The Slow Pace of Rapid Technological Change: Gradualism and Punctuation in Technological Change

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Discussions of technological change have offered sharply contrasting perspectives of technological change as gradual or incremental and the image of technological change as being rapid, even discontinuous. These alternative perspectives are bridged using the punctuated equilibrium framework of evolutionary biology. Using this framework, it is argued that the critical event is not a transformation of the technology, but speciation—the application of existing technology to a new domain of application. As a result of the distinct selection criteria and the degree of resource abundance in the new domain, a new technological form may emerge. The new technological form may be able to penetrate other niches and, in particular, may precipitate a process of 'creative destruction' and out-compete prior technologies. This framework is applied to an historical study of wireless communication from the early experimental efforts of Hertz to the modern development of wireless telephony.

1. *Introduction*

Discussions of technological change have offered sharply contrasting perspectives. On the one hand, we have arguments regarding the gradual, incremental nature of technological change (Dosi, 1983; Rosenbloom and Cusumano, 1987; Basalla, 1988). In contrast, others have offered the image of technological change as being rapid, even discontinuous (Tushman and Anderson, 1986; D'Aveni, 1994). Indeed, the *locus classicus* of evolutionary perspectives of technological change (Schumpeter, 1934) offers the dramatic imagery of 'waves of creative destruction'.

How might these alternative perspectives be reconciled? As suggested by Tushman and Romanelli (1985), the punctuated equilibrium framework of

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evolutionary biology (Gould and Eldridge, 1977) offers a powerful lens with which to view processes of both gradualism and discontinuous change. Management theorists, however, have tended to apply the punctuated equilibrium framework to a given level of analysis, whether it be a management team (Gersick, 1991), organization (Tushman and Romanelli, 1985) or technology (Tushman and Anderson, 1986). These arguments correspond to an early view within the biological literature of what Simpson (1949) termed quantum evolution. The most prominent proponent of this perspective was Goldschmidt (1940), who argued for the importance of occasional mutation events with substantial developmental effects. Within evolutionary biology, this quantum view of change has been generally abandoned (Strickberger, 1996).

The modern perspective, introduced by Gould and Eldridge (1977), hinges not on a single mutational event but on speciation—the separation of reproductive activity. The initial speciation event is minor in the sense that the form does not differ substantially from its predecessor. However, as a result of a separate reproductive process driven by genetic drift and a possibly distinct selection environment, the speciation event may trigger a divergent evolutionary path.

These ideas are applied here to provide insight into the pace and nature of technological change. Discontinuities are generally not the product of singular events in the development of a technology. As in the process of punctuation in the biological context, the critical factor is often a speciation event, the application of existing technological know-how to a new domain of application. The technological change associated with the shift in domain is typically quite minor; indeed, in some instances, there is no change in technology. While the speciation event is, in an immediate sense, technologically conservative, it may have significant commercial impact which, in turn, may trigger a substantially new and divergent evolutionary trajectory.

The lineage development of a technology within a new domain of application differs as the result of two basic forces. First, the new domain of application may have a distinct basis of selection; the critical attributes of functionality and degree of price sensitivity are likely to differ substantially across domains. Second, domains may differ substantially in the resources associated with them. A modest niche may only sustain a moderate rate of technological progress. In contrast, a more mainstream market may permit a much faster pace of development.

The process of 'creative destruction' occurs when the technology that emerges from the speciation event is successfully able to invade other niches, possibly including the original domain of application. This is the situation

Christensen and Rosenbloom (1995) identify in the disk drive industry, where the drives developed for the initial niche market of portable computers ultimately become viable in the mainstream desktop market. However, such 'invasion' of the original, or predecessor, application domain need not occur. The domains may differ sufficiently in their selection criteria that the two forms can coexist.

These ideas are developed in the context of the history of wireless communication. The history of wireless communication is traced from the early experiments of Hertz on the existence of electromagnetic waves to the advent of cellular phone systems. In examining this broad history, three sets of considerations are highlighted. First, the degree of technological change required for wireless communication to enter a new domain of application is examined. Second, the distinct selection, or performance criteria, in each domain of application are identified. The identification of the selection criteria, in turn, provides a basis to consider the lineage development of wireless technology within a domain of application. Although the technological shifts associated with the speciation events were quite modest, the commercial impact of these speciation events was often dramatic. The commercial import of these speciation events fostered rapid lineage development of new technological forms, which in turn provided the basis for subsequent speciation events. In this manner, an incremental view of radical technological change is set forth.

Wireless communications encompasses an enormous range of devices, technologies and domains of applications. The discussion here focuses on the principle developments within this broad arena. The analysis begins with the initial experimental transmission of electromagnetic waves by Hertz. The initial speciation event examined is the development of wireless telegraphy. The subsequent speciation events addressed are the shift to the wireless transmission of voice communication in the form of wireless telephony and broadcast radio. Clearly there are a number of other 'branches' that could be considered, including paging devices, microwave transmission and broadcast television. For the purposes of an article-length treatment of these issues, it is necessary to bound the domains considered. Indeed, even within these bounds, it is a challenge to provide a rich, yet succinct account of the technological changes.

Niches and Speciation

The core of any viable speciation theory is a mechanism for the disruption of the within-species pattern of ancestry and descent (Eldredge and Cracraft, 1980). This separation may occur by a variety of means. The mode most emphasized in the biological literature (Mayr, 1963) is geographic separation. This may be a wholly new niche (allopatric speciation) or, as Bush (1975) suggests what may be more common, the exploitation of the periphery of an existing niche.

How might we characterize niches with respect to human ecology (Hawley, 1950)? While this has been a long-standing challenge, with regard to the more narrow problem of the evolution of technological artifacts, the task is a bit less daunting. In the fields of marketing, strategic management and economics, populations of (potential) consumers are distinguished by the functionality they desire and their willingness to pay for these various attributes of functionality (Lancaster, 1966; Kotler, 1991).

A key element of innovative activity is the identification of promising domains of application for existing technologies. This argument provides a somewhat different perspective on the Schumpeterian notion of entrepreneurship as a creative recombination of existing ideas (Schumpeter, 1934). Creative recombination has generally been interpreted as the melding of two functionally distinct technologies; the emphasis here is on the recombination of technology from one application domain to another. The identification of promising domains of application is often quite uncertain. Basalla (1988, p. 141) notes that

> When an invention is selected for development, we cannot assume that the initial choice is a unique and obvious one dictated by the nature of the artifact. Each invention offers a spectrum of opportunities, only a few of which will ever be developed during its lifetime. The first uses are not always the ones for which the invention will become best known. The earliest steam engines pumped water from mines, the first commercial use of radio was for the sending of coded wireless messages between ships at sea and from ships to shore, and the first electronic digital computer was designed to calculate firing tables for the guns of the United States Army.

This creative linkage of technology to application domain is a quintessential entrepreneurial activity.

Lineage Development: Selection Criteria and Resource Abundance

Given the speciation event, why might we observe a radically divergent technology emerge and why might this lead to a rapid pace of technological change? The nature and pace of technological change are driven by two elements of the selection process. The first is a process of adaptation: the technology becomes adapted to the particular needs of the new niche that it is exploiting. The second element corresponds to the resource abundance of the niche. As a result, the mode of development is influenced by the particular features of the niche, while the pace of development is driven by the resources that this niche is able to provide.

A technology naturally adapts to the niche to which it is being applied (Basalla, 1988). This adaptation reflects the distinctive needs of the niche regarding functionality. The new application domain may value particular elements of functionality that were largely irrelevant to the prior domain to which the technology was applied. In the case of Christensen and Rosenbloom's (1995) work on the disk drive industry, we see that the attributes of size, weight and power requirements become relevant in the new niche of portable computers. These same attributes had had little relevance for manufacturers of desktop machines.

