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Finding the organizational sources of technological breakthroughs: the story of Hewlett-Packard's thermal ink-jet

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Which firms are more likely to invent technological breakthroughs, such as Hewlett-Packard's invention of the thermal ink-jet? I induct theory for this question by interpreting the history of the breakthrough as a recombinant and boundedly rational search process. The firm increased its odds of success by generating many high-variance inventive trials; it mixed and juxtaposed diverse technologies, professions and experience, managed by objective and collocated. The firm exploited this variance with effective selection processes, strong socialization norms, deep experience with the components of invention, rapid prototyping and testing, and scientific knowledge and method.

1. Introduction

Which types of firms are more likely to invent technological breakthroughs? While inventors and organizations generally seek breakthroughs as opposed to incremental inventions, the importance of the question has recently increased, for a variety of reasons. Breakthroughs by definition are much more valuable than incremental improvements, both technologically and financially. Recent econometric work has quantified the positive skew of the pecuniary distribution and shown it to be quite dramatic. For example, Scherer and Harhoff (2000) estimated that the top 10% of patents garner 48–93% of the financial payoffs. Recent strengthening of intellectual property protection and the development of intellectual property markets has also improved the incentives for breakthrough invention (Dickinson, 2000). As a result of these and other perceived opportunities, private firms have increased their investment in research and development (Mervis, 2002). Given these trends, the organizational sources of breakthroughs deserve attention.

Despite the importance of the question, however, there exists little agreement about which firms invent breakthroughs. Previous research can be roughly categorized into two streams. Scholars in the first stream argue that smaller, entrepreneurial and 'outside' firms are more likely to achieve technological breakthroughs (Schumpeter, 1939; Cooper and Schendel, 1976; Abernathy and Utterback, 1978; Tushman and Anderson, 1986; Utterback, 1996). Klein (1977: 17) argues that 'In fact, of some 50 inventions—most of which were included in the Jewkes, Sawers, and Stillerman study—that result in new S-shaped curves in relatively static industries, I could find no case in which the advance in question came from a major firm in the industry.' Others, however, have argued (Schumpeter, 1942) and illustrated (Christensen, 1993; Lim, 2000) how large, incumbent firms are quite capable of breakthrough invention. Anecdotal evidence remains mixed. For example, while AT&T invented the original semiconductor, smaller firms contributed to subsequent breakthroughs (Mowery and Rosenberg, 1997). Large sample empirical results also remain mixed, and with the exception of Ahuja and Lampert (2001), do not focus explicitly on breakthroughs. For example, Sorensen and Stuart (2000) found that firm size had a positive effect on invention quality in the semiconductor industry and a negative effect in biotech. Henderson and Cockburn (1996) found that size had a positive effect on the discovery of new drugs, but only if firms could leverage knowledge spillovers across a diverse research portfolio. Sorensen and Stuart (2000) also found that age, arguably a proxy for incumbency, had a positive effect on the number of inventions for both industries, but mixed effects on the quality of patents. Such contradictory results imply that the theoretical focus on age and incumbency remains insufficient, and that other factors deserve attention. For example, while Ahuja and Lampert (2001) control for age and size, they demonstrate how breakthroughs become more likely if a firm works with new and unexplored technologies.

This theoretical and empirical confusion has many causes. Most importantly, the bulk of the literature on organizations and radical technological change includes many phenomena that do not address the actual creation of technological novelty, let alone breakthroughs. Examples of this work include responses to breakthroughs invented elsewhere (Cooper and Schendel, 1976), adoption of external and already invented technology (Rogers, 1983), and successful commercialization following a breakthrough (Tushman and Anderson, 1986). With the exception of careful historical analysis of the actual generation of inventions (e.g. Usher, 1954; Bijker, 1987; Basalla, 1988; Vincenti, 1990), most of the research on technological change has considered issues that occur subsequent to the act of creation (Rosenberg, 1982; Rogers, 1983). This is an important distinction, however, for, as Schumpeter argued, 'the making of the invention and the carrying out of the corresponding innovation are, economically and sociologically, two entirely different things' (Schumpeter, 1939: 85).

Paradigmatic assumptions of the nature of technological change have also precluded investigation into breakthrough inventions. In particular, many scholars argue that radical technological change is discontinuous with previous technologies (Constant, 1980; Ayres, 1988; Mokyr, 1990). Taken to an extreme, however, discontinuous views deny the value of careful historical analysis 'because the emergence of novelty is treated as inexplicable' (Usher, 1954: 60). Such assumptions also preclude any efforts to understand the organizational sources of breakthrough invention. An intermediate view acknowledges that technological change varies in its pace, but that the causes of such variation can be studied (Basalla, 1988). For example, theories of punctuated equilibrium (Tushman and Anderson, 1986; Bak and Chen, 1991) imply that large events are far less likely to occur than small events, but that both types of events are driven by consistent processes. The study of a phenomenon should ideally not be limited by paradigmatic assumptions. In addition, few researchers have identified their underlying assumptions or definitions of invention, or built upon an explicit model of the creation of technological novelty. Theory has remained weak and untestable as a result.

Purely methodological issues have also obstructed progress, mainly because breakthroughs are extremely rare events. Focusing attention purely on the actual breakthrough creates a severe selection bias. Fortunately, however (from a research standpoint), invention is a process and not a single event. Induction from an extended case history can consider the many failed trials as well as the few small successes and even fewer major breakthroughs. Consideration of the multiple inventive episodes also increases the number of observations and quality of the resultant theory. Hypothesis testing also remains a challenge, because breakthroughs remain hard to define and quantify (Ahuja and Lampert, 2001). Furthermore, most statistical tools of inference consider only the mean effect, and many methodologies encourage investigation and elimination of outliers. Dropping the outliers of inventive distributions means dropping the most important and rare data—indeed, it means dropping the outcome of interest.

Keeping these criticisms in mind, this paper will induct explanations for the organizational influences on breakthrough invention, based on a detailed history of Hewlett-Packard's (HP's) invention of the thermal ink-jet.[1,2] The thermal ink-jet constitutes a breakthrough technology by many measures (*Wall Street Journal*, 1999). It has been the basis of an important peripheral component in the diffusion of computing technology, the inexpensive and personal desktop printer. The invention also satisfies wider definitions of impact (Tushman and Anderson, 1986). It has succeeded in providing personal printing at pennies a sheet in a manner that is fundamentally different from previous impact, thermal, laser and even continuous ink-jet technologies. In so doing, thermal ink-jet technology has also upset the dominance of previous firms and structure of the printing industry. Finally, it has been applied in

[1]Ichiro Endo of Canon Inc. also invented thermal ink-jet printing, independently and earlier than HP's efforts [*Hewlett-Packard Journal* (hereafter *HPJ*), March 1984]. The two companies became aware of the other's efforts in September of 1981 and began cooperating in 1983. The HP engineers whom I interviewed maintained that the cooperation had little effect on the early inventive efforts described here. Canon's experience does not contradict the arguments developed in this paper (Robinson and Stern, 1997).

