THE ECONOMIC IMPLICATIONS OF EXAPTATION

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Abstract

Accounts of economic change recognize that markets create selective pressures for the adaptation of technologies in the direction of customer needs and production efficiencies. However, non-adaptational bases for technological change are rarely highlighted, despite their pervasiveness in the history of technical and economic change. In this paper the concept of *exaptation* - a feature co-opted for its present role from some other origin - is proposed as a characteristic element of technological change, and an important mechanism by which new markets for products and services are created by entrepreneurs. Exaptation is shown to be a missing but central concept linking the evolution of technology with the entrepreneurial creation of new markets and the concept of Knightian uncertainty.

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Key words

Exaptation – entrepreneurship - Knightian uncertainty - new markets.

Introduction

Despite their pervasiveness, many phenomena go unrecognized and un-researched for long periods of time. The management theorist Karl Weick uses the example of battered child syndrome (BCS), which was first suggested in 1946 by John Caffrey, a pediatric radiologist who noticed a pattern of injuries invisible to the naked eye but visible on X-rays (Weick 1995:1-2). Caffrey's report was based on six case histories of young children whose parents' accounts of the child's history were silent about how the injuries occurred. However, it was not until 1961 that BCS became an observable phenomenon "out there" in the world, after a panel at the American Academy of Pediatrics annual meeting and the publication of the panel's findings in the *Journal of the American Medical Association*, which was based on hundreds of reported cases accumulated nationwide. Like many phenomena, BCS was invisible, unknown and ignored until it was named and elevated as an issue. Moreover, such phenomena are often bundled with other associated phenomena and remain unattended to by researchers for as long as they are obscured in a broader taxonomy. This can result in incoherent theoretical accounts, with important theoretical insights badly matched with empirical phenomena organized in conflicting taxonomies. It can also result in limiting the range of hypotheses available for testing.

This paper addresses one such phenomenon in the literature on economic and technical change – the phenomenon of *exaptation*. An exaptation is a feature co-opted for its present role from some other origin. Exaptations are pervasive in the history of technology and markets (Mokyr 1998), a point we will illustrate with some examples in the account that follows. This paper will show how exaptations are an important part of what entrepreneurs do, and cause, and that identification of this phenomenon helps makes sense of empirical phenomenon in technological and economic change that have received relatively little attention, such as the genesis of new markets. Despite the pervasiveness of exaptations in economic and technological development, the subject has to date been relegated to a provincial role in discussions of change. In this paper we hope to illustrate why exaptations are, in fact, a central issue in the republic of technological and economic change. This paper describes what exaptations are and why they are important.

The paper is organized as follows. First, different meanings of adaptation are discussed and exaptation is defined. Second, three examples of exaptations – some of them well known in the literature on technological change – are explicated in order to illustrate the concept in concrete terms. Third, the economic implications of exaptation are explained, in particular the important link between exaptation, uncertainty and profits. The paper ends with a conclusion that highlights main themes and implications. The whole paper can be summarized in three succinct points, which represent the core ideas defended in the paper:

1. Exaptations - features of a technology co-opted for their present role from some other origin – are a central and pervasive phenomenon in the development of technology over time and, as such, are an important phenomenon in any theory of economic change. A strong focus on the adaptation of technology products and processes to user needs and efficiency criteria has generally obscured the phenomenon of exaptation, which points to the *non*-adaptive origins of many technologies, and the process by which they are later co-opted for other roles.

2. The ordering of events in technological history is important, and exaptation is one concept that points to process issues that are material to the pattern of change and development of technologies. Unlike biological systems where the timing of adaptations may be immaterial, in economic systems the costs of creating information means it makes all the difference in the world if a technology has already been developed and can be exapted from a prior use to a new domain of use. The relative costs of producing and using information therefore suggests that the normal pattern of technology development ought to show frequent sideways exaptations of technologies fueling gradual adaptive development of a technology. Exaptation therefore suggests swapping lineage for breadth as a key researchable phenomenon of technological development. Since the key agent of exaptation is the entrepreneur, the concept of exaptation also suggests a central role for entrepreneurship in the development of technology, putting the pilot back accounts of the development of technology in ways that accord with both common observation, empirical research and prior theoretical accounts.

3. The concept of exaptation points up the fact that the functions a technology is selected for are only a subset of its causal consequences, and that no finite limit exists to the exaptive potential of a given technology, be that product or process. The lack of the ability to pre-state all possible

product and service markets has the familiar ring about it of the phenomenon Frank Knight (1921) pointed to as the true causal locus of profits and the contractual organization of the firm – what we now call Knightian uncertainty. Exaptation is thus shown to be a missing but central concept that links the development of technology, the entrepreneurial creation of new markets (Venkataraman 1997) and the concept of Knightian uncertainty.

Different meanings of adaptation

The term *exaptation* was originally coined in evolutionary biology, in an article addressing missing terminology in the science of form (Gould and Vrba 1982). Since then, the term has been selectively adopted by historians of technological change who study technological change in evolutionary terms, in particular by Mokyr (1998). The notion of exaptation is to be contrasted with the notion of adaptation, which has a range of meanings generally consistent with the idea fitting well for a particular role. The Romans, for instance, found that bronze swords were not well fitted to their desired role as they were prone to bend in the cut and thrust of close quarters battle; as a result they experimented with different metallurgy until they produced swords of superior functionality by virtue of having a better balance between flexibility and rigidity. Such instances represent conscious design efforts to adapt form to function (well). In nature the Darwinian algorithm of the overproduction of progeny with random variations and their elimination by environmental selection is generally thought to exert the same pressures towards adaptation as the battlefield did for the Roman sword. Both of these processes – Lemarkian directed design or design by natural selection – refer to historical processes that change natural and manmade artifacts in the direction of functional adaptation. The key idea is that adaptation is a matter of design *for* a task, whether that occurs through variation-selection-retention processes or Lemarkian learning processes (Nelson and Winter 1982, Nelson 1995).