These needs should be viewed both in terms of the relative importance of various attributes, such as different price/performance tradeoffs among potential consumers, but also the minimal threshold of functionality for a technology to be viable in a given application domain (Adner and Levinthal, 1997). A horseless carriage that is likely to breakdown after a quarter of a mile is a novelty, not a substitute for a horse.

The other class of factors are the resources available to sustain the innovative activity. While a new application domain may have a distinct set of selection criteria, if the resources in this niche are quite limited, then we should not expect to observe the rapid development of new technological forms. It is the combination of a distinct selection criteria and the availability of substantial resources to support innovative efforts associated with the new application domain that results in a speciation event with dramatic consequences for technological development. The pace of development becomes much more rapid if the technology is able to satisfy the needs of not only the possibly peripheral niche to which it may have first entered but, as the technology develops in functionality or cost is reduced, the technology may subsequently penetrate larger, more mainstream niches.

Punctuation and Speciation

Ideas of punctuated equilibrium have been associated with Schumpeter's notion of creative destruction (Tushman and Anderson, 1986). Creative destruction occurs, however, not as a direct result of a speciation event. The phenomenon of creative destruction is associated with the 'invasion' of the technological form that has evolved in the new domain of application into other domains, including the domain of application of the antecedent technology.

Radial tires were initially developed in the distinct niche of high-performance sports cars (Foster, 1986). This niche valued the high performance of these tires. The resources made available from the success of radials in this niche lead to increased efficiency in the production process. That reduction in cost, in conjunction with a different attribute of radials—their greater longevity relative to bias-ply tires—allowed radial tires to penetrate the mainstream niches of replacement tires and ultimately the original equipment market of automobile manufacturers.

This successful 'invasion' of the mainstream niche is the dramatic event on which commentators tend to focus. However, that dramatic invasion is the outcome of a substantial period of development in a relatively isolated niche. Indeed, a development process that could only occur because this alternative application domain has distinct selection criteria that allows a new technological lineage to emerge. Prior to any lineage development, there is little possibility that the new technological form can out-compete the refined variant of an established technology in its primary domain of application. As Rosenberg (1976) argues in his analysis of the development of the machine tool industry, even those technologies which ultimately became widely diffused, general-purpose technologies initially focused on the needs of a particular application domain.

What permits the new technology to have some basis of viability is the existence of niches, or peripheral elements of existing niches, that exhibit a somewhat different set of selection criteria. The initial substantiation of the new technology is very unlikely to dominate the existing technology 'on its own terms'. The distinct niche provides the resources with which the new technology may develop. The path of lineage development may allow the new technology to successfully invade other niches and, in Rosenberg's term, become a general-purpose technology.

In many cases, this invasion of other niches may not occur. As a function of the resources available to support technological development and the distinct selection criteria in the new application domain, even in its developed form the new technology may not be viable in other niches. For instance, the teletype endured even with the full development of telephone technology, because it had the attribute of providing a written record that was valuable in business transactions, as well as allowing for asynchronous communication. Its demise waited for the development of an alternative form of written networked communication—improved facsimile technology and the develop-

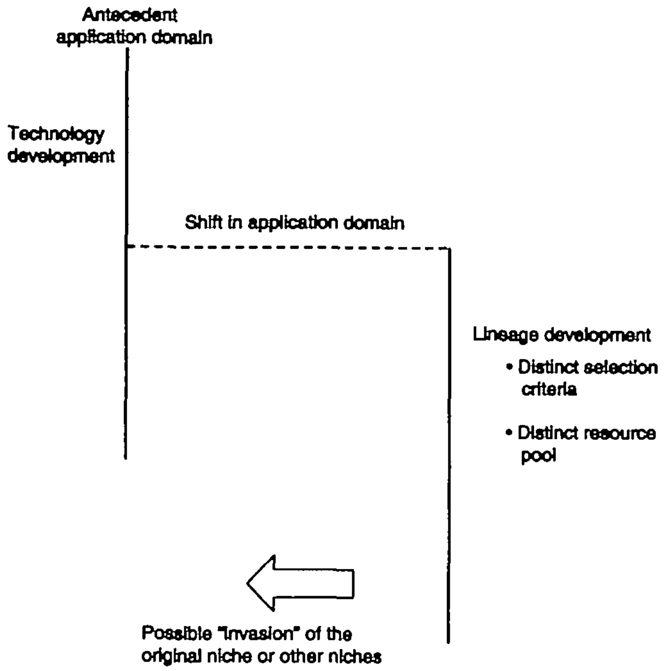

FIGURE 1. Speciation in technological development.

ment of large-scale computer networks. A final component in the persistence of a technology in a given domain of application are various forms of switching costs. These may be costs incurred by individual actors, or more tellingly, costs associated with network externalities (David, 1985; Arthur, 1989).

Figure 1 summarizes the argument. A technology undergoes a process of lineage evolutionary development within a given domain of application. At some juncture, that technology, or possibly set of technologies, is applied to a new domain of application. The technological shift necessitated by this event is argued to be modest. The lineage development that ensues within the new domain of application, however, may result in a technology quite distinct from the antecedent technologies with which this lineage was initiated. There are two basic factors that may differentiate the evolutionary path of this new lineage: the distinct set of selection criteria in the new application domain and the set of resources available in this domain. The technology may remain specific to this niche or, as it develops, it may be able to penetrate other application domains. In particular, the developed form of the new technological lineage may result in the 'creative destruction' of the technology associated with the antecedent application domain.

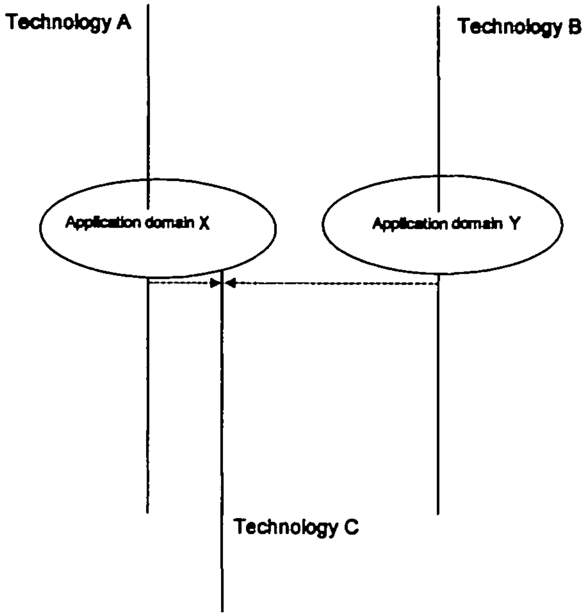

FIGURE 2. Technological convergence.

Melding of Technological Lineages—Convergence and Fusion

The argument developed here has focused on the development of a new technological lineage as a result of applying existing technology to new domains of application. New lineages may also emerge as the result of melding or hybridizing two formerly distinct technologies in a common application domain (Kodama, 1992; Yoffie, 1996). This common domain may be an application domain to which one of the two antecedent technologies is already associated, as characterized in Figure 2, and can be viewed as a process of technological convergence. Consider the development of the CAT scanner (Teece, 1987). In terms of the figure, medical imaging can be viewed as application domain X, to which X-ray technology (technology A in the figure) is already associated. Computer technology (technology B in the figure) is previously associated with data processing (application domain Y) and is creatively combined with X-ray technology in the context of medical imaging to form the new technology of CAT scanning (technology C).