[2]I developed this history from archival sources and interviews. This particular story was part of a larger project on the history of printing technologies at HP. I presented inventors with a poster sheet of paper and a tape recorder, and asked structured, but open, questions. In addition, I worked as an engineer at HP from 1985 to 1995. This experience enables me to add personal insight to the story, but at the same time, probably made me less critical and aware of the socialization processes that I underwent myself.

many new technological contexts, such as optical switches, DNA micro-arrays and organic solar-cell manufacturing (*The Economist*, 2002).

In order to provide a consistent and explicit paradigmatic basis for theory building, I will interpret HP's experiences as an evolutionary and recombinant search process (Nelson and Winter, 1982; Fleming, 2001; Simonton, 2002). The recombinant view begins with the classic definition that inventions are either novel combinations of physical components (Smith, 1776: 10; Schumpeter, 1939: 88; Usher, 1954; Basalla, 1988) or rearrangements of previously tried combinations (Henderson and Clark, 1990; Baldwin and Clark, 2000). There are no limits to recombination; inventors can attempt combinations of any components within their purview. Inventors remain severely bounded, however, by limitations in cognition (March and Simon, 1958) and technological foresight (Vincenti, 1990), with the result that invention is usually a local and stochastic process. There may be ways to limit or manage the uncertainty associated with recombinant search (Rivkin, 2000; Gavetti and Levinthal, 2000), but there is no way to eliminate it (Dosi and Egidi, 1991). The parameters of the distribution may be influenced, but recombinant search remains a stochastic process.

Two themes emerge from the case study. First, HP's technological diversity and organizational processes enabled it to quickly sample a huge technological space. Such mechanisms included social and technological mixing and juxtaposition, recycling of engineers, management by objective, and high numbers of high variance inventive trials. Exploring new technological space generally implies increased rates of failure, however. HP's organizational norms and processes helped it deal with this downside of exploration. Such mechanisms included strong socialization processes, deep understanding of the previously uncombined technological components, rapid prototyping based on previous experience with the components of invention, and the use and generation of scientific knowledge.

2. The technological and industrial context of HP's ink-jet breakthrough

Despite the firm's eventual technological and commercial success, HP was not a prominent firm in the printing markets of the late 1970s and early 1980s. Most market publications did not mention HP (*Graphic Communications Market Place*, 1978) while others indicated a small presence for the firm (*Digital Design*, 1980, 1981). HP has long put marks on paper, however. HP's original motivation to print came from their early success in electronic instrument and measurement products (Packard, 1995). In using their own products, HP engineers quickly tired of manually writing measurement readings. In order to record output from their Model 200T Frequency Oscillator, they built and introduced the model 560A Digital Recorder in 1957 (A. Bagley, personal interview).

HP's efforts continued across a bewildering array of technologies. The firm purchased outside firms (F. L. Moseley of San Diego, CA and Sanborn Company of Andover, MA) and initiated an electromechanical stylus[3] project in Palo Alto, CA in 1962 (R. Monnier, personal interview). The San Diego organization eventually developed the electromechanical stylus technology (*HPJ*, May 1973), X–Y plotters[4] (*HPJ*, December 1968, February, September and December 1969, September 1977) and thermal dot matrix print/plotters (*HPJ*, September 1978). Sanborn became HP's medical products division and subsequently developed hot stylus technology[5] (*HPJ*, February 1972). Other HP divisions developed a variety of technologies, including dot matrix thermal thin-film printers (*HPJ*, December 1972, May 1973, November 1976, June 1976, April 1978), impact printing[6] (*HPJ*, June 1976) and electrosensitive stylus[7] technologies (*HPJ*, October 1970) in Colorado, thermal printhead technology in Pennsylvania (*HPJ*, December 1974) and Oregon (*HPJ*, March and July 1980), and a full line of dot matrix impact printers and laser printers[8] with Canon technologies in Idaho (*HPJ*, November 1978, June 1982; D. Donald, personal interview). In total, the *HPJ* presented eleven different printer technologies in twenty-three issues between 1957 and 1982—and these represented only the commercialized technologies that the *HPJ* staff chose to highlight.

Although HP was pursuing a wide variety of printing technologies by the late 1970s, other firms invested efforts specifically in the primitive ink-jet technologies of the time. In 1962, Mark Naiman of Sperry Rand received a patent for a 'Sudden Steam Printer' (US Patent 3,179,042) that closely resembled the eventual breakthrough. The crucial difference was that HP's (and Canon's) invention used a smaller orifice to eject a single and more controllable droplet. Shortly thereafter, Lewis and Brown (US Patent 3,298,030) applied Kelvin's 1867 idea of using electrostatics[9] to form separate

[3]Ink stylus technologies run a stylus with an ink source over a strip of moving paper. Electromechanical stylus technologies control a conventional pen stylus with analog electronics and mechanical devices.

[4]Plotters use mechanical mechanisms and servo-motors to place and draw a pen across a page.

[5]A heated stylus passes over a blackened page with an over-coating of white wax. The heated stylus melts the white wax and exposes the blackened page underneath.

[6]Impact technologies act like a typewriter. They strike the page like a hammer through an inked ribbon.

[7]Electrosensitive stylus approaches use special layered paper and a metal stylus without ink. The top layer of the paper is white zinc oxide. Underneath the top layer is a layer of electrically conductive aluminum and then a layer of black non-conductive material. When a voltage is applied to the stylus, the current breaks through the zinc oxide, shorts out and vaporizes the aluminum, and exposes the black material beneath.

[8]Laser printing technologies use lasers to electrostatically charge a photo-conductive drum. The charged drum is then passed through dry particles of ink that have the opposite charge. The particles of ink then adhere to desired sections of the drum. They are then transferred and fixed to paper.

[9]Electrostatic control works by individually charging each ink droplet in a stream of droplets and then deflecting individual droplets with a changing electric field.

characters (Robinson and Stern, 1997). As a constant stream of drops exited a piezo-electric[10] drop driver, they either charged and deflected a drop to a page or caught it uncharged in a gutter.[11] IBM devoted the entire January 1977 issue of their journal to a description of their 46/40 drop driver product (Buehner *et al.*, 1977). In contrast to *HPJ* articles that focused on products, however, the IBM journal articles focused more on science and followed the conventions of scientific publication (indeed, the IBM journal is listed in the scientific index, while the *HPJ* is not). Also in contrast to HP's initial efforts in Palo Alto, IBM split the locations of product development (staffed by engineers) in Lexington, KY and research (including Ph.D.s in mathematics and physics) in Endicott, NY and Boulder, CO.

All of these ink-jet products failed commercially due to their complexity and attendant poor performance. The technologies remained sensitive to ink composition, atmospheric humidity and paper texture. Inventors and their firms persisted, however.[12] While not well known for their printer products, HP's inventors had a wealth of (often failed) experience across a wide variety of technologies and markets. Its inventive efforts not only included conventional printing technologies but also encompassed technologies that were not commonly associated with printing, such as semiconductor design and manufacturing techniques. The firm had great technological and inventive potential, but remained relatively unsuccessful in the commercialization of its products; as a result, its managers had little reason to avoid exploration of new technologies and products out of fear of cannibalizing their existing market share. HP certainly did not dominate the printer market, but it was far from being an 'outsider,' particularly in a technological sense, as some explanations of breakthroughs have argued (Schumpeter, 1939; Klein, 1977).