However, the blanket application of the term "adaptation" obscures the fact that all adaptation is not the same. In particular, the whether an adaptation was built for the function it *now* performs, or whether it was built for a *different* function under different selection criteria that have since passed, marks an important difference in the nature of change processes. Technologies that were built for one purpose very often later used for other purposes for which they were not designed – indeed, we will find that this is a normal process by which technologies become pervasive.

Definition of Exaptation

According to Gould and Vrba (1982), who originally coined the term, exaptation is a concept that is defined by its relation to adaptation. Adaptations are features of a technology – process or artifact – that were designed for their performance in their current role. The operation of such adaptations is their function, and functions positively selected for are by definition adaptations. Characteristics or features that are not built for selection in their current roles are designated as the effects of technologies, and "We suggest that such characters, evolved for other usages (or for no function at all), and later "coopted" for their current role, be called *exaptations*." (Gould and Vrba 1982).

Mokyr, one of the most careful historians of technological change, follows closely to this definition of the phenomenon of exaptation, saying that the term "refers to cases in which an entity was selected for one trait but eventually ended up carrying out a related but different function" (Mokyr 1998). This definition captures the idea that exaptations are features of a technology that are co-opted for their present role from some other origin or utility. Whereas adaptations have functions for which they are selected, exaptations have effects that are not subject to present selection pressures, but might come to be of significance sometime later.

A classic example of a technical innovation that illustrates both the processes of adaptation and exaptation is the compact disk. Originally developed in the late 1960s at the Pacific Northwest National Laboratory in Richland, WA, like most inventions the compact disk was an adaptive design for a specific task: solving the problem of poor sound quality and wear and tear suffered by vinyl phonograph records. Its inventor, James T. Russell, developed the system based on the idea of using light as a medium because he envisioned a system that would record and replay sounds without physical contact between its parts. The CD-ROM was therefore patented in 1970 as a digital-to-optical recording and playback system. However, researchers at the lab with large quantities of experimental data *exapted* CD-ROM technology for another use: a data storage medium for computers. This was a function the CD-ROM was *not* designed for, but nevertheless proved very effective. As a result, during the 1970s the lab refined CD-ROM technology for any form of data, and set the stage for the eventual commercialization of the technology both the music and computing industries.

What exaptations are not

It is important to be clear about what exaptations are not as, like any other pervasive phenomenon, they are otherwise apt to be confused with other phenomenon and misdiagnosed. First of all, many economists might recognize some affinity between the concept of exaptation and the concept of *externalities*, which are generally defined as "The effect of one person's decision on someone who is not a party to that decision." (Coase 1988). The difference between the two concepts is that exaptation is a phenomenon that is related to context changes that happen over time, and is not amenable to analysis at a point in time. Exaptations are the effects of technologies that are *later* co-opted for their usefulness. By contrast, externalities are not rooted in changes in context.

Second, exaptations are not another way of describing the entrepreneurial process of creatively combining existing ideas (Schumpeter 1934). Schumpeter's suggestion that entrepreneurs creatively assemble existing ideas into something new has generally been taken to mean that entrepreneurs combine two or more distinct technologies (Levinthal 1998:220). Exaptation instead points to a different phenomenon, one that depends on context changes that change the utility of technologies. Exaptation therefore thrives on acts such as connecting a technology with a new domain of use – in other words, on technology-domain combinations, not on technology-technology combinations. Indeed the combination of technology and new domain of use is "a quintessential entrepreneurial activity." (Levinthal 1998:220).

Third, many researchers might suggest that exaptations are simply unintended consequences of technologies. However, this ignores the fact that the act of exapting a technology normally requires deliberate leveraging of effects of a technology that would otherwise have been dormant or perhaps gone unnoticed. Effects that are exapted may, after the fact look like unintended consequences of the original design of the technology, but one organization's "unintended consequences" only exist because an entrepreneur has put those effects to work by exapting them.

Finally, basic research often gives rise to inventions that initially are designed without a use in mind, and therefore cannot be called adaptive in the first place. One widely quoted study from the 1970s found that 41% of all basic scientific inventions and discoveries had no immediate use, but that over long periods (around 25 years) these discoveries were converted to useful ends (Comroe 1977). As such these basic inventions fall into a category of exaptables as a case of technologies that are not created because of their immediate functionality. The concept of exaptation merely points up with more precision that the operative principle of such research endeavors is explicitly non-adaptive.

So, to recap, the difference between today's adaptive functions (and/or unintended/random consequences) and tomorrow's exaptable effects marks off the critical distinction between adaptations that arise as a result of selection processes and effects – things caused, produced, results or consequences – that were not initially designed with a use in mind, but represent a pool of tools available for later co-optation by exaptation.