Alternatively, one may observe the melding, or fusion (Kodama, 1992), of two technologies not formerely linked with one another in an application that is novel with regard to both of the antecedent technologies. Such a process is characterized in Figure 3. Kodama (1992) suggests that the melding of optics

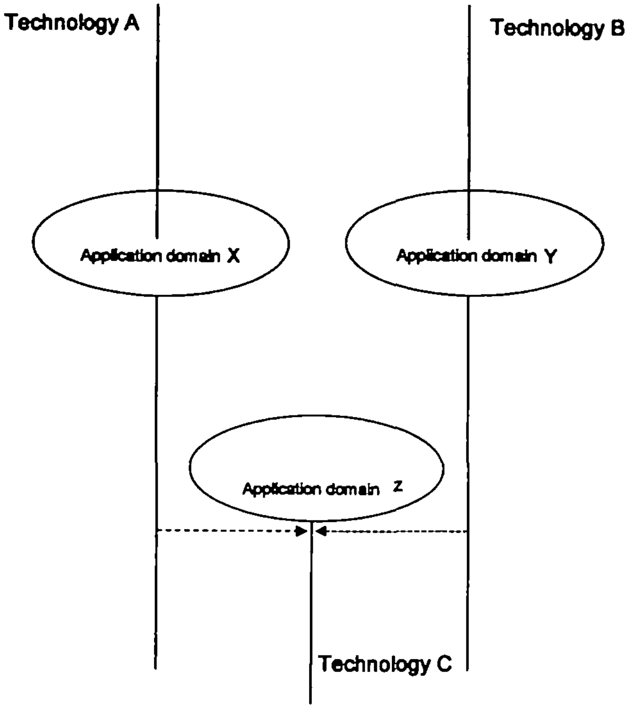

FIGURE 3. Technological fusion.

and electronics in the context of fiber-optic communications technology is an example of such fusion. Technology fusion 'blends incremental technical improvements from several previously separate fields of technology to create products that revolutionize markets' (Kodama, 1992, p. 70).

Biological evolutionary processes are not capable of such convergence or fusion. By definition, species are not capable of interbreeding with other species and producing fertile offspring (Strickberger, 1996). The evolution of technologies, however, is not restricted to processes of natural reproduction. Agents of technological change are continually generating the 'creative recombinations' of which Schumpeter spoke. Many of these creative recombinations produce new forms that prove unviable in the market place. Witness the many varients of pen-based computing and personal digit assistants (PDAs) that have been commercial failures (McGahan *et al.*, 1997).

In the history of wireless communication, there are clear examples of both technological convergence and fusion. In particular, at several junctures the lineage development of wireless technology was greatly facilitated by the 'borrowing' of technical knowledge formerly associated with other application domains. Thus, there are important examples of the pattern depicted in

Figure 2, including the application of technology from the electric power industry to the development of more powerful transmitters for wireless telegraphy and the application of key findings from Edison's efforts at developing an incandescent light to the development of improved receiver technology for wireless telegraphy—a development effort that ultimately led to the discovery of the vacuum tube.

2. *Development of Wireless Communication Technology*

The development of wireless communication technology has, at many junctures, been heralded as revolutionary, including the introduction of wireless telegraphy, radio broadcasting and wireless telephony. However, these seemingly radical changes provide a striking illustration of the characterization offered here of gradual technological evolution within a lineage with dramatic changes initiated by the application of existing technology to new domains of application. As indicated in Figure 4, the development of wireless communication technology can be construed as consisting of four distinct epochs, with each epoch corresponding to a different application domain, and associated with each application domain a distinct selection environment regarding functionality and resource availability.

The initial developments by Hertz occurred as a result of his interest in testing Maxwell's theoretical work regarding electromagnetic waves. The critical functionality in this application was the reliable measurement of electromagnetic waves. For the second application domain of wireless telegraphy, a new functionality of distance was required. This selection criteria focused efforts at enhancing the power of transmitters and increasing the sensitivity of receivers. The effort to develop superior receivers for wireless telegraphy (and an effective repeater for wired telephony) ultimately lead to the development of the vacuum tube (Aitken, 1985). The vacuum tube provided the basis for a continuous wave transmitter, a technology which was readily applied in the new application domains of radiotelephony and broadcasting.

These shifts in domain of application are significant breakpoints in the technology's development. The initial prototype of the technology, however, that entered a given new domain, whether it was Hertz's laboratory equipment, Marconi's early wireless or initial efforts at broadcast radio, was readily derived from the existing state of knowledge. The shifts were nevertheless important in that they signaled a shift in selection criteria, or, put differently, the critical functionality of the technology. The entry to a new application domain not only changed the selection criteria, but it also radically changed

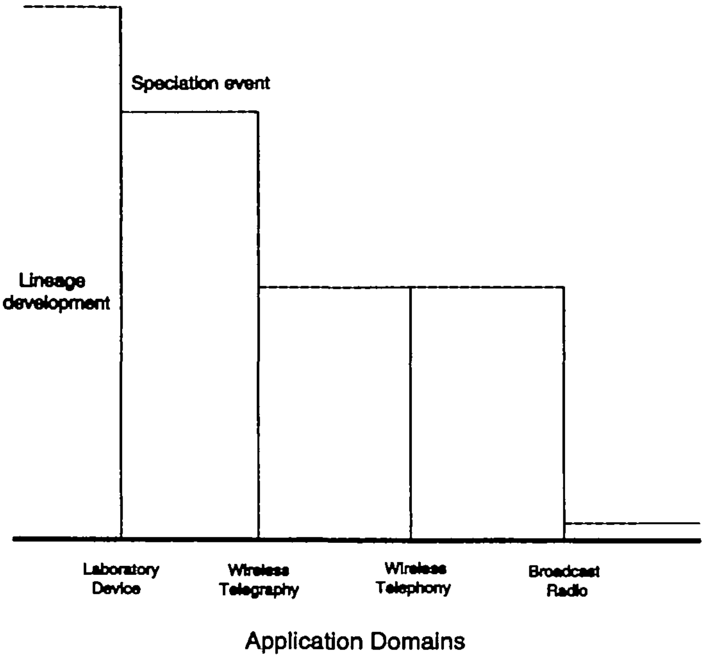

FIGURE 4. Punctuation and gradualism in the development of wireless technology.

the resources available to support the development of the technology. Contrast Hertz's assembly of components laying about the laboratory he took over in Karlsruhe, Germany with Marconi's ability to generate financial backing for a corporation to pursue the commercial application of electromagnetic waves as an alternative to wired telegraphy (Garratt, 1994) and the commitment of resources by the already established corporate entities of Westinghouse, RCA,[1] and General Electric to its refinement.

Each of the four application domains is briefly outlined. The analysis of each application domain is organized around two sets of issues. One is the technological requirements of introducing wireless technology into the new application domain. Was the innovative use of wireless technology in a new application domain preceded by major technological developments initiated with that purpose in mind, or was the technology able to enter the new domain of application as a result of the lineage development in the context of an existing application domain? The other issue addressed is the nature of the

[1] The name Radio Corporation of America (RCA) is potentially confusing in this context. RCA was founded by General Electric, AT&T and United Fruit (joined latter by Westinghouse) in order to pool their patents in the pursuit of wireless telegraphy (Aitken, 1985). RCA was not founded in anticipation of broadcast radio and indeed the emergence of broadcast radio shortly after the founding of RCA caused considerable conflicts among the parent companies.

selection criteria across application domains that causes wireless technology to diverge and take on distinct forms.