3. An odd couple: the wide-ranging empiricist and the narrow analyst

A college dropout in mechanical engineering, John Vaught had nonetheless worked quite successfully since 1963 as a technician and engineering associate[13] in a variety of

[10]Piezo-electric technologies take advantage of crystals, ceramics or plastics that bend in response to electric current. By positioning a piezo-electric on the wall of a short capillary tube, electric pulses applied to the crystal cause pressure changes. These pressure changes in turn eject ink out one of the tube ends.

[11]A messy affair at best.

[12]Indiro Endo had already discovered the use of a heat source placed further back in a capillary tube by this time. His discovery arose from a serendipitous combination of components that his laboratory had assembled in their quest for an ink-jet breakthrough. He basically observed ink squirting out a capillary tube (actually a syringe) when a soldering iron happened to touch the tube right behind the top (D. Donald, personal interview).

[13]An engineering associate does engineering level work without having completed a professional degree. HP promoted Vaught to full engineer in recognition of his outstanding contribution.

firms. His technical experience included infrared radiometers, mass spectrometers, electron spectroscopy, spectrophotometer, optical read-only memory and HP's 2680 laser scanning optics.

> [Vaught] was a self-taught engineer without a college degree . . . accustomed to working quite differently from those with academic training: he was an experimentalist who often began work in a new area without reading the patents or papers that would ground him in the relevant theory or practice. (Robinson and Stern, 1997: 161–162)

Vaught freely admits, 'I bore easily' (J. Vaught, personal interview). He liked HP, however. 'HP Labs was a wonderful place: I had to work in a single field for only two or three years and then like magic it was a whole new field; a paradise for creativity' (J. Vaught, personal mimeo).

Vaught's partner provides a study in contrasts. Dave Donald earned a Bachelor's degree in physics in Wooster, OH and Bachelor's and Master's degrees in electrical engineering at MIT. He joined Xerox in 1965 and worked on dry printing engines.[14] In 1972 he moved to Smith Corona Marchant to work on dry engines. He moved to HP in 1975 to work on HP's first laser printer, the 2680 (another dry engine technology). At the time of their ink-jet invention, Donald had only a limited awareness of previous ink-jet technologies. Where Vaught had a tendency to take things 'very far, very fast' (J. Meyer, personal interview), Donald was the consummate engineer: methodical, informed and very aware of details. Judged by their invention of the prototype ink-jet, the juxtaposition of skills and personalities proved to be fruitful. Vaught provided the creative and rapid variation, while Donald provided the discipline and careful attention needed to learn from and document the variation.

Vaught and Donald had both worked on Boise division's adoption of Canon laser printing technology, the 2680 line printer (this large computer-room product preceded HP's success in the smaller desktop versions). Back in Palo Alto they pursued electrostatic gravure[15] printing solutions without success for the better part of a year.

> The work that we did began in Boise in 1977. We worked in 1978 in Palo Alto attempting to get engines, alternate engines to the dry engine of the classic type . . .In December of 1978 both [Vaught and I] agreed that we had to throw something at the paper, that the previous, almost entire year, we had worked in a situation where we were using gravures and electrostatics and we concluded that we did not want the paper to cooperate; that the past nine months we had worked on something where the paper had to cooperate very, very carefully, and if the humidity was bad the paper wouldn't cooperate well and you'd be dead in the water. So that was a blind

[14]Dry printing engines use dry powdered toner, today most often with a laser. Ink-jet squirts wet ink.

[15]Gravure printing uses electric fields to pull ink from an array of tiny reservoirs onto a page of paper.

> alley that involved gravure and electrostatics. So John said, 'We gotta do heat', but I thought heat was old. Naiman's patent in 1965 was in fact heat, it really was old art.[16] (D. Donald, personal interview)

Vaught and Donald continued down blind alleys until the Christmas holiday of 1978. At HP, the morning of Christmas Eve is usually spent eating, bringing children in to meet co-workers and mostly socializing, and the afternoon is given as paid time off. It was on this morning in 1978 that a group of engineers gathered in a corridor at HP Labs and began dreaming about the ultimate printer. Their wish list included 2 kHz[17] droplet speed, the potential for color and a page-wide array of nozzles (J. Vaught, personal mimeo). Vaught recalls the stream of inventive episodes that followed when he returned in January of 1979:

> My first thoughts for a design were quite conventional, a Kynar PT[18] on top of long channels. But before the parts got out of the shop I conceived of a pair of electrodes using the ink between them as a resistor to vaporize a small portion of ink very near the end of the tube thereby ejecting a droplet. We built such a device and Dave provided the electronics to drive it. It failed because we couldn't get the resistivity of the ink low enough to produce enough heat and it also produced hydrogen and oxygen at the electrodes.[19] New idea! Let's produce a small spark between the electrodes and ignite the bubbles to eject the drop. It worked! One small problem, we couldn't produce the explosive mixture of gasses rapidly enough to meet the 2 kHz vision. Oh well, let's just put all the energy required for vaporization in the spark and forget about hydrogen/oxygen explosions. It worked! About this time we got permission to turn the gravure printing investigation into an ink-jet investigation. Finally, we were out from under the table. Dave and I life tested this version and got two days operation at 2 kHz before it failed which was not nearly long enough. Electrode erosion was the culprit. Then came the idea of a small resistor on the inner wall of the capillary to provide the energy necessary for vaporization. All this time Dave is strongly urging me to enter all these ideas in my lab notebook; what a waste of time I argued. (J. Vaught, personal mimeo)

The erosion of the electrodes prompted the realization that they needed some other way to heat the ink (J. Vaught, personal interview). Donald recalls, 'We talked about

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[16]Donald was not aware of Naiman's technology or patent at that time.

[17]2 kHz equals a rate of 2000 times per second.

[18]A Kynar PT is a piece of polytetraflouroethylene plastic that functions as a piezo-electric driver.