Reasons for exaptations

Exaptations may have three possible origins. First, they may have been adaptations to prior circumstances – in other words, actively selected in for the task at hand. For instance, compact disk technology was an active adaptation. Second, they may have been features that were selected in as part of a bundle of features, but in-and-of themselves made no particular contribution to the performance of the technology. In other words, they were neutral or immaterial in regard to the selection regime. For instance, vitrification, a process originally developed for environmental remediation (mainly the safe processing of high level radioactive waste), is proving to be eminently exaptable for processing biological hazards (such as hospital wastes and even destroying stocks of biochemical weapons) owing to the fact that the extremely high temperatures utilized in the process kill most biological agents. Third, technological features may have been unavoidably selected in as part of a bundle of features, even though the particular feature was a negative drain on performance of the whole. The feature might have been an unavoidable constraint. For instance, in the post World War Two period innovations in plastics production were largely based on utilizing unwanted byproducts of petroleum refining processes.

This structure of exaptive possibilities follows from two characteristics of artifacts, whether those are natural, artificial or social in nature[2]. The first is near decomposability. In his original exposition of the architecture of complexity, Simon (1996/1969) pointed to fact that complex systems such as those observed in technology

[2] Social artifacts would include the socially complex routines (Nelson and Winter 1982) or techniques (Mokyr 1990) which are often taken as the basic unit of selection in theorizing about evolutionary processes in economic systems. These routines and techniques are almost always confederations of subroutines or sub-techniques organized hierarchically.

have a structure that is best described as nearly decomposable: that is, they display a hierarchical structure where the overall structure of an artifact is decomposable into subparts and the subparts display short-run behaviors that are approximately independent of the short run behavior of other subparts. Over the long run the behavior of components depends on the aggregate behavior of the other components. As a result, sub-optimal subpart design is one of the pervasive features of technologies, but these subparts are selected and proliferate by virtue of being only one aspect of the entire artifact, and the entire artifact may display adaptive characteristics. Indeed, non-adaptive subparts within an adaptive whole are usually taken as a sure sign of a hierarchical architecture (Axelrod and Cohen 1999). More recent research into modular design (Langlois and Robertson 1992, Schilling 2000) illustrates the same point: designers select the overall best technological solution for the problem at hand, but every solution has more and less optimal features. As a result, the raw material for future exaptations is everywhere.

A second characteristic of technologies that suggests the later exaptation of possibilities is the lack of a finite list of causal consequences of a technology in its context. Unexpected features of everyday life bear testimony to this deep philosophical point – that the list of possible descriptions of any object in context is infinite. Parochial examples abound of objects being used in previously unimaginable ways (as any traveler can attest from a visit to a foreign land far removed from the norms of her homeland). Famous examples include the creativity displayed in crises, including the multiple creative exaptations that the Apollo 13 ground crew came up with to save the crew drifting in space with a dwindling oxygen supply.

To summarize, technologies are typically aggregates of subparts and one cannot know in advance all the uses that some oddball subpart of a technology might have in some oddball situation sometime in the future. Primarily this is a practical matter in the development of technology, but this phenomenon also has a sound philosophical basis. Sometime in the future, such a technology will clearly have not been designed to be adaptive to the situation, but will have been co-opted anyway.

Examples of Exaptation

1. *Edison and the phonograph*

According to the account related by the technology historian Basalla (1988), Edison's invention of the phonograph in 1877 appears to represent an archetype of the exaptive possibilities created by a new technology. The basic technology can only be described as fully pregnant with possibilities, and its immediate uses were by no means self-evident. Edison, who owing to his own deafness consistently directed his inventive genius towards technologies that amplified and reproduced sound, invented the phonograph with a mind to recording dictations for later reproduction. Basalla recounts that in 1878 Edison published an article specifying ten possible ways in which the invention might be useful to the public:

> "He suggested that it be employed to take dictation without the aid of a stenographer; provide "talking books" for the blind; teach public speaking; reproduce music; preserve important family sayings, reminiscences and the last words of the dying; create new sounds for music boxes and musical toys; produce clocks capable of announcing the time and a message; preserve the exact pronunciation of foreign languages; teach spelling and other rote material; and record telephone calls. This listing is important because it represents Edison's own order of priority for the potential uses of his talking machine." (Basalla 1988:139-140).

Needless to say, Edison chose to sell the phonograph to the market he had designed it for: to business offices as a dictating machine. He persisted in marketing the phonograph for this use for ten years. Frustrated at times by the lack of progress in commercializing the technology, at one point in the early 1880s Edison declared that the technology had no commercial value at all. Since Edison regarded the technology as a serious invention, he resisted all application of the technology to domains of use that, in his mind, trivialized his invention. Of course, it was therefore left to other entrepreneurs to exapt the technology to a new domain of use. The exaptation was the primitive jukebox, which co-opted the phonograph from its origin as a dictation device to a new role - automatically playing popular music in public places with the deposit of a coin. The jukebox, which became the first major use of Edison's superb new technology, of course never appeared on Edison's list of uses, even though the exaptation was in retrospect obvious, something that was further underlined by the immense popularity of the new device. Yet no one could have predicted this rather context dependent consequence of Edison's new technology, which initially proved useful in the odd public environment of funfairs and seaside resorts as a novelty attraction. Like all artifacts, the jukebox came to be as a creature of its context, and then stayed for a while.

