for regret over an earlier experiment that could have benefited others.

That last observation raises another question: What motivated a manager to pay for an experiment in the first place? Surely nobody was trying to do a favor for an unknown later participant in the market, so why conduct a lesson at all? While some lessons were conducted for the gains they generated for a firm, sometimes it seemed as if economic incentives did not drive a trial. Other inducements mattered just as much—the itch of curiosity, or the sporting thrill from doing something before others. Similarly, why did anyone let a lesson spread? Sometimes competitive pressures induced firms to learn from one another. Yet it also seemed as if lessons spread for reasons far less weighty than the market consequences, as when a manager boasted to a friend about inventing a clever enhancement, or about earning customer kudos for solving a common problem in a novel way.

Regardless of the reasons, the experience in wireless spectrum illustrates the benefits to enabling experiments by market participants. Expensive lessons appeared cheap to later borrowers, although no accountant would (or could) have recorded their value in a ledger, and both users and suppliers benefited.