[19]Howard Taub reports that they added salt to reduce the resistivity, and while that helped, they could not add enough salt to make it work (H. Taub, personal interview). Naiman also mentions adding salt in his patent.

explosives, having the ink explode, having chemical explosions, Olivetti actually did it, they didn't come to market, but they did it' (D. Donald, personal interview). Vaught also considered lasers before hitting on the idea of using a thin-film resistor. The thin-film resistor on the side of a capillary tube proved to be the breakthrough combination. Indeed, Donald believed that the true difference between their version and Naiman's sudden steam printer was positioning the heat source further back from the orifice, such that the bubble never reached the orifice. Ironically, the resistor came from a cannibalized HP thermal printer (J. Vaught, personal interview). HP folklore attributed Vaught's seminal inspiration to the coffee percolator he kept on his desk (H. Taub, personal interview). Vaught talked about his cognitive processes of invention:

> You think of things that are totally unrelated . . . Inventors just don't go home and see it at that moment in time. It is something that has happened way back in time. Due to a lot of things. As near as I can recall the percolator [inspiration] . . . it wasn't [rising] bubbles, if you think about it, if you left the top off, it went poof, poof, poof and blew gobs of coffee all over the place. When it comes to the moment of truth, you think about a lot of things. (J. Vaught, personal interview)

The inventive euphoria faded at this point due to a lack of support and resources, mainly because it remained unclear how the device actually worked (J. Meyer, personal interview; Robinson and Stern, 1997). Vaught and Donald's manager felt that the market window of opportunity was too small and redirected the engineers' efforts. Vaught continued to sell his invention, however, to anyone who would listen (M. Mason, personal interview). While Donald transferred to another project, Vaught's enthusiasm eventually won resources for further work:

> Vaught carried the ball in selling the invention . . . After the inventor sees it, the inventor says to heck with it, the management doesn't care, and walks away as I did, or he says I don't care I'm gonna push these guys anyway, and they can't do anything cause I'm at the bottom of the totem pole,[20] and they can't push me any lower. And then he gained the help of a guy named Larry LaBarre, who was known on a first name basis by the top people in the corporation, Hewlett and Packard and also Barney Oliver, the three men who really determined what went on. They knew John's enthusiasm as conveyed by Larry LaBarre. That sense of mutual trust then got transmitted to the very top of the corporation, completely around the guys who managed the project. (D. Donald, personal interview)

[20]Vaught's official title at the time of the invention was 'Associate Member of Technical Staff', a position intermediate between a technician and an engineer.

4. Explaining and prototyping the ink-jet: artisans, engineers and scientists

With Hewlett, Packard and Oliver's personal backing, the project now gathered many eclectic people trained in various crafts and engineering and scientific disciplines. For example, John Meyer (personal interview) brought a Ph.D. in physics and an undergraduate apprenticeship in photolithography. He recalls a great deal of informal communication: 'We were very much involved during this time, ideas were flowing freely back and forth, people were doing things in one area and other people working on different aspects of it, it wasn't compartmentalized. We had these regular meetings [within HP Labs] where progress was shared.'

Meyer also described how Vaught was able to very quickly explore a multitude of prototypes by working informally with his friends in the integrated circuit laboratory. Vaught would ask Harold Levy and Glenn Rankin to vapor deposit metallic glass ('metglass') upon a glass substrate. The metallic glass compounds, such as cobalt, nickel and tungsten, formed a resistive sheet on top of the inert glass substrate. Vaught would then etch away a narrow neck in the shape of an isthmus (Figure 1). By connecting a power source to both ends of the isthmus he could generate a great deal of heat from current crowding through the neck. Machine shop friends would then saw-cut a narrow groove within a second microscope slide. Vaught would lay this groove on top of and perpendicular to the isthmus on the first slide. This channel would hold ink right above the resistor, enabling a current pulse to vaporize bubbles in the ink channel. The bubble

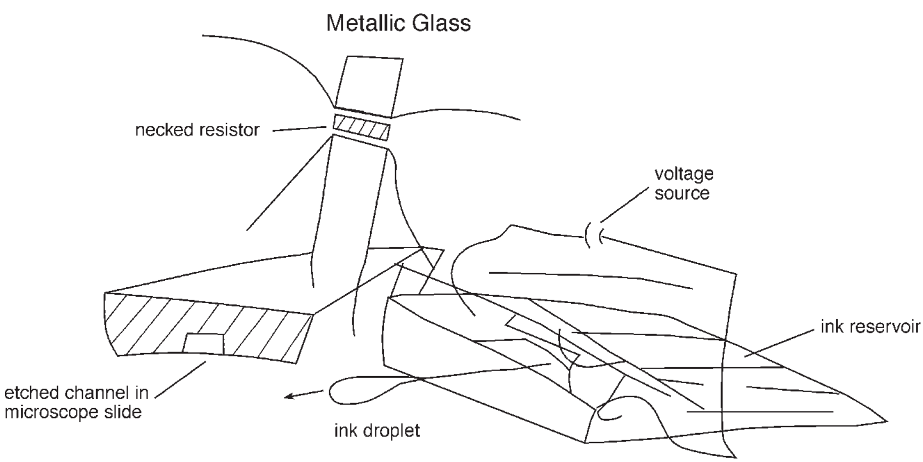

Figure 1 John Meyer's drawing of the metallic glass prototypes (J. Meyer, personal interview). John Vaught would first deposit metallic glass on the microscope slide and then etch it down to a necked resistor. He would then etch out a channel in another slide and fill it with ink. Finally, he would place the first slide above and perpendicular to the direction of the ink droplet. Ink drops would eject when he subjected the necked resistor to a voltage pulse.

first expanded but would quickly collapse as the heat dissipated. This bubble expansion and collapse acted like a piston and caused ink to spurt out the side.

Nobody could yet explain why this resistor and groove actually worked, however: 'Much of the development of the Think-jet technology involved understanding bubble formation' (Allen *et al.*, 1985). Everyone could see that bubbles caused the ink to eject, but it actually was not regular boiling. Meyer and his colleagues drew explanations from the very different technological context of casting and nuclear reactors:

> It wasn't clear at an elementary level how it actually worked . . . [It's] not a boiling phenomenon, it's a transient nucleation and vaporization of ink . . . The pressures are hundreds of atmospheres. Came across this first of all in metal casting where people accidentally dropped liquid metal into water and there you have a metal surface which was immaculately smooth so there were no cracks or fissures or anything to form nucleation sites. It would literally explode because the surface of the water in contact with the liquid metal would go right up through to the superheated[21] limit of the water and have this explosive vaporization and it would spew liquid metal all over the place and have a nasty accident. (J. Meyer, personal interview)

In order to understand the problem, Ross Allen, Bill Knight and John Meyer developed a model of bubble nucleation with inputs from many sources. They exhaustively recorded ink temperature and ejection as a function of the electrical pulse and pulse-shape through the resistor. They developed simulations of ink fluid flow within the nozzle (Figure 2) and these simulations in turn demanded original numerical techniques to accurately model the phenomena (Allen *et al.*, 1985). HP Labs' director Barney Oliver suggested that they talk with high-temperature physicists at Cal Tech (Robinson and Stern, 1997), so they read Cal Tech Professor Plesset's explanations of 'micro-jets' and other scientific literatures. These efforts and Meyer's serendipitous perusal of a Russian physics article on superheating inspired the final combination of very high resistance, a preheat pulse and then a sharp trigger pulse.