Experimental Demonstration of Radio Waves

Distinct selection environment of new application domain While there were a number of amateur and professional scientists experimenting with electromagnetic waves in the mid-1800s, Hertz had a quite focused goal of validating experimentally Maxwell's hypothesis that electromagnetic waves traveled at the speed of light—indeed, that light was simply the range of the electromagnetic spectrum that could be seen by the human eye. Hertz had a minimal threshold of functionality that electromagnetic waves be measurable. This required a predictable source of electric charge, a detector tuned for waves of the length and frequency that were emitted, and a method of measuring the ensuing wavelength (Garratt, 1994).[2] This was not a trivial accomplishment in Hertz's time. This same degree of functionality constituted a maximum for his purposes as well. He had no need or interest in sending a signal beyond the confines of his laboratory and the signal need not convey anything other than its existence for his purposes.

Technological requirements of shift Hertz was neither the first to consciously emit electromagnetic waves, nor the first to detect such transmissions. By 1842, Joseph Henry had detected spark transmissions from a distance of over 30 feet (Susskind, 1964). Not only was there past and ongoing experimental work, but the theoretical foundation for the properties of electromagnetic waves had been well developed by Maxwell and subsequent researchers. Maxwell's work not only indicated the existence of such waves, but also the effect of conductors, the phenomenon of interference or stationary waves, and the knowledge of how to produce waves of a given length (Lodge, 1902).

In addition, existing experimental practice in optics included an ability to measure wavelengths (Garratt, 1994). By directing waves on a reflector, the emitted and reflecting waves would interfere with one another and produce a series of 'standing' waves that could be measured. Aitken (1975) suggests that this application of ideas from optics to the longer waves of radio frequencies

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[2] Amore subtle requirement for Hertz was that he could only effectively measure short electromagnetic waves. A critical element of the experiment (see the subsequent section) was the use of interference to generate stationary waves. Hertz's laboratory was a lecture hall 15 m in length. In order to measure a stationary wave, there had to be at least two peaks in the electromagnetic wave between the radiating antenna and the reflecting device. With a long electromagnetic wave, Hertz would not be able to generate two peaks within the physical confines of his laboratory.

was Hertz's most original contribution. While certainly creative, it is also consistent with the theoretical argument developed here in that it represents an application of an existing 'technology' from optics to a new domain of application of electromagnetic waves.

Hertz also made substantial refinements in the methods by which electrical discharges could be generated and controlled. Starting from the well-established practice of using a Lyden jar to store and discharge electricity, 'it was through these small, incremental, one-step-at-a-time changes that Hertz's transmitter came into existence' (Aitken, 1975, p. 54). The antenna that Hertz developed could radiate waves more effectively than the Lyden jar and the frequency of the oscillations could be controlled by manipulating the inductance and capacitance of the antenna according to the established principles developed by Maxwell.

Wireless Telegraphy

Technological requirements of shift The required insights to initiate wireless telegraphy were more commercial than technological. One of the first articulations of that vision was an article in 1892 in a popular publication called the *Fortnightly Review* by Cookes, a prominent scientist and lecturer. In this publication, he suggested the possibility of 'telegraphy without wires, posts, cables, or any of our present costly appliances'. Cookes went on to address what was preventing this vision from becoming a practical reality. He noted that Hertz had already shown how electromagnetic waves could be focused and radiated in a desired direction and received at a distance. All that was necessary was to improve devices that already existed: simpler and more certain ways of generating waves of desired length, more delicate receptors and better means of directing the waves.

The only modification of Hertz's equipment necessary to provide at least a limited wireless telegraph was the addition of a Morse coder at the transmitter and the already existing filing-tube receiver as a detector. Indeed, Lodge, in his lectures on Hertz's experiments to the British public, generated a wireless Morse code message. Lodge, however, framed his public lectures and demonstrations as contributions to the electrical theory of vision and titled his lectures to the British Association 'On Experiments Illustrating Clerk Maxwell's Theory of Light' and 'On an Electrical Theory of Vision' (Garratt, 1994). For Lodge, the generation of a coded message was simply a by-product of demonstrating the existence of Hertzian waves. In terms of technological artifacts, there was nothing new in the equipment that Marconi used to demonstrate the possibilities of wireless telegraphy to the British postal service, consisting of essentially the same type of transmitter and receiver that Lodge had used in his public lectures two years earlier.

Distinct selection criteria Lodge himself, quoted below, expressed the sense that it was the result of a fundamentally different focus and set of objectives, rather than technological barriers, that caused him and other researchers not to pursue aggressively the commercial development of wireless technology (Lodge, 1902, pp. 45, 84).

> Numbers of people have worked at the detection of Hertz waves with filing tube receivers, and every one of them must have known that the transmission of telegraphic messages in this way over moderate distances was but a matter of demand and supply. . . . There remained no doubt a number of points of detail, and considerable improvements in construction, if the method was ever to become practically useful. . . . The idea of replacing a galvanometer . . . by a relay working an ordinary sounder or Morse was an obvious one, but so far as the present author was concerned he did not realize that there would be any particular advantage in thus with difficulty telegraphing across space instead of with ease by the highly developed and simple telegraphic and telephonic methods rendered possible by the use of a connecting wire. In this non-perception of the practical uses of wireless telegraphy he undoubtedly erred. But others were not so blind.

In contrast to Hertz and Lodge, Marconi, with little formal education, was focused exclusively on the commercial possibilities that electromagnetic waves offered. Marconi founded the Wireless Telegraph and Signal Company in 1897 to pursue the commercial development of this technology. The choice of the particular commercial markets with which to apply the technology illustrates the importance of peripheral niches. Preece, the director of the British postal service, in commenting upon Marconi's system after the initial demonstrations, stated that wireless telegraphy was appropriate for 'small islands, lighthouses, and above all moving ships' (Aitken, 1976, p. 216). Wireless communication was to be used in special circumstances in which the existing technology was not feasible. In particular, there was no consideration to wireless as a substitute for the existing technology of wired telegraphy. The first customers of the firm were the British Army and Navy (Basalla, 1988). The initial non-military market was the maritime industry which used the technology for ship-to-shore communication.

The Marconi Company subsequently engaged in one market, transatlantic communication, that at first blush looks as if it was in competition with an existing technology, that of undersea cables. However, this capability to engage in transatlantic transmissions was not initially developed to compete with the existing wired telegraphy system, but to provide maritime coverage for the east coast of North America and the approaches to Europe (Maclaurin, 1949). Consistent with this aim, the US-based transmitting station was located at Cape Cod—appropriate for maritime communications but not an obvious location for connecting to or competing with the existing system of transatlantic telegraphy used by the newspapers and financial organizations. Subsequent development efforts at transatlantic wireless telegraphy were prompted by a concern with the vulnerability of undersea cables during wartime and the monopolistic pricing of the cable operators.

The focus of Marconi and others interested in the commercial development of wireless technology was on very long wavelengths in the belief that these lower frequencies would generate a signal that covered greater distance (Maclaurin, 1949). This shift in the area of the electromagnetic spectrum provides a narrow, technical illustration of the idea of shifting selection criteria. Hertz, constrained by the physical limits of his laboratory, could only succeed in his experiments if he were able to generate much higher frequency waves than had previously been used. The pioneers of the commercial development of the technology completely abandoned this range of the spectrum in pursuit of their goal of long-distance communication.

Lineage development: development of continuous wave To achieve greater distance than that realized with the existing systems of radio transmission, Marconi experimented with alternative antenna designs, a process of experimentation that ultimately resulted in what is now termed a ground-plane antenna (Garratt, 1994). In principal, it was no different from the standard dipole antenna in use at that time; the key refinements were that it was vertically polarized and that the earth served as one of the dipole arms. These changes substantially increased the range of transmission and formed the basis for Marconi's subsequent efforts, including the initial transatlantic transmissions. The basic virtue of the new antenna design was that it permitted the use of longer wavelengths, which were not restricted to line-of-sight usage.