Also like most exaptations, the jukebox followed the familiar pattern of being initially technologically conservative in that it primarily drew on the features that were inherent in Edison's technology and available for exploitation given context changes created by switching the technology into a different domain of use (Levinthal 1998). Jukeboxes then took up an development trajectory all of their own, being gradually adapted to perform better given the demands of their selection environment, and perhaps occasionally making a technical contribution to the exaptive pool of possibilities constituted by the general technological paradigm of phonography. Of course, by popularizing phonograph technology and creating a need for a stream of freshly recorded new music, the jukebox laid down the basis of an eventual new industry – the music industry.

For his part, in 1891 - fourteen years after the invention of the phonograph - Edison still staunchly refused to accept the jukebox as a legitimate use of phonographic technology, because he believed that it detracted from his efforts to establish the phonograph as the technology of choice for dictation in the serious domain of the business office. Only in the mid-1890s did Edison come to accept that the primary use of the phonograph would be for entertainment purposes, after the technology had reached widespread acceptance in the public's eye in the form of the jukebox.

Curiously, history does have a habit of repeating itself. According to Basalla (1988:140), one might have expected that the lessons of the phonograph would have served as a guide to the budding Tokyo Telecommunications Company (later Sony) as it attempted to introduce the tape recorder after World War Two. Tape recording technology was originally developed during the war as part of the German war effort, but Sony noted its eminently exaptable qualities and quickly developed the technology for the public domain, initially selling it to Ministry of Justice courts as a device for recording court proceedings, and to universities and schools for the teaching of languages. Clearly Sony's sometimes lauded intuition for mating technologies with use domains was somewhat clouded in the case of the tape recorder, for at one point the firm produced a pamphlet listing 999 possible uses of the tape recorder in its search for a market. It wasn't until the 1960s that tape technology was exapted to a new domain of use – primarily tapes for *playing* pre-recorded music - after which sales of the new device took-off, with 8 tracks being responsible for bringing pre-recorded music, long known in the household in the form of the phonograph, to mobile transport: the automobile. Once again we see that the context change that a new domain of use represented led to a creative exaptation of technological features that were non-obvious in prior contexts. The rest – including the Walkman, which was another exaptation – is history.

2. The architecture of tractors

A simple but illustrative example of exaptation in the agriculture industry is recounted by Kauffman (2000). Late in the nineteenth century, engineers struggled to invent the tractor. Typical of many important but simple insights, the idea of agricultural equipment powered by the internal combustion engine was fairly obvious to many individuals and organizations, but operationalizing the technology proved troublesome. The Charter Gasoline Engine Company of Sterling, IL, first successfully mated an internal combustion engine to a Rumley steam-traction-engine chassis in 1889, producing six of the machines, making Charter the first producer of the "tractor". Of course, taking the internal combustion engine to the agricultural industry was a clear domain shift for the technology which, in principle, was an attractive replacement for the prevalent power source of ages: horse power. But engines with suitable power outputs were large and heavy, so much so that they buckled the tractor chassis. And engineers developing the technology knew that the weight of the tractor was unattractive to farmers because heavy equipment compacts soil, and compacted soil typically reduces crop yields.

So the engineers, for all their efforts, appeared to be at a dead end. Then, at some point in time, somebody suggested that, as the engine block was so huge and so rigid, why not use the engine, coupled with the equally heavy and complex gearbox and drive axle components, as the chassis of the tractor. The front axle, ancillary equipment and drivers seat could be attached to the engine-gearbox-axle arrangement, which would be the chassis itself, allowing the engineers to dispense with a separate chassis, and a lot of weight as a result. Thus the chassis of a tractor is actually an exaptation of the engine-gearbox-axle equipment that was necessary to make the tractor a tractor in the first place. Once the exaptation was produced, it was of course widely imitated by all producers, becoming the standard architecture for the tractor industry up to the present day.

The architectural exaptation of the tractor engine provides a good example of the way a domain shift changes the salient features of a technology in ways that were non-obvious beforehand. Indeed, the lesson of such a shift is that it might, per the phonograph and tape recorder example, be illustrative of other "hidden" structural features of a technology and become a template for other domain shifts and exaptations. Putting the internal combustion technology into a different domain of application and re-contextualizing its function resulted in the features of the technology being harnessed for useful purposes in a very different way than had been conceived in other domains of application.

3. *Continuous exaptation by the Japanese auto industry*

The history of the Japanese automobile industry in the U.S. nicely illustrates how exaptations can pile up, one upon another, and be of enormous strategic and economic importance despite having rather modest technical underpinnings. In the 1960s, Japanese cars were introduced into the U.S. and became popular because they were cheap. In contrast to cars produced by the Big Three (General Motors, Ford and Chrysler) Japanese cars generally had a smaller overall architecture, were modest in terms of their interior size, were powered by much smaller engines (generally four cylinders), and were sold primarily on the basis of their low prices.

After the first oil crisis in 1973 and the quadrupling of the oil price, the scale of the small – sometimes rather tinny – Japanese car became a sizable advantage in the marketplace, which started to put premium of low fuel consumption. Good fuel efficiency was a by-product of the Japanese selling philosophy in the U.S. market, yet this change in utility of a prior feature that was not designed with the U.S. market in mind represented a classic exaptation by consumers of one feature of Japanese car design that hitherto had been of incidental relevance to most buyers. As a result, the popularity of Japanese autos increased dramatically, and fuel consumption became a positive design and selling point in the introduction of new models (for instance, the Honda Accord introduced in 1976 was advertised boasting 40% better fuel efficiency than comparable domestic models).