Further progress required better reliability, because the constant bubble collapsing eroded the electrodes. These problems motivated widespread exploration of resistor materials and configurations. The goal was a resistor which stood up to the cavitation damage, generated a great deal of heat very quickly, worked reliably over the lifetime of the product and used a low-voltage power supply so that manufacturing would be easier. Howard Taub, a physics Ph.D., worked with different materials, including silicon oxide, tantalum, tungsten and tungsten carbide, and performed thermal modeling to understand how thick the layers should be. The resistor layout took on the appearance of a large sandwich stack. Because there was no published literature that pertained to the problem, Taub adopted a careful empirical approach instead: 'It was a long road to solving the problem. We tried different things, geometry and layers . . . fluid change,

[21]Superheating occurs when a substance remains liquid while above its boiling point.

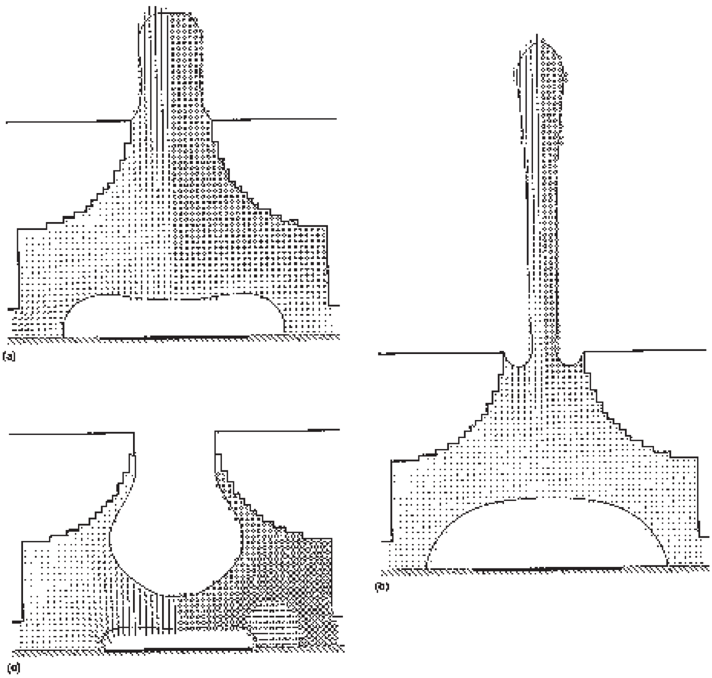

Figure 2 Simulation plots of ink droplet ejection (reprinted by permission from *HPJ*, May 1985: 26). The upper left illustrates 5 μs after bubble formation and the right illustrates 15 μs after formation. The ink droplet is about to separate in the right illustration. The lower left illustrates the bubble collapse that was to cause the cavitation difficulties.

fluid mixtures. We were wrestling with all these different things' (H. Taub, personal interview).

5. Transferring and manufacturing the ink-jet

Even before Taub finished, management directed that a line division pick up the technology for commercialization. Laboratory personnel began transferring the technology to a thin-film manufacturing division in Corvallis, OR. Niels Nielsen and his Corvallis engineers quickly built their own prototype printhead from a variety of locally available components that

> . . . featured an orifice plate made from a piece of thin brass shim stock in which a single orifice was punched by hand, using a sewing needle borrowed from an engineer's wife. This orifice plate was aligned by hand over a conventional thermal printhead substrate and fastened in place with a thin sheet of solid epoxy preform adhesive, which also served to define the gap between the substrate and the orifice plate. (Nielsen, 1985)

Nielsen's engineers dropped their prototype printhead assemblies (Figure 3) into

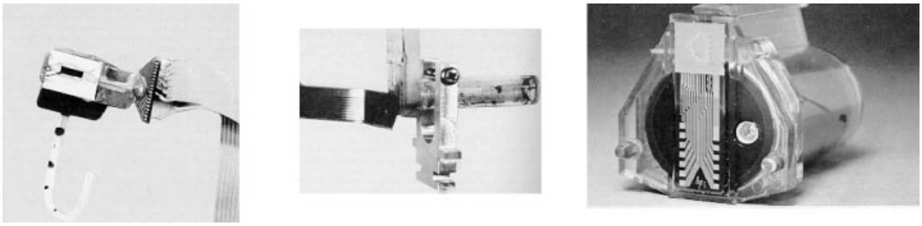

Figure 3 From left to right, the first seven-orifice Corvallis prototype; the first prototype placed within an existing HP printer; and the HP Model 2225 Printer thermal ink-jet printhead (reprinted with permission from *HPJ*, May 1985: 5, 6 and 10).

existing thermal printers and quickly demonstrated the ability to print characters. HP's semiconductor expertise and fabrication facility in Oregon also proved themselves invaluable: 'We had a pathway, we leveraged all of our silicon processing capabilities' (H. Taub, personal interview). Work continued until a potential showstopper emerged only 2 months prior to product announcement. With the shrinking of the printhead size and denser packing of the resistors and jet orifices, the vaporization dynamics between orifices became interdependent. Firing one orifice would cause proximal orifices to eject ink and dribble. Previous solutions in the industry included longer individual ink tubes between the central reservoir and each orifice. Such tubes introduced inertia into the ink flow, however, and slowed refill and firing rates.

The electronics background of HP's engineers inspired an electrical engineering analogy that solved the problem. The hydraulic problem between orifices is similar to cross-talk problems in an electrical circuit with multiple components. The printing industry's previous and conventional solution of longer individual tubes was analogous to electronic solutions of series inductors between each component. Instead of using series inductors, however, electronics engineers prefer to solve the problem by placing shunt capacitors to ground between components.[22] Such capacitors can accommodate a brief surge of current demand for each element without disturbing other elements. Analogous to individual shunt capacitors connected to ground, each printhead orifice included a small individual reservoir connected directly to the outside atmosphere.

After all this effort, the original Think-jet product did not meet with universal commercial acclaim. Customers wanted 'better print quality, a variety of typefaces, and the ability to print on paper [sheets as opposed to feed-form computer paper]' (Packard, 1995: 118). The follow-on project, named Maverick, also failed because it was too expensive. It was not until 1990 that HP was able to begin cutting the price, eventually to $99.99 by 1999 (with full color and 600 dots per inch). It was not until a decade later

[22]Capacitors store up electrical charge. They quickly discharge such stored energy as current when the voltage across them changes. If they are placed in between components, they can de-couple the effects of the components' transitory power demands upon the larger circuit.

and countless additional failed trials that Vaught and Donald's original invention became a successful innovation.[23]

6. Organizational influences upon recombinant search: generating variance

HP's experiences highlight how invention is a difficult and cumulative effort that generally fails. I will interpret the firm's efforts as a repeated and continuous process of recombinant search. Each new combination or rearrangement of components constitutes an invention, regardless of the strangeness of the combination or its success. While any assumptions and paradigmatic lenses distort reality, they also highlight particular aspects of a phenomenon. A recombinant view highlights the components that were available to the inventors, the processes that generated new combinations and selected particular combinations for further search, and the organizational influences on both. I will first focus upon the processes that enabled HP to generate a large number of new combinations. HP's inventors also increased the variance and positive skew of their inventive distribution by bringing together a wide variety of previously uncombined components. HP accomplished this with the juxtaposition of diverse technologies and professional experiences, and various mechanisms, such as physical collocation, the encouragement of informal social networks, the recycling of engineers across disciplines and management by objective.