As Marconi focused his attention on the very long range transmission of transatlantic coverage, he and the Marconi Company supplemented the use of large antennas with increased voltage of the transmission itself. Indeed, Marconi ultimately brought in engineers from the electric power industry to help develop the desired high-voltage systems (Aitken, 1976)—an example of convergence of formerly distinct technological lineages.

The most profound lineage development, at least with respect to the opening up of new potential domains of application, consisted in changes in the electrical charge itself. The spark transmitter developed by Hertz and built upon by Marconi and others generated a series of damped sine waves. When Hertz measured the length of standing waves, he was actually measuring the strongest signal present, not the only signal. A spark transmitter was inherently a 'dirty radiator', polluting the spectrum with radiation that was unnecessary and interfering with the signals of other users (Maclaurin, 1949).

A continuous-wave transmitter awaited the development of the vacuum tube. While the vacuum tube was critical in paving the way for wireless communication of the human voice, and in turn wireless telephony and radio broadcasting, the development of the vacuum tube occurred in the context of efforts to enhance the sensitivity of receivers for wireless telegraphy and the transmission of long-distance, wired telephone transmissions. Fleming, the developer of the diode, was a university professor who was retained by the Marconi Company to improve its transmitting and receiving apparatus (Inglis, 1990). He developed a more sensitive detector for radio signals—a device called a rectifier which converts the alternating current of electromagnetic waves to direct current. The utility of the diode was limited by its inability to amplify electrical signals. This limitation was overcome by de Forest's innovation of the triode,[3] an invention that grew out of the need to enhance the sensitivity of wireless receivers (Inglis, 1990). An unintended consequence of de Forest's refinement of the triode for Federal Telegraph was the discovery that it oscillated, which implied that the device could generate a continuous wave and not merely act as a detector of radio waves.[4]

The further development of the triode was stalled both by technical challenges and by the conflicting patent claims of Fleming and de Forest (Aitken, 1985). By 1912, however, de Forest was able to construct a crude amplifier for voice circuits that he demonstrated to AT&T's engineers (Inglis, 1990). At the time, AT&T was eagerly searching for an amplifier, or repeater, that would make transcontinental wired telephone service possible (Inglis, 1990). With their understanding of amplification, AT&T engineers were able to considerably refine de Forest's device and by 1915 achieved a transcontinental telephone circuit using electron tube amplifiers, or repeaters (Inglis, 1990). As a by-product of that effort, 'they also developed much of the electron tube apparatus required for wireless telephony and broadcasting

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[3] The triode was simply a diode with a electrical control grid added. The virtue of the control grid was that by application of a low-power input signal to the grid, an output signal of much greater power could be produced (Inglis, 1990).

[4] Indeed, there is strong evidence to suggest that de Forest was actually unaware of this property of his invention until it was pointed out by others (Aitken, 1985).

transmitters' (Inglis, 1990, p. 32). The legal dispute over intellectual property rights was ultimately settled by the pooling of patents, controlled at that time by General Electric, American Telephone & Telegraph, and Westinghouse, and the founding of RCA in 1920 (Aitken, 1985), with RCA having the mission to commercially apply vacuum tube technology for wireless telegraphy and AT&T having the right to use the technology for its phone system.

It is important to note that two of the important actors in the development of wireless telegraphy, Fessenden and Elwell, did consider the possible implications of their innovative efforts for wireless transmission of voice communication and, indeed, they both made attempts to apply their technology to that end.[5] Their failure in wireless telephony and broadcast radio was both a result of the limitations of the current technology (they both lacked a continuous wave transmitter) and, equally important, an inability to identify and pursue a market that would support their efforts.

Fessenden pushed spark technology to its limit with the alternating spark transmitter, which emitted a rapid series of sparks and in that manner approximated a continuous wave. Elwell developed the oscillating arc transmitter. Both developments in transmission technology were applied to wireless telegraphy, with Elwell's efforts at Federal Telegraphy having much greater commercial impact than Fessenden's efforts at National Electric Signaling Company (NESCO). However, neither of their efforts in transmitter development were ultimately applied to the context of wireless communication of voices.

The one important lasting contribution of this research program was not a technological artifact, but Fessenden's identification of the heterodyne principle. This discovery stemmed from Fessenden's search for a more sensitive receiver. The heterodyne principle itself, the mixing of two waves of different frequency to produce a new wave with a frequency determined by the difference of the two input waves, was already well known in the context of audio frequencies. Fessenden's contribution was to apply this concept at radio frequencies and note the potential it held for transforming an inaudible radio wave to an audible frequency.[6]

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[5] De Forest, subsequent to his development of the audion to enhance the reception of wireless telegraphy, applied the audion to both the reception of wireless telegraphy and wireless telephony, although without much commercial success (Aitken, 1985). However, in his efforts at wireless telephony, he used an oscillating arc for a transmitter and not a vacuum tube.

[6] For instance, if a radio wave with a frequency of 100 kHz is mixed with a wave of 98 kHz, it will produce a new wave, in the audible range of 2 kHz (as well as a high-frequency wave determined by the sum of the two input waves of 198 kHz).

Broadcasting

Technological requirements of shift The term 'broadcast', in the context of wireless communication, originated with the Navy, where it referred to the transmission of a radio message, initially wireless telegraphy and then wireless telephony, to multiple receiving stations without the need to acknowledge receipt of the message (Archer, 1938). Both Fessenden and de Forest engaged in experimental radio broadcasts. On Christmas Day of 1906, Fessenden broadcast music to radio operators on Navy vessels and ships of the United Fruit Company out in the Atlantic, who had been previously alerted by telegraph (Aitken, 1985). De Forest broadcast from the Metropolitan Opera House in 1910 (Douglas, 1987). However, both Fessenden and de Forest engaged in these broadcasts to generate publicity for their companies and were not contemplating the possibility of commercial radio broadcasts.[7] Furthermore, the sound quality of these broadcasts was rather poor. Neither Fessenden or de Forest were using continuous wave transmissions—a necessary precondition for high-quality wireless transmission of voices. The broadcasts were striking to their listeners because of the novelty of communication of voices, but were not sufficiently clear to be used for general listening (Douglas, 1987).

What is conventionally viewed as the first radio broadcast in the modern sense of that term occurred in 1920 and is attributed to Frank Conrad, a Westinghouse engineer and amateur radio operator who participated in Westinghouse's efforts in the development of vacuum tubes for radio-telephones.[8] Westinghouse had received a special license from the US Government to build and operate two experimental stations for telegraphic and telephonic communication, one of which was located at the company's East Pittsburgh plant and the other at the home of Conrad (Dunlop, 1970). Conrad began playing records on his amateur station on a regular basis and by September of that year a Pittsburgh department store began advertising and selling simple receivers with which Conrad's broadcasts could be heard (Dunlop, 1970). Westinghouse, recognizing the publicity Conrad was receiving and noting the possible profits from the sale of receivers to a new

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[7] Wireless entrepreneurs in many instances funded their initiatives by direct (and largely unregulated) sales of stock to an often naive public. Indeed, in the case of the companies founded by de Forest, the 'profits' he and his business partners pocketed derived from stock sales, not from revenue from operations (Douglas, 1987).

[8] Furthermore, for the current argument, identifying the first broadcast is not critical. What is important is that the initial experiments in broadcast were not preceded by self-conscious scientific efforts to make these broadcasts possible and, indeed, that such efforts were not required.

class of consumers, decided to develop its own station, KDKA, in October 1920.