In the mid-1980s, a different fitness trait of Japanese autos was exapted in a story that is strongly analogous to what happened in the 1970s with size and fuel consumption. For many years, Toyota in particular had championed lean production techniques for automobile manufacturing, based on principles such as flexible manufacturing processes and just-in-time delivery (Womack et al 1990, Womack and Jones 1995). The goal of Toyota's production practices were to achieve manufacturing efficiencies in three areas: first, by building the right products to meet variable demand for different models in different markets; second, by feeding the market with a stream of new products that appeared on a much shorter timeframe than had been traditional in the industry; third, to reduce manufacturing faults to an absolute minimum by getting everything in the build process right first time, thus reducing expensive retrospective fixes at the end of the production line or, worse still, at the dealer's premises after the customer had experience a fault or failure.

However, Toyota's production system also came with an important exaptable feature - the quality of the finished product also continuously improved, something customers experienced directly in terms of finished product quality but also in terms of reliability and low servicing and maintenance costs. These factors were associated with the lean production techniques that Toyota had introduced originally in the 1960s for production efficiency purposes, but had the knock-on effect of improving product quality, a consequence bearing the classic trait of an exaptable feature - it was *not* initially selected for, but none-the-less became a salient adaptable feature later as engineers and customers alike began to appreciate the win-win nature of lean production – based on the realization that it meant firms would produce better quality products, not worse ones. This point was generalized in the "quality movement" in the 1990s, when firms started to realize that better product quality did not cost more but in fact often costed less, something that was highly counterintuitive until the TQM (Total Quality Management) movement became widespread. Also as a result, in the 1990s high quality and low running costs became general selling points of many Japanese autos.

Significance of Exaptation

1. *Exaptation, uncertainty and profits*

The nature of exaptation suggests that one cannot pre-state a finite list of all possible exaptations of the myriad of technologies that exist in the world. We cannot predict ahead of time what the list might look like, even if we had knowledge of the complete array of technologies and artifacts that presently exist in the world, as we cannot predict all of the context dependent oddball ways in which some weird subpart of a technology might have a use in some oddball situation sometime in the future. Indeed, some apparently oddball technology might become a very profitable product for some entrepreneur who has been granted a patent on the artifact. We have learned that this occurs because technologies are typically complex aggregates of subparts that are not conducive to a finite list of descriptions in their context.

This lack of the ability to pre-state all possible products and services has the familiar ring about it of the phenomenon Frank Knight (1921) pointed to as the true causal locus of profits and the contractual organization of the firm – what is now well known in the literature as "Knightian uncertainty". This suggests some coherence and integration between Knight's ideas and exaptation.

To briefly recap Knight's reasoning, which has received several fine treatments in the literature (for instance, Langlois and Cosgel 1993, Boudreaux and Holcombe 1989), Knight pointed to a typology of uncertainties, under the guise of risk (situations amenable to estimation by statistical analysis), uncertainty (situations amenable to Bayesian updating of probabilities based on learning about the environment) and true uncertainty (Knightian uncertainty, which is not amenable to probabilistic calculation). Knight suggested risk and uncertainty were in principle always insurable, and therefore could never be the source of profits. True uncertainty, however, would never be insurable as nobody could know in advance what to write the insurance contract for. Knight therefore suggested true uncertainty was the cause of all profits, and necessitated the contractual structure of the firm, where residual profits are owned by the stockholders whose equity in the firm "insured" other stakeholders with whom the firm had contracts.

The concept of exaptation, which suggests the impossibility of pre-stating a complete array of markets, therefore ties the concept of Knightian uncertainty to something very concrete and observable in the world. One of the regular debates about Knightian uncertainty is whether it should be taken as axiomatic and, if not, what concrete experiences in the world suggest that we should care about the phenomenon of Knightian uncertainty? Theorists often turn to Popperian arguments (Popper 1958) about the consequences of fundamental scientific discoveries and inventions, which create a stream of fundamental uncertainties, thus impoverishing predictions of the future based on present and past data. Therefore exogenous events are called upon to provide the underlying reasoning behind Knight's argument for the third type of uncertainty. Excellent though this argument is, our thesis here is that exaptation provides a complimentary *endogenous* explanation. It is a conceptually clear and empirically observable phenomenon that logically implies Knightian uncertainty. Exaptation thus connects Knightian uncertainty to concrete events in the world thus affirming the efficacy of Knight's idea by linking it to the development of new technology and new markets.

2. *New markets, primary exaptation and secondary adaptation*

While the development of technologies and markets is always a messy affair often spanning tens of years, we tentatively suggest that the underlying processes of technical development will be found to proceed according to the following high level pattern: 1). technology genesis by adaptation in the original domain or via discoveries and inventions from government-funded basic research; 2). primary exaptations where the technology branches off by being linked to a new domain of use; 3). secondary adaptations developing the technology based on the selection criteria of the new market and; 4). technical developments in one branch of the technology then feedback to the broader industry using the technology.

In a study of the development of wireless communications technology, Levinthal (1998) points to this adaptation-exaptation pattern as wireless technology developed from initial applications in wireless telegraphy to broadcast radio to wireless telephony. Each successive exaptation resulted in the creation of a new industry, yet was initially based on extremely modest technological shifts – classic exaptations of features that were developed in one domain but also proved to have useful effects in the context of other domains. For instance, it took Westinghouse a matter of a few weeks and a few thousand dollars to develop a consumer broadcast radio set for the mass market. Subsequent development of wireless in each of these industries proceeded by better adapting the technology to the specific domain of use, based on feedback from the domain, but also indirectly contributed to the pool of technology available for future exaptations, which included paging devices, television and radio frequency identification devices. Simple initial technical exaptations typically prefigured more important technical developments with significant commercial impact.