On a purely technological level, recombination from a wider variety of technologies increases the possibility that a previously untried combination will be attempted. This follows because the potential combinatoric space is greater, and decreases the chance that a particular combination has already been tried. All else being equal, inventors from firms that encompass greater technological diversity are more likely to put together a previously untried combination. For example, Vaught and Donald considered and built numerous combinations of inks, resistors, slides, electrodes, explosives, lasers and piezo-electrics. Taub searched many landscapes with his different combinations and configurations of materials and fluid mixtures in an attempt to solve the cavitation problems. It is less likely that the engineers from a purely mechanical or purely electrical engineering firm would have thought of or built such crazy combinations, simply because they would have lacked access to or inspiration from such a wide variety of readily available components. Locally available manufacturing tools and process expertise also contribute to diversity in technological components. For example, Vaught relied heavily on friends in semiconductor manufacturing and the machine shop to fabricate his devices. This would have been much more difficult without the collocation of printing, mechanical design and integrated circuit fabrication facilities. Finally, the sheer physical availability and proximity of diverse components increases the possibility

[23]Space limitations prevent discussion of HP's innovation and marketing of the ink-jet. I refer the reader to Robinson and Stern (1997).

that they will be combined in a new way, as Endiro's serendipitous invention of the ink-jet at Canon demonstrates. Such luck is less likely in technologically focused organizations.

Diverse contexts will also promote analogies and technological brokering (Hargadon and Sutton, 1997), problem redefinitions and divergent thinking. Diversity enables engineers to generate and trade analogies from disparate fields, as the percolator and metal casting anecdotes illustrate. As another example, the cross-talk problem might have been solved electrically by reducing the rate of firing. Instead, it was solved hydraulically by adding a small cavity near the firing orifice. Professional training also matters—technicians possess a different skill set from engineers and scientists, and will redefine the problem in a new and potentially productive way. Socio-psychological research supports these arguments: Nemeth (1986) demonstrated that exposure to a diversity of opinions encourages divergent thinking and generates more creative solutions. Every day of coping with diversity encouraged evaluation from differing viewpoints, with the result that recombinant potential was not prematurely rejected. Vaught's refusal to accept that 'heat was old' illustrates this.

Firms will also benefit from consciously and constantly mixing and juxtaposing their technologies. This will increase the chances that their inventors will synthesize a new combination. From a strategic viewpoint, firms should create such 'technological turbulence' in order to maximize the variance of their inventive draws. HP's organizational norms and practices actively supported such juxtaposition and turbulence. For example, rather than hire and fire as business needs dictated, HP recycled its engineers with its lifetime employment policy.[24] Managers actively relocated and redistributed inventors from completed or canceled projects throughout the company. As Vaught said, 'I had to work in a single field for only two or three years and then like magic it was a whole new field; a paradise for creativity' (J. Vaught, personal mimeo). This recycling aided breakthroughs in three ways. First, it mixed inventors from different backgrounds together and hence increased the possibility of a fortuitous meeting. Secondly, it minimized the costs of transfer between divisions. Shared and informal norms of interaction enabled engineers to shorten their period of socialization and psychological safety building (Edmondson, 1999), and to become productive sooner. Previously socialized engineers could also access technologically unfamiliar but similarly organized resources more quickly. Finally, recycled engineers facilitated the accretion of dense, rich and interconnected social networks. A recycled engineer provided a bridge between the technologies, expertise, friendships and reputations of his or her old and new divisions. Such dense networks also aided the development and retention of gatekeepers (Allen, 1977), because an inventor's reputation became known beyond his or her immediate division. Dense, informal networks and strongly embedded gatekeepers increased the effective flow of information and recombinant potential of the organization.

[24]HP has always maintained that lifetime employment is dependent on business conditions.

Geographical proximity also encouraged the juxtaposition of previously uncombined technologies. Although HP spread its divisions out amongst many geographical locations, it maintained its central research laboratory in a relatively small Palo Alto campus. Simple physical proximity increased the probability of unplanned meetings and non-professional friendships in cafeterias and at Christmas parties or softball games. Such friendships and the close availability of diverse resources greatly aid wide recombinant search, as argued above with Vaught's reliance on his friends in the fab. These observations imply that technologically diverse organizations will increase the exploration and variability of their inventive draws if they are physically proximate. These observations also apply to the opening controversy of this paper, given that firm size and diversity will probably correlate. The benefits of size and diversity will be increased if engineers with different technological experiences are co-located and encouraged to interact.

These arguments for the benefit of diversity can also be motivated through the lens of institutional theory and the social construction of technology (Bijker, 1987). These theories imply that firms perceived as technologically 'diverse' are simply those that encompass previously untried combinations of technologies. For example, prior to the invention of the ink-jet in the 1980s, it would have seemed unlikely that an assemblage of resistors, ink and semiconductor manufacturing techniques would have disrupted the printing industry. Today, however, it is taken for granted that low-end printing firms (and even instant photography firms; see Tripsas and Gavetti, 2002) encompass and refine such technologies. Such focused firms are more likely to develop technologies that work because they are refining within a technological space that has been previously proven to be fertile. They are less likely, however, to invent a radical breakthrough, because they are generating combinations that are similar to previously successful combinations.

HP's Management by Objective (MBO) policy also supported recombinant search by increasing motivation and freedom—and also by enforcing discipline on the inventors. Management practices MBO by articulating a broad goal (e.g. invent useful technologies that you or other inventors can turn into products) and allowing employees broad latitude in its attainment. MBO provides inventors with intrinsic motivation and control of their work, which Amabile *et al.* (1994) have shown to result in greater creativity. More importantly, MBO institutionalizes a productive tension between inventors' dreams and fiscal reality. MBO gives inventors large but not complete control of the decision about when to abandon the pursuit of a particularly risky line of invention. Such shared judgement is absolutely crucial, because inventors and their managers must balance the generation of new possibilities against the need to fully characterize, learn about and commercialize previously uncovered opportunities (March, 1995). For example, Vaught and Donald had the luxury of unstructured work time when they ignored their management and continued to work on the ink-jet. Their success also depended greatly on their friends' unstructured time and willingness to help. Such time and willingness would be less likely in a firm with a highly structured and closely managed environment. On the other hand, management hastened the transfer of the project to a manufacturing division before the technology had been perfected. This forced convergence upon the variation generation process. And while it is easy in hindsight to fault the manager that ended the project prematurely, he was simply playing his institutional role of balancing the inventors' personal enthusiasm against the opportunity costs of foregoing other approaches. MBO provides productive tension in recombinant search; it creates variance, by giving inventors resources and latitude to search; but it also exploits that variance, by demanding refinement, learning and convergence upon a workable set of technologies.