What is striking about this episode is that the innovation of broadcasting was largely a conceptual, rather than a technical breakthrough:

> KDKA, with its six 50 watt tubes, was indeed using 'state of the art' technology, but nothing that had not been familiar to radio engineers for several years. It was no technical breakthrough that created the broadcasting industry almost overnight. What made the KDKA experiment significant . . . was its disclosure that a market existed and that it could be reached with a relatively small investment. That market was, initially, the community of radio amateurs, individuals who knew how to string up a wire antenna and tune a crystal set and were delighted to share those skills with their friends, families, and neighbors. But beyond those amateurs was a vast potential audience with an apparently insatiable appetite for news and music whose existence had previously been almost totally unsuspected. (Aitken, 1985, pp. 471–472)

The critical technical stumbling block for radio broadcasting lay with the transmission of voice communication over the airways. This was a challenge that was overcome in the pursuit of more sensitive receivers for wireless telegraphy and a repeater for wired telephony. The reception of a continuous wave modulated by an audio frequency was not problematic—any simple rectifying detector would serve to demodulate the signal and reproduce the sound in earphones or, after amplification, in a loudspeaker. It was for this reason that simple crystal sets were so effective in the early days of broadcasting.

The modest technical demands of early receivers for a broader consumer market are illustrated by RCA's development efforts in this area. Sarnoff, the one corporate actor who seemed to anticipate the possibilities of commercial broadcasting, pushed the RCA technical committee early in 1920 to fund a project for a 'radio music box'. Engineers at GE had estimated that it would cost ~$2000 to build a prototype and that it could be done in 4–6 weeks (Aitken, 1985). RCA's technical staff, while skeptical about the effort, agreed to go ahead. The experimental broadcasts of Conrad, and Westinghouse's subsequent development of its own radio station obviously changed the saliency for RCA of the mass consumer market for radio receivers, as well as for other latent participants. Nonetheless, the modest engineering commitment necessary to develop a 'radio music box' indicates the incremental nature of that effort.

Lineage development Early radio broadcasting technology was primitive, but with its dramatic commercial success the technology developed rapidly. The early transmitters had <5 kW of power and were of low efficiency. They used the techniques of low-level grid modulation that AT&T had developed for wireless telephony (Inglis, 1990).

Radio receivers themselves went through substantial changes during the early years of radio broadcasting. Many early receivers used a 'cat's whisker' crystal detector, rather than an electron tube, and earphones were often used in place of loudspeakers (Inglis, 1990). Often these receivers were sold as kits that were assembled by users. Tuning was a particular problem in early receivers. To change stations, each stage in a series of amplifiers had to be turned individually and precisely with an array of knobs on the front panel (Inglis, 1990). Batteries were used as a power source for early sets. By the mid-1920s, these sets began to be supplemented by receivers using Armstrong's superheterodyne circuit that could run on alternating current (Inglis, 1990). The superheterodyne had perhaps a more important virtue of enhancing tuning.

The major development in radio technology subsequent to the superheterodyne was the development of frequency modulated (FM) broadcasting. Ironically, though FM transmission was developed to enhance the quality of radio broadcasting, it had little impact in its intended domain of application for many decades. The early important commercial uses of FM transmission were in wireless telephony for mobile communication.

Armstrong developed prototypes of FM transmission in the early 1930s and publicly demonstrated a working wide-band FM system in 1935 (Erickson, 1973). FM's slow commercial development in broadcasting stemmed from a number of sources. First, ownership of amplitude modulated (AM) broadcasting rights were a valuable asset that the established broadcasters did not want to see diluted by the opening up of the spectrum that FM, which was targeted at higher frequencies, represented. In addition, Sarnoff and RCA had committed to the development of television broadcasting which would compete for the same high-frequency region of the spectrum as FM broadcasts. Thus, for both sets of reasons, the established radio broadcast systems resisted Armstrong's innovation (Erickson, 1973). Finally, one could argue that the greater audio quality of FM did not offer an appreciable advantage for the bulk of radio broadcasting—news, radio shows and the popular music of the time. Only for classical music was there a clear benefit to the FM system. It was only with the growth in popularity of rock music in the late 1960s that there was a mass need for the higher fidelity of FM broadcasting. Furthermore, the relatively low price of FM broadcasting rights was a further reason that the new stations dedicated to rock music were attracted to FM transmissions. It was FM's broadcasting other virtue, the much greater freedom from interference, that caused it to have an early important role in wireless telephony (Calhoun, 1988).

Wireless Telephony and Mobile Communication

Distinct selection criteria The slow development of wireless telephony, in contrast to the rapid development of broadcast radio, illustrates the importance of the viability of the speciated technology in its new domain of application. Elwell, using his arc transmitter, was able to demonstrate the wireless transmission of voices between Stockton and Sacramento, California in 1910. However, in the context of a California already heavily wired for phone communication, it was not a commercially viable substitute (Aitken, 1985).[9] There was the further problem that AT&T would not allow a wireless competitor to interconnect with its wired system—a problem that was to plague the more contemporary efforts at wireless telephone service of MCI (Cantelon, 1995).

Wireless telephony proved viable not in the mainstream application domain of phone service to fixed locations, but in settings in which mobile communications were important. Initially, this was in the context of maritime applications (ship-to-shore and ship-to-ship communications). Realizing the importance of wireless communication technology for coordinating the fleet and perhaps anticipating involvement in World War I, the US Navy began a program to develop ship-to-ship and ship-to-shore voice communication in 1915. By 1929, commercial radiotelephone services began to be offered on luxury cruisers. Not only did maritime applications place an high value on the functionality provided by wireless communication, but the large size and power requirements of wireless telephony at that time did not hinder their use on-board ship. These considerations of size and power requirements were, however, an important limitation in applying wireless telephony to mobile land-based communication.

In addition to the value of wireless telephony to offshore islands and ships, it held great promise for transoceanic communication. Indeed, submarine cables capable of transoceanic voice transmission did not come into existence until 1955 (Coates and Finn, 1979). In contrast, AT&T established the first transoceanic telephone link between New York and London, in conjunction with the British Post Office, in 1927 (Colpitts, 1971). Thus, the diffusion of

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[9] It is interesting to note in this regard that in contemporary times, wireless telephony may be a viable substitute to wired phone systems in the context of transitional economies which have a poor infrastructure of wired phone service (Lavin, 1996).

radiotelephony across application domains paralleled that of wireless telegraphy, first with maritime applications and subsequently transoceanic applications. Land-based mobile communication, an application domain distinctive to wireless telephony, had to await further lineage development of the technology.

Lineage development Public service agencies, particularly police departments, took the lead in the development of land-based mobile communications (Kargman, 1978). Civilian use of land-based mobile communications started as early as 1921 with experiments by the Detroit police force with radio dispatch (Noble, 1962). The Police Commissioner was concerned that the 'modern' automobile had given the criminal an advantage in speed that could not be overcome by the use of police cars controlled by telephone call-boxes (Noble, 1962). The early car radios proved unreliable in that they could not withstand the buffeting of mobile use. Subsequent work on receiver technology, particularly the work of Bates refining the superheterodyne design, lead to the first operational system in 1928 (Calhoun, 1988). These initial systems only allowed for one-way communication from the base to the patrol cars. With the reduction in the size of transmitters, two-way transmission capabilities were developed in 1931, and by 1934 radio dispatch technology was widely diffused among municipalities.