One of the messages of Levinthal's study is that, unlike biological systems where the timing of adaptations may be immaterial, in economic systems the costs of creating information means it makes all the difference in the world if a technology has already been developed and can be exapted from a prior use to a new domain of use. As long ago pointed out by Arrow (1962) the indivisibility of information means that while technology is expensive to create, the costs of reusing it are marginal and often close to zero. So while the absence of a market for new products creates substantial uncertainty that undermines already risky investments in research to produce new technology, the low cost of reusing existing technologies makes these technologies an attractive basis for cooptation into new domains of application. Firms endeavoring to develop new markets confront a frighteningly long list of uncertainties: will buyers adopt the new product and, if so, over what time frame?; will the technology work and be produced at the price point required to make a sale? (usually determined by substitutes/alternatives); and will the firm be insulated enough from competitors to get a return on its up-front investments? (usually determined by several isolating mechanisms: speed to market, patent protection, secrecy, complimentary assets, barriers). Non-existent markets do not generally support extensive research and development of technologies, suggesting that the normal pattern of technology development ought to show frequent sideways exaptations of technologies fueling gradual adaptive development of a technology in a particular domain. Exaptation therefore suggests swapping lineage for breadth as a key researchable phenomenon of technological development.

One of the questions such a pattern raises is the genesis of the exapted technology. The history of any technology will likely show a sequential mixture of initial development through adaptation followed by primary exaptations and secondary adaptations. Most new technologies will have their genesis in adaptive processes going on in other domains of use: military demands drove several of the major technologies in the post World War Two era – including integrated circuits, aeronautics and nuclear power (Hooks 1990, Cowan 1990). In studies of industrial innovations, von Hippel (1988) has shown that most innovations are initially developed by users as adaptive solutions to particular problems, and then commercialized separately. Much original software development proceeds this way - i2 Technologies finite scheduling software for manufacturing plants is a good example of this (i2 Technologies 2002). And Christensen (2000) has shown that in the computer disk drive industry technologies which were developed on an adaptive (and often exploratory) basis but rejected as inferior are sometimes exapted off the research bench into new domains of use in which they later develop very successfully. Indeed, these low cost technologies became “disruptive” when market needs converged or the technology developed to the point of being general purpose. A pattern of “creative destruction” (Schumpeter 1976) sometimes followed, with the best technology invading other niches, sometimes including the one from which it originally was exapted (Levinthal 1998).

Exaptation compliments suggestions that much technology development proceeds along paradigmatic lines, within an established trajectory (Dosi 1983) and often as an industry standard (Tushman and Anderson 1990). These arguments suggest that technologies accumulate much change gradually via adaptive processes – qualities the CD-ROM, tractor and jukebox all display. However, each of these technologies also bears witness to the process of exaptation in its developmental history, a point that has received less attention in the literature on technological and economic change.

3. *Entrepreneurship viewed as a* non-*adaptive process*

The concept of exaptation suggests the hypothesis that entrepreneurship – whose quintessential act is linking a technology with an application use – might bear consideration as a *non-adaptive* process.

This seems a strange line of argument – that entrepreneurship might be identified as a non-adaptive process. After all, most economic theories of the entrepreneur are clearly adaptive: for example, Kirzner's (1973, 1997) view that entrepreneurs are alert to possibilities for better meeting market needs strongly suggests adaptation.

The counterpoint to this is a somewhat subtle line of reasoning that begins with the most unsubtle of thoughts: that new markets do not pre-exist, and no entrepreneur can adapt to a market that is not there. Before any adaptation can happen, a market has to be produced.

This problem of adapting to things that first have to be produced is an analog to the problem of pre-adaptation in biology (Gould and Vrba 1982) where for many years biologists struggled with the notion that nature sometimes produces features of an organism that *later* become of adaptive significance. In biology, the issue is especially stark, since nature has no mechanism of foresight at all so, unlike entrepreneurs, nature cannot be thought of as adapting ahead of time to circumstances it sees ahead of it, however faintly (Kirzner 1997). The biological analog therefore highlights the issue in the starkest of terms.

Arguably the most embedded assumptions of new market development come from the marketing strategy literature (Kotler 1994, Iacobucci 2000). This literature frames a firm's chances of success in new markets in terms of the introduction of products that are well adapted to emergent customer needs. This requires firms to collect market research, forecast market demand, and develop their technology to meet product design requirements dictated by the market. But since "Markets that don't exist can't be analyzed…" (Christensen 2000:xxi) entrepreneurs seeking to create new markets have to rely on their judgment (Knight 1921), intuition (Christensen 2000) or equivalent psychic talents. Other researchers have proposed elaborate Popperian methodologies to be used by entrepreneurs to test their hypotheses about emergent markets (Harper 1995).

This whole edifice of failed reasoning can be swept away with the hypothesis that new markets develop as the result of the application of an existing technology to a new domain of use – in other words, that new markets are the result of a pattern of adaptations in one domain, followed by primary exaptations of the technology to a new domain, followed by secondary adaptations of the technology to the demands of the new domain. Technologies can only be termed adaptively developed when their origin is attributable to design for this particular role. When an entrepreneur flips a technology into an adjacent possible market, this is truly an exaptation of the technology, not an adaptation.