7. Organizational influences upon recombinant search: exploiting variance

The downside of exploring entirely new combinations is that the success rate will be more uncertain and poorer on average (Fleming, 2001). The ink-jet inventors invariably described a difficult process of failure, interspersed with occasional and usually partial success. Historians concur with this observation: 'Quite simply, the vast majority of attempts at innovation fail' (Rosenberg, 1996). Vaught and Donald spent a year before 'concluding that we did not want the paper to cooperate'. Taub documented countless combinations before solving the cavitation problem. If all these trials were considered together, they would be quite unsuccessful on average. Trying new combinations and generating variance therefore remains a necessary but insufficient condition for firms that desire breakthroughs. Assuming that a firm has the slack resources to sustain exploration (and HP had ample slack resources during the period of study), it must manage the downsides of exploration and persist through repeated failure. HP accomplished this with strong socialization and integration norms, rigorous selection processes for common language and communication skills, deep experience with the constituent technologies of recombination, rapid prototyping and testing, and the application and generation of scientific knowledge.

Technological diversity appears to have enabled HP to quickly sample many technological landscapes, albeit at the expense of many failures. This interpretation is consistent with research in social psychology that has demonstrated a variety of—often negative—relationships between diversity and performance (Williams and O'Reilly, 1998). The passage of time and socialization, however, can ameliorate many of the dysfunctional aspects of diversity. Inventors coming together from diverse backgrounds need time to work out dysfunctional group dynamics and differing functional views of the world (Dougherty, 1992). They need to first understand how to communicate. For example, the electrical engineer needs to explain to the mechanical engineer how to read an electronics schematic. More importantly, they need to build their psychological safety (Edmondson, 1999) and gain each other's respect and trust. This is especially crucial because breakthrough invention requires personal and professional risk. It requires inventors to propose radically new combinations—most of which are likely to fail. Vaught and Donald respected each other enough personally to propose and counter-propose a gamut of strange possibilities, including lasers, explosives and, eventually, a laughably mundane thin-film resistor inside a capillary tube. Finally, if all these social integration efforts fail, time allows uncomfortable inventors to leave, such that the remaining group members are more productive. These arguments imply that recently introduced inventors will be less likely to immediately invent breakthroughs: they will need time and strong socialization norms before they become productive.

To further support these processes of social integration, HP minimized other types of diversity. Hiring processes required rigorous assessments of candidates, such that an inventor could trust his or her colleagues to be relatively competent technically.[25] While HP attempted to maximize gender and racial diversity, it also selected employees for their communication skills. English was the universal and well-understood language at the HP Labs and the US divisions, such that language was not a barrier to creative communication. This attention to the selection processes further supported the development of psychological safety, which 'stems from mutual respect and trust among team members' (Edmondson, 1999).

In addition to gaining respect for one another and learning how to work together, inventors need time to learn about the diverse resources that are available within their organization's social network. They also need time to develop personal relationships throughout this network so that they can apply resources. Without such personal networks it would have been difficult for the developers to quickly access the disparate experience and knowledge that enabled wide-ranging recombinant search. This access enabled HP's engineers to avoid inventing everything from scratch; instead they borrowed and integrated well-established knowledge and components. For example, rather than build a new printer to house the prototype printhead, Corvallis engineers quickly kludged the head into an existing HP thermal dot matrix printer. Such opportunistic borrowing and re-use enabled rapid prototyping and testing of new and unpredictable combinations. Given that the specific prototyping needs to support wide-ranging recombinant search cannot be predicted, such rapid iterations would not have occurred without deep knowledge of many available building blocks and the social network to access them. Firms whose engineers lack such deep knowledge and networks would be less likely to come up with a breakthrough, because they could not quickly explore and test unforeseen opportunities.

Unfortunately, the benefits of the passage of time are temporary. Diversity is in many ways a dynamic demographic property based mainly on inventors' previous education and experiences (Simonton, 2002). Because inventors within an organization share

[25]Before I was offered an engineering job fresh from my undergraduate degree, I underwent a campus screen, a 3 hour technical phone interview, and an 8:00 a.m. to 6:30 p.m. day of further technical interviews—followed by dinner with my prospective manager. I followed very similar procedures when I managed the hiring process. I cannot offer more than anecdotal evidence from my experience as a Silicon Valley engineer, but it was generally accepted that the better, more technical and more prestigious firms (such as IBM) provided more rigorous technical screens.

knowledge and accumulate similar experiences, the diversity within an organization will decrease over time if not renewed by outside learning, personnel movement (March, 1991), or the adoption and integration of outside technologies (von Hippel, 1988). If inventors are not prompted by outside learning or new colleagues, they are less likely to think of radically new combinations or novel rearrangements. They are less likely to import an analogy from another technological community or think of a new application of an existing technology in a new market. As Bijker (1987) described with Baekeland's invention of bakelite, inventors are more likely to create a breakthrough when they have only recently arrived at a problem. Vaught's example and philosophy certainly support this view.

These arguments imply that incumbency might not decrease a firm's ability to invent a breakthrough, as long as it can continuously juxtapose and recombine previously disparate personnel and technologies. The personnel and technologies need not necessarily come from outside the firm. If the firm is large and diverse enough, it will also do well to simply shuffle its technical workforce periodically. Such a strategy could help avoid competency traps (March, 1991), where the rational pursuit of refinement over risky exploration leads a firm down a garden path to obsolescence. Indeed, if inventors benefit from a deep knowledge of their components, then the most effective strategy would be for a firm to bring together previously separate experts. Utterback's (1996) argument and Fleming's evidence (2001) that breakthroughs come from recombination of well-understood technologies supports this strategy. Rather than worrying about externally caused technological obsolescence, firms might stay inventive by focusing on increasing the recombinant mixing and turbulence amongst their current set of inventors and technologies. This strategy becomes more viable as firms increase in size, because they can better avoid combinatoric exhaustion (Fleming, 2001; Simonton, 2002).

In addition to its experience, strong norms and common language, HP also dealt with the downside of exploration through the application and generation of scientific knowledge. The institutions of science benefited HP in two ways: they enabled the firm to draw from already published and externally available knowledge, and when that proved insufficient, to generate new knowledge. The first benefit arose from extra-corporate communication and the second from training in the scientific method. Even when employed by private firms, scientists are more likely to be members of an extra-corporate community (Price, 1986). Membership of such a community can provide inter-personal knowledge of active centers of research, as Barney Oliver's referral to Cal Tech demonstrates. It also provides awareness of the extant literature, as John Meyer's Russian literature insight demonstrates. Such connectedness to the outside community increases the possibility that a firm will invent a technological breakthrough for two reasons. As with the ink-jet, inventors can access knowledge that helps explain their empirically generated opportunities (Gibbons and Johnston, 1974). And while the above narrative does not provide an example, external scientific breakthroughs can also motivate particular recombinant search, as demonstrated by efforts in drug discovery to use an understanding of a disease mechanism to winnow the recombinant space (Drews, 2000).[26]

In addition to enabling a firm to recognize and apply external knowledge (Cohen and Levinthal, 1990), scientific capability also enables a firm to generate internal knowledge. Training in science and its methods improves an inventor's ability to design and learn from experiments. Taub's exhaustive search of the resistor configurations and materials provides a pertinent example. Even though he never understood the underlying phenomena completely, he was able through careful experimentation to reduce the technology to practice. His approach bears much similarity to other engineering technologies that have succeeded without a complete scientific understanding. For example, airplanes fly (even today) without a complete theory of turbulence (Mowery and Rosenberg, 1997) and semiconductors were first usefully applied in the crystal radios of the late nineteenth century, long before Shockley offered his explanation of carrier injection (Gibbons and Johnson, 1970).