Although widely diffused, mobile communications still had important limits. In particular, there were a variety of problems associated with propagation disturbances. Radio signals were broadcast using amplitude modulation, where the strength of the signal varied to convey sound. Armstrong's system of communicating by modulating the frequency of the radio wave (i.e. FM) proved an enormous benefit in that it overcame the problem of static—or random amplitude noise from natural and man-made sources (Calhoun, 1988). This was a particular problem for mobile communications, since the receiver was constantly changing its position and problems of static and 'flutter' could not be overcome by manual tuning as in the case of a fixed location receiver. Another important virtue of FM for mobile communication is that FM requires far less power, allowing for smaller receivers and transmitters.

These two advantages resulted in FM quickly becoming the dominant mode of transmission for mobile communication. In contrast, as noted earlier, the feature of greatly enhanced dynamic range and hence fidelity did not provide a basis for successful early penetration in radio broadcasting. By 1939, the Connecticut State Police established the first FM communication system (Noble, 1962). Calhoun (1988, p. 28) suggests that 'the advent of FM technology was the first great watershed in mobile radio. . . . Although there have been major advances in network-level architecture, improvements in components and in the network interface, *no fundamental breakthroughs in the technology of the basic mobile radio link have reached the market since the late 1930s*' (emphasis in the original). Again, it is important to keep in mind that Armstrong developed the FM system to enhance the quality of radio broadcasts. Its application in mobile communication was not intended and did not provide the motivation for his efforts.

World War II provided a tremendous stimulus to refine FM-based mobile communications. Several hundred thousand mobile radios were manufactured for the war effort, resulting in improvements in packaging, reliability and cost (Calhoun, 1988). The technical history of mobile communications equipment design since 1940 is in many important respects a history of developments to improve the efficiency of spectrum utilization (Noble, 1962). During the 1940s, requests for spectrum for two-way mobile radio increased dramatically for uses ranging from police, fire departments, electric, gas and water utilities, railroads, buses, streetcars, trucks and taxis (Calhoun, 1988). There have been two foci of this effort to more efficiently utilize the limited spectrum for mobile communication: the reduction of transmission bandwidths, referred to as channel splitting, and the development of automatic trunking of radio communications.

A mobile telephone service that allowed users to interconnect with the land-line system was initiated in St Louis in 1946 by AT&T (Calhoun, 1988). These systems were an immediate success. Within a year, a mobile telephone service was offered in over 25 US cities at rates of $15.00 a month and 15¢ a minute (Calhoun, 1988). The systems used FM transmission with a single powerful transmitter that provided coverage of >50 miles, a range more than adequate for most metropolitan areas.

The penetration of mobile telephone services was constrained by the limited channels available for use. Ratios of subscribers to channels of 50–100 were common (Calhoun, 1988). As a result, the service was quite poor with the probability of a phone call being 'blocked', because all available channels were in use, becoming as high as 65% (Calhoun, 1988). As recently as 1976, the New York metropolitan area of 20 million people had only 12 channels available for mobile phone use.

The major development that overcame this constraint of limited spectrum was the development of cellular systems. The notion of cellular system architecture was initially put forth by Bell System engineers in the 1940s. The cellular idea departed from the convention adopted from broadcasting of a single transmission source. Rather, there would be many low-powered transmitters providing coverage for a portion of a broader region. The enormous advantage of this system is that a given channel or frequency could be 'reused' across cells. Conceptually, as cells are made smaller, it is possible to increase the system capacity indefinitely. Practical development of such a system posed significant system engineering challenges to gracefully 'hand-off' a call as an user passed from one cell into another.

Furthermore, a viable cellular system still required a certain critical mass of channels or spectrum. Therefore, while Bell engineers laid out the system requirements for a cellular system as early as 1947, the Federal Communications Commission (FCC) did not allocate sufficient spectrum to mobile telephone use to make the development of such a system viable (Calhoun, 1988). Television, which the FCC tended to view as more of a mass medium of communication, and thereby more worthy of spectrum allocation, received the bulk of the high-frequency spectrum. In 1949, when deciding how to allocate the ultra high-frequency (UHF) band of the spectrum, the FCC declined the Bell System's proposals, refusing to allocate any of the UHF spectrum to mobile telephony and instead created 70 additional television channels.

In the face of the tremendous underutilization of the UHF frequencies by broadcasters and the overwhelming need for spectrum allocation for mobile communications, the FCC finally began to reconsider its position (Calhoun, 1988). However, it was not until 1982 that the FCC ruled that two 20 MHz licenses would be issued for each metropolitan area (Calhoun, 1988). The first US cellular system, operated by AT&T, began in Chicago in October 1983 (Calhoun, 1988).[10] Digital systems hold the further promise of allowing each frequency, even within a cell, to sustain multiple conversations and, as a result, can greatly expanding the carrying capacity of a given frequency allocation at a much lower cost than cell-splitting.

3. *Technical Forms and Niches*

The speciation events in wireless communication consisted largely in creating new opportunities, though in some cases they ultimately led to the replacement of existing technologies. Wireless telegraphy was developed to serve remote locations such as lighthouses and ships. The subsequent niche it entered was that of long-distance transoceanic service. In this application domain, wireless faced competition from the established technology of

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[10] AT&T, however, was to be a cellular operator for a total of 79 days as the Bell System was broken up and the regional Bell Companies took over cellular operations.

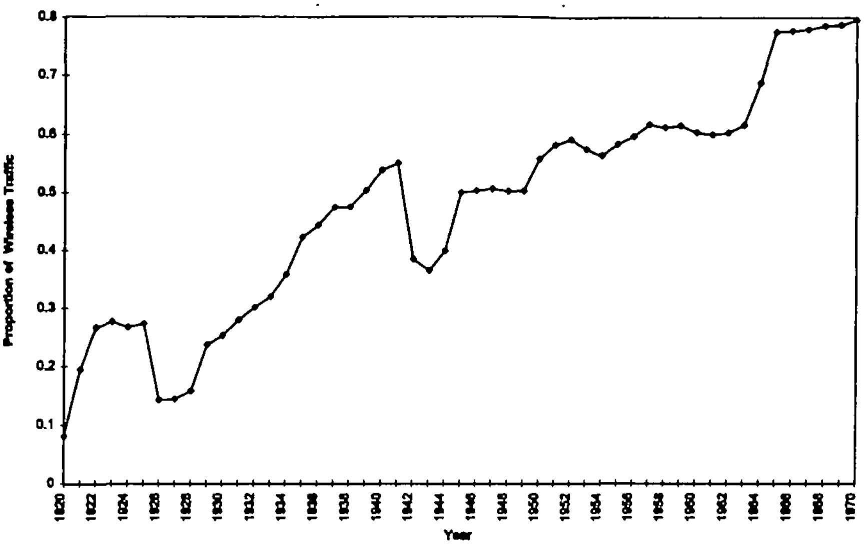

FIGURE 5. Competing forms in international telegraphy—wireless and wired telegraphy. (Data from Coates and Finn, 1979.)

transoceanic cables. Though cable and wireless telegraphy have coexisted, it is a competition that wireless has largely won. Wireless has enormous cost advantages over cable, but suffered competitively initially as a result of its susceptibility to occasional interruptions caused by atmospheric conditions. The primary reason for the coexistence of the two systems, rather than the complete domination by wireless, stems from the sunk costs of the existing cable lines. However, after 1928, new capacity was satisfied by wireless. This is reflected in both the volume of international messages via cable and wireless (see Figure 5) and the fact that no new telegraph cable lines were added after 1928 (Coates and Finn, 1979).