We are not disturbed by the suggestion that complex technologies are developed through a mixture of exaptations and adaptations, which seems to us to accord better with the messy empirical facts about how technologies and markets develop than views that suggests neat adaptive responses to market needs that are themselves the constructs of supposedly prescient entrepreneurs.

Of course, the list of researchable non-adaptive mechanisms entrepreneurs harness to create new markets includes processes other than exaptation. As a point of illustration, McKelvey (1998) relates the following account about the market for HGH (human growth hormone). HGH was a product developed on an adaptive premise if ever there was one, and was one of the first products resulting from the crop of fundamental scientific discoveries that gave birth to the biotech industry. The problem with HGH was that the market was not large enough to recoup the enormous investment in research and development that had gone into the drug. But markets can be redefined, and one way to redefine them is to get the U.S. medical association to redefine its technical classification of “small”. This exactly what the biotech firm that developed HGH did, in a move that dramatically increased the number of individuals “qualifying” for the product. As McKelvey points out, “[T]he market for what appears to be a niche product has expanded dramatically. It has changed from an early estimate of $10 million to actual sales of over $1 billion by 1995. This indicates how much the definition of dwarfism has changed.” (McKelvey 1998)

Such acts are undoubtedly entrepreneurial, yet hardly qualify as adaptive responses to the market since their chief premise is changing the nature of the market.

4. *Process versus equilibrium analysis – the usefulness of exaptation and like concepts*

What concepts are most useful in explaining the process by which the bird’s wing was created? How can we reason coherently through accounts of how things have come to be? Exaptation is one idea that helps pluralize our notions of the processes of design by pointing to the non-adaptive processes by which technologies develop, as well as the adaptive ones.

The relevance of the concept of exaptation is a matter of some contention in debates on biological evolution, with neo-Darwinians such as Dennett (1995) insisting that the distinction between adaptations and exaptations is meaningless because nature never distinguishes between the two, while on the other side some theorists such as Gould (2002) believe the concept of exaptation is useful in explaining the evolution of, for instance, flight, which is hard to explain without a clear understanding of how feathers developed for one reason (warmth) but were later "exapted" for another use (flight).

Similarly, in technical development we need process concepts that are useful for dynamic analysis, including concepts like exaptation that point to differences along the way, not blanket adaptation which fails to reveal timing differences that are important (nature does not weigh costs and decide whether it is best to invest in R&D or utilize what is already available, but economic agents like entrepreneurs do). A dynamic conception of adaptation and its alternatives – of the full panoply of processes by which new technologies and markets are created – is part of a more fine-grained analysis of the nature of change processes. Static cross-sectional economic models may use a static definition of adaptation, but sciences of change (such as evolutionary economics) need dynamic concepts that allow the analyst insights into which processes are at work, or not.

Future Research Directions

Several avenues of future research might be pursued on the topic of exaptations, in particular empirical studies that unravel the historical patterns of adaptation and exaptation suggested in this article. Of the theoretical implications, one of the most pregnant of possibilities is a thorough treatment of the relationship between the scholarship of Schumpeter (1976) and Knight (1921) on economic change, uncertainty and profits.

Consider for a moment Schumpeter's account of economic change. Schumpeter's reasoning begins with a stylized account of the circular flow of the flow of goods and services (Schumpeter 1934). Into this flow an entrepreneur introduces a new combination – for example, a new product – that disturbs the circular flow. The entrepreneur reaps temporary monopoly profits from introducing the new combination just as long as competitors fail to catch-up by imitating the new product. One imagines that the system returns to equilibrium once the new product becomes a norm.

What is the underlying cause of the disequilibrium created by the entrepreneur's introduction of a new combination? One view is to suggest that Schumpeterian entrepreneurs bring new technology (information) to the economic system, in the form of innovation in production and transaction technologies. In this case Schumpeterian profits are essentially returns to new information and their longevity depends on the pace of information flow around the economy.

A second view would begin by holding technology constant in the economic system and directing analysis to new combinations of technologies. Given the functions of each of the technologies combining them will not make any difference to the equilibrium of the system since the combined effects will be the sum of the parts, including their interactions. Schumpeter's insistence on the importance of combinations might then indicate he had something different in mind when two technologies are combined – he might have been pointing to a difference in the set of effects caused by the combination. Sound familiar? For instance, when one combines an internal combustion engine and other technologies in a particular domain of use (say agricultural machinery) and come up with an internal combustion engine that doubles as the tractor chassis? Sounds an awful lot like an exaptation.

This suggests a hidden assumption underlying Schumpeter's reasoning of the dynamic system of economic change. We can pinpoint this as the idea that combinations are one of the common ways in which technologies are connected with new domains of use and when technologies are connected with markets in new ways, there is a possibility that exaptations will occur. When combinations do not lead to exaptations, the equilibrium of the system will not be disturbed. Adaptive responses to market demands that rely simply on combining two technologies would not cause perturbations in the circular economic flow (of course, in general equilibrium, all combinations are reasoned to already be optimally allocated to their best uses). What causes disequilibrium is exaptations, which introduce new effects into the flow of the economy, throwing it off its otherwise steady equilibrium state. The Schumpeterian entrepreneur, then, creates disequilibrium whenever she creates an exaptation.