Applying external knowledge and generating internal knowledge also decreases the variability of a firm's inventive draws. Scientific knowledge provides inventors with a better understanding of the fundamental interdependencies that cause rugged technological landscapes (Fleming and Sorensen, 2002). This understanding provides them with a map of the terrain. Instead of iterating blindly across a rugged and interdependent landscape, inventors can proceed more directly to the locations of optimal configurations. Doing science also decreases variability because it encourages more rigorous search and selection criteria. Andrew Carnegie recognized the advantage of scientific knowledge and the employment of chemists when he commented that 'Nine-tenths of all the uncertainties of pig iron making were dispelled under the burning sun of chemical knowledge' (Rosenberg, 1985).

Science did not inspire Vaught's and Endiro's inventions, however. Furthermore, IBM failed to discover the breakthrough combination, even though it invested heavily in basic research and employed numerous Ph.D.s in mathematics and physics. These examples remind us that the pursuit of science and invention of technology are highly interdependent but distinct activities (Price, 1966; Kranzberg, 1968). The technologist's goal is to create a useful tool, independent of whether she understands the intricate nuances of its functionality. The scientist's goal, on the other hand, is to publish a complete and correct explanation of some phenomenon. The scientist's goal becomes more obtainable with greater focus on a more limited problem. This same focus decreases the range of explanation or technological application, however, such that a

[26]Although the ink-jet story does not provide a convenient example, connectedness also enables a firm to appropriate domain specific progress that has occurred outside of the firm (i.e. knowledge that particular combinations work). In contrast to more discipline-based scientific knowledge that aids the firm's internal search processes, exploiting domain-specific spillovers enables a firm to directly capitalize on other firms' progress. This may not always be a positive influence, because firms may also learn from others' mistakes (for example, Donald's assertion that heat had been tried previously), be misled by strategic misinformation or lose their own proprietary knowledge (for examples of all three, see Lim, 2000).

greater orientation towards science—or at least the norm of publication—might well retard the possibility of a technological breakthrough.

The temporary cancellation of the ink-jet also demonstrates how highly HP engineers and managers (who had been the best engineers before being promoted) valued rational and analytic explanation. In many ways, they acted like the frustrated scientists described by Noble in his description of the development of the engineering profession (Noble, 1977; see also Kranzberg, 1968).[27] Such hyper-rationality, while it generally results in better decisions, can be taken too far—as it almost was with the ink-jet. Breakthrough technologies do not need to be explained in order to have huge impact. Other examples of important technologies that were not completely explained before their successful application include aniline dyes, concrete, steel and food preservation through canning (Rosenberg, 1985).

While technological diversity and the application of science have independent effects on the possibility of breakthroughs, HP's experience suggests a powerful interaction effect. The ink-jet would not have succeeded without Vaught's exuberant exploration *and* his colleagues' scientific bent. When an intuitive empiricist like John Vaught creates a breakthrough, a firm with scientists is more likely to be able to explain and develop it. Even though scientists may not have known which landscape to search at the outset (indeed, nobody could have known), a firm with scientists is more likely to succeed in reducing a difficult and interdependent invention to reliable practice. The argument resonates with historians of technology (see also Rosenberg, 1985):

> Experimental and theoretical research in both engineering and science are often most fruitful when done together—or at least in interactive proximity. (Vincenti, 1990: 232)

> '. . . industrial problems throw up observations which are unlikely to crop up in a university laboratory . . .' The fact is that industrial activity, especially but not only in high-tech sectors, provides unique observational platforms from which to observe unusual classes of natural phenomena. (Turney, 1991, quoting Rosenberg)

Diverse recombinant exploration and science each provide complementary but distinct tools in the pursuit of breakthroughs. When an invention obviously works but cannot be explained, scientific knowledge can provide insights that enable inventors to reduce the proto-seminal combination to practice. When extant scientific knowledge proves insufficient, the firm can perform its own investigation. Finally, if neither knowledge nor method enables success, technological diversity provides a fertile stockroom from which to restart the search process.

[27] One of my managers admitted as much. Even though he had Master's degrees in electrical engineering and business administration and managed a laboratory of almost 100 professionals, he was still most proud when he could do 'good physics'. I also worked for other managers who had worked with Vaught and dismissed his contribution as luck, mainly because he could not explain it.

8. Conclusion

Why did HP (and Canon) invent the ink-jet? Many other firms actively pursued the breakthrough, but HP was more likely to succeed for a variety of reasons. Despite its technological incumbency in a wide variety of printing technologies, HP had remained a niche player in printing markets. Its managers remained relatively open to breakthroughs because new technologies would not cannibalize existing sales. The firm eventually succeeded because its inventors had already engaged in wide, repeated and often failed recombinant search for many years prior to Vaught's seminal invention; HP increased its chances with a stochastic process by stacking the dice with variability and rolling repeatedly. In close conjunction with many draws from a highly skewed distribution, however, HP's norms and processes also encouraged learning and convergence. The interaction of these variation and selection processes enabled HP to understand its wild draws better, cull the less promising draws more quickly and eventually reduce a very difficult technology to practice.

While I have interpreted HP's experiences in electro-mechanical invention as a process of recombinant search, the idea can also be applied to the creation of novelty in other contexts (Nelson and Winter, 1982). Process invention can be interpreted as the recombinant search for useful production steps (Romer, 1993), and innovation can be interpreted as the recombination of technological inventions and applications or markets (Schumpeter, 1939). An entire Gordon Conference has recently been structured around recombinant search methods in materials science (Gordon, 2002). Pharmacology provides another pertinent example: 'Large numbers of hypothetical targets are incorporated into *in vitro* or cell-based assays and exposed to large number of compounds representing numerous variations on a few chemical themes' (Drews, 2000). Such strategies are more successful when the assays represent target diseases accurately and, as with HP's experience, when the results can be easily observed and rigorously tested. Large number strategies in pharmacology have been complimented by the addition of scientific knowledge about disease mechanisms and the recent publication of the human genome. While this knowledge greatly decreases the need for blind search, invention still results when a chemical or other intervention is combined with a physiological condition. Much pharmacological invention still occurs with intuitive experimentation by practitioners with old drugs and new disease targets, such as anti-inflammatories as a preventive for coronary failure (Taubes, 2002). While these anecdotes support the idea of recombinant search, inferences from a single case study must obviously remain limited until additional qualitative comparisons or large sample modeling can be completed. Fortunately, the recent availability of large sample patent databases (Hall *et al.*, 2001) and advances in econometrics (Cameron and Trivedi, 1998; Ahuja and Lampert, 2001) mean that technological breakthroughs need not remain completely unpredictable events.

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