The persistence of telegraphy, both wired and wireless, in contemporary times is at first sight rather surprising given the availability of both domestic and international phone services. However, this persistence reflects the critical role of distinct functionality provided by alternative technologies. One typically thinks of telegraphy in the context of Morse code transmissions. The modern application of telegraph technology, however, is the teletype, which is an application of telegraphy that encodes and transmits alphanumeric data. Indeed, starting from its inception in the early 1930s, teletype messages have become the dominant use of telegraph services (Statistics of Communications Common Carriers, 1977).

The important functionality of the teletype that has lead to its persistence in a wide array of business transactions is the fact that it provides a written record of any correspondence, making it preferred to voice communication for many purposes. Another advantage relative to telephone communication is the freedom to transmit without consideration for differences in time zones. It is the relatively recent development of the widespread application of fax technology and the even more recent development of widespread computer networks that is leading to a decline in teletype communication.

Wireless telephony has not been a substitute technology for wired telephone service, at least in competition with an existing wired network.[11] Rather, wireless telephony has opened up new possibilities for mobile communication. Initially, these applications were focused on public safety uses, such as police and emergency services. In more recent years, wireless technology has penetrated more mainstream, mass consumer markets. The speed with which mobile phone service developed was largely constrained by regulatory factors and the battle for access to the frequency spectrum. From a technological perspective, the 'cellular revolution' had been largely achieved by the 1940s, notwithstanding the dramatic commercial developments of the last decade.

At least initially, these commercial discontinuities took the form of providing communication services where none existed before rather than new technology for existing services. Such a pattern is likely to prototypical, rather than peculiar to wireless communication. A new technology will be viable if it out-competes existing technologies on some performance criteria, whether an element of functionality or cost. It is unlikely that a new technology will be able to out-compete an established technology in its primary domain of application.

The technology finds an initial toehold for viability in the competitive ecology of alternative technologies in some specialized domain of application. In order to be viable, the technology must have some basis by which it is differentiated from the refined variants of existing technologies. Often that initial niche are applications, such as the military, where distinctive performance on some dimension of functionality is highly valued and provides a basis for competitive viability. However, in other cases, such as minimally invasive surgery or pen-based computing, the early domains of application are ones that not only value the distinctive functionality, but ones in which relatively crude forms of the new technology are sufficient to suit the needs of the application domain, such as gallbladder versus heart surgery in the case of minimally invasive surgery, or the use of pen-computing for structured forms rather than tasks that require handwriting recognition.

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[11] There is the interesting possibility of wireless phone service being a viable competitor with a wired network in the context of emerging economies that lack a developed wired system.

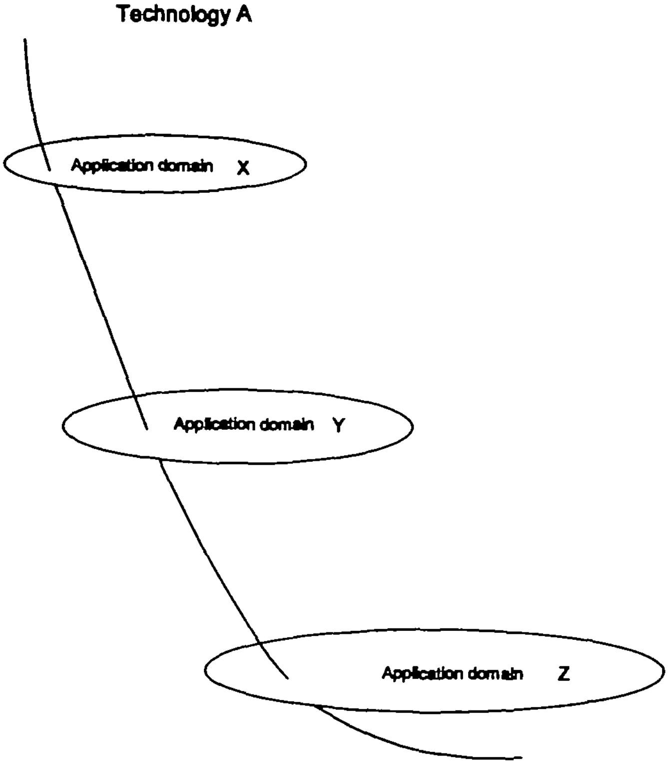

FIGURE 6. Technology evolution and penetration of application domains.

The above argument suggests the following possible patterns of technology development. Initially, the focus of activity is on the new, or peripheral niche that has provided the basis for the speciation event. A critical factor in the evolution of a technology is whether the technology, as it develops, is able to penetrate a broader set of niches. Figure 6 illustrates such a pattern. For instance, the video recorder was initially developed in the context of the distinct niche of broadcasters (application domain X). As the manufacturing process was refined and the product design simplified, it was possible to penetrate a new niche (application domain Y) of industrial and commercial users (Rosenbloom and Cusumano, 1987). Finally, this development continued to the point that the product was able to penetrate the mass consumer electronic market (application domain Z). It is important to note that, at each point in its development, video recording technology was commercially viable and profitable within the niche in which it was operating.

In the context of the history of the video recorder, we see a movement from a peripheral niche to penetration of the broad niche of the mass consumer market. In ecological terms, we might think of this as the artifact shifting from a specialist to a generalist. No longer must the video recorder look for resources for its survival and development to the narrow niche of television broadcasters, but the entire set of households becomes a basis for resources.

This need not be the only sort of pattern one might observe. It is quite possible that the technology is not able to go beyond the initial, peripheral market. For instance, gallium arsenide was heralded as a replacement for silicon in semiconductors in the early 1980s based on the superior speed that it provided. However, the technology has proved commercially viable only in the context of supercomputer applications and communications devices (Wiegner, 1988). Recently, the demand for Gallium arsenide has increased, but this demand in still in the context of communications devices, not mainstream computing applications (Ristelhueber, 1993).

4. *Conclusion*

An obvious limitation of the empirical analysis is the focus on the evolution of a particular technology—that of wireless communication. However, the choice of this technological domain was not based on its fit with the theoretical framework, but rather its fit with popular views of technological development consisting of radical or revolutionary changes.[12]

Yes, wireless communication technology has undergone extraordinary change in the hundred years since Hertz's experiments. However, the dramatic breakthroughs that set the technology on a new course were less technological in nature than discoveries of new domains of application. As noted by his Nobel Prize citation, Marconi's contribution to science was most importantly his demonstration of the possibilities for wireless telegraphy. The miracle of broadcast radio was initially demonstrated by ham radio operators, not the large corporate entities pursuing wireless telegraphy.

These 'speciation' events were, of course, made possible by wonderfully creative development efforts—development efforts that commanded tremendous amounts of time and financial resources. However, these efforts were supported within the existing application domains. Broadcast radio and wireless telephony could not have been possible in the absence of continuous-wave transmitters, but the impetus to develop that technology and the resources to do so came from efforts to enhance the distance and

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[12] A further criterion was the existence of a long and well-documented history of the technology's development.

clarity of wireless telegraphy and AT&T's interest in developing an effective repeater for long-distance, wired phone service.

The framework developed here of speciation of existing technologies to new application domains with distinct resources and selection criteria provides a structure with which one can make sense of rapidly changing technological environments. In particular, it offers a bridge between the notion of the gradual cumulation of scientific knowledge and the phenomenon of dramatic transitions from one technological regime to another in the commercial sphere.

The dramatic commercial impact of technological change is not the result of singular, transformational events. Speciation, in an immediate sense, is technologically conservative; however, it may prefigure rapid technical and commercial changes. The commercial impact may reflect the growth of the technology in its new application domain, as was the case of broadcast radio. The ultimate commercial impact of the new technological form precipitated by the speciation event, however, may also reflect the penetration of other market niches and a Schumpeterian revolution of the competitive exclusion of prior technologies.

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