Now, this means that the exaptation is the causal locus of disequilibrium, in much the same way as exaptations are the locus of uncertainty in Knight's economic reasoning, which raises an interesting question about Schumpeter and Knight: aren't they then saying the same thing? Indeed, our contention is that Knight and Schumpeter *are* saying the same thing. The concept of exaptation suggests a line of reasoning for a hypothesis that economists intuitively know - that Schumpeterian profits amount to the same thing as Knightian profits as they are both returns to true uncertainty.

Conclusion

We suspect that exaptation – using things for purposes other than those for which they were designed – is an extremely pervasive feature of economic change and that the average reader can immediately name several examples from their own experience. According to Mokyr, "Exaptation… can be widely documented in the history of technology." (Mokyr 1998). The question that therefore arises is, Why has the conflation of historical genesis and current use of technologies attracted little research interest?

Our suggestion is that the lack of attention given to the subject reflects the fact that key theoretical approaches to the development of technology are built on a conceptual structure that excludes the phenomenon of exaptation as a relevant concept. The lack of recognition of this concept arises for the same reason that exaptations were long relegated to a quiet corner of evolutionary biology: *because the underlying assumption of technology researchers is that adaptation is the predominant mode of change in technological systems*. A strong focus on the adaptation of technology products and processes to user needs and efficiency criteria has generally obscured the phenomenon of exaptation, which points to the *non*-adaptive origins of many technologies, and the process by which they are later co-opted for other roles, in particular, the production of new markets. Exaptation flies in the face of the standard assumptions about change driven by Lemarkian adaptational processes that produce the evolutionary trends theorized in the literature (Nelson and Winter 1982).

Contrary to this view, like Gould and Vrba, we "suspect that the subjects of non-adaptation and cooptability are of paramount importance in evolution." (Gould and Vbra 1982). The concept of exaptation suggests an enormous pool of co-optable effects are exaptable from the technologies available in any economic system. Exaptation therefore supplies a missing thought about the wellsprings of variation, and is an important concept in creating a balanced analysis between criteria of necessity (selection mechanisms) and criteria of contingency (sources of variation). Since the key agent of exaptation is the entrepreneur, the concept of exaptation also suggests a central role for entrepreneurship in the development of technology, putting the "pilot" (Cohendat et al 1999) back accounts of the development of technology in ways that accord with both common observation, empirical research and prior theoretical accounts.

Of course, in more than one way, with exaptation there is the faint but rather disconcerting odor that something dicey is going on. First, entrepreneurs appear to use artifacts and technologies that are *already there*. Normally theorists suggest that the road from rags to riches is paved with entrepreneurial acts that arbitrage things of value (Kirzner 1997) or create original artifacts (Schumpeter 1976). The practice of exaptation, after all, seems to bear some relationship to bait-and-switch practices that might be considered rather nefarious in other contexts: bait a technology in one market and then switch it to another. Indeed, exaptation does suggest leveraging the impact of context changes on things that already exist rather than creating artifacts de novo. Brand new markets change the relevance of effects: for instance, the U.S. coffee business has a different context since the advent of Starbucks, which has produced several exaptations in specialty coffee business in the past ten years, producing a new technology of coffee retailing in the process. But exaptations are apt to create a feeling of unease and discomfort as there is always a sense of a "something for nothing" phenomenon and rabbits being pulled out of hats.

The second sense in which there is an odor of something dicey occurs because returns to intellectual property are being harvested elsewhere, often outside the domain and outside the control of the original creators of the information. Arrow recently noted that, "Information is the basis of production, production is carried on in discrete legal entities, and yet information is a fugitive resource, with limited property rights… I would surmise that we are just beginning to face the contradictions between systems of private property and of information acquisition and dissemination." (Arrow 1999:162-3). Fundamental trade-offs exist between the economics of technology creation and the economics of connecting technologies with application domains. Clearly both matter, and exaptation complicates them.

In order to overcome the sense that something dicey is going on, we have to accept that, contrary to some of the our more beautifully crafted economic theories, the life of any technology is actually persistently full of exaptations, and that the creative harnessing of possible effects of existing things is one of the bedrock concepts of value creation. Consider economic analogies to Kauffman's squirrel story:

> "A particularly ugly squirrel named Gertrude was atop a tree 65,433,872 years ago. She was ugly because she had folds from her forearms stretching to her hind limbs. So ugly was Gertrude that she was shunned by the other squirrels and was sadly alone atop a magnolia tree eating lunch. But just yards away, high in a pine, was Bertha, an owl. Bertha spotted Gertrude and thought, "Lunch!" Bertha flashed downward through shafts of light toward Gertrude. Gertrude looked suddenly up and was terrified. "GAAAAAAH," she cried and jumped in desperation from the top of the magnolia tree, flinging her arms and legs wide in terror. And yes, Gertrude flew! Yes, she flew away from the magnolia tree, eluding the bewildered Bertha. Later that month, Gertrude was married… Her odd flaps turned out to be a consequence of a simple Mendelian gene, hence her kids had the same wondrous capacity to fly. And that is how flying squirrels got their wings, more or less." (Kauffman 2000:131).

The phonograph, tractor chassis and Japanese cars all display the same characteristic of being technologies whose effects were exaptable in much the same way as skin folds in flying squirrels. Our contention has been that these exaptations are central phenomena in technology and market development.

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