



## The complex search process of invention

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### ABSTRACT

We inductively develop a process model of individual search in the context of technological invention, an important aspect of economic development that is also fundamental to the success of many organizations. Using an extensive archival content analysis of notable inventors we find that the search and discovery process of invention is inherently complex, non-linear, and disjointed. Successful inventors are skilled at managing these complex systems, receptive to feedback, and able to revisit and change course. Our search model includes a stimulus, net casting for information, categorizing that information, linking unrelated ideas, and discovery. Our findings articulate the search process as a complex progression through a series of simple stages. As such, the study contributes to our understanding of complexity and the complex systems view of the invention process.

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### 1. Introduction

The concept of search is fundamental to both organizational learning (e.g. Huber, 1991) and behavioral theories of the firm (Cyert and March, 1963). Among other things, individuals within a firm search for information and answers that will enable them to decide which actions to take (e.g. Derfus et al., 2008), close gaps between their actual and aspirational performance (e.g. Levinthal and March, 1981), and develop new innovations (e.g. Katila and Ahuja, 2002) and find new opportunities (Kornish and Ulrich, 2010). While we know a great deal about how organizations start, stop and allocate resources to search, our knowledge of individual search processes is limited. That is, what we do know about the topic is focused almost entirely at the organizational level of analysis. Thus, how individuals search for the ideas that they discover is not well-understood. By focusing on the search routines and the discovery process of inventors, this study bridges this research gap and provides a foundation for further empirical study of search processes in other contexts and levels of analysis.

Technological invention is an important element for economic development as well as the success of technology-based organizations. Thus, understanding the process through which individuals develop new technologies is central to organizational as well as to more macro-focused research. In particular, the processes through which individuals search for new technological inventions – that

is, look to the environment to improve current technology and products (Nelson and Winter, 1982: 210) – have drawn increasing interest in recent organization research. Drawing from behavioral theory and organizational learning perspectives, researchers have studied what triggers search (Greve, 2003; Greve and Taylor, 2000; Singh et al., 2010), what the optimal processes of search are (Grimpe and Sofka, 2009; Levinthal and March, 1981; He and Wong, 2004), and when searchers decide to stop searching (Cyert and March, 1963). The main findings of this research show that both problems and opportunities initiate search, and that search stops when a satisfactory result is discovered (Greve and Taylor, 2000). Researchers have also proposed that search proceeds in a problem-solving or hypothesis-testing fashion (Winter, 1984). At the same time, search is constrained by cognitive and physical limitations: cognitive frames (Gavetti and Levinthal, 2000) and limited resources (Helfat, 1994) often restrict search range to include only local environments.

In this study, we construct an inductive case-based model of the search and discovery process. Our focus is on the specific case of new technological inventions. To construct the model, we employ an archival content analysis of first person accounts of ten notable technology inventors. Using the insights from each inventor and triangulating across the inventors, eight common themes of the search and discovery process emerge. We structure and refine emerging themes analyzing and reanalyzing the data, looking for patterns, and organizing them (Eisenhardt, 1989). This iterative process leads to several important findings. We find that the search and discovery process of technological invention is inherently complex: nonlinear and disjointed rather than linear and cumulative. Moreover, the data show that successful inventors

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are skilled at managing such obscurity: they make complex systems simple by abstracting out the unnecessary and minor, and use negative feedback to start over and change course. Thus, they undertake a complex progression through a seemingly simple set of stages. Based on our findings, we develop theory and present a model of search that illustrates it as being comprised of underlying routines including casting for information and re-categorizing that information. Further, we also find that inventor's new ideas lie at the intersection of existing, yet seemingly disparate, landscapes that requires them to manage interdependencies and react to a complex system of continuously changing internal and external factors.

The study provides several contributions to search and complexity theories. First, we highlight the search process of individuals. Indeed, the traditional focus of research on the concept of search has been on the organization. Second, the study contributes to the complex systems view on invention at the individual level (Arthur, 2009). This represents a contribution to the complex systems literature both in terms of the context of invention and level of analysis. We highlight the skills of interpreting, managing, and utilizing feedback that inventors in our sample used during their search process. Finally, unlike extant conceptual models found in the literature, we present grounded theory and an empirically derived process model of individual search that can begin to enable researchers to examine more closely search processes, versus using distal proxies of search, of both individuals and organizations, such as patent search, R&D expenditures or number of scientists.

## 2. Literature review and research background

The concept of search has been examined in a number of academic disciplines. However, there has been a relative dearth of studies that seek to study the actual routines and the process of search. For example, economists have elicited mathematical models that illustrate the degree to which individuals search for jobs (Lipman and McCall, 1976) and new technologies (e.g. Jensen, 1982; Reinganum, 1982). Similarly, marketing researchers have used economic and mathematical models to examine consumers' search for low prices (e.g. Meyer, 1997; Miller, 1993). Marketing research has also examined the extent to which individuals will search before selecting consumer goods (e.g. Mitra et al., 1999; Stewart et al., 1989). In general, the findings in these areas focus on the rules individuals use to decide when additional search is necessary or not.

Organization theory research on the topic of search draws from a learning foundation (March and Simon, 1958). Thus, learning outcomes as a result of search behavior have been examined in a variety of contexts such as the selection of exchange partners (Rangan, 2000), acquisition performance (Katila and Ahuja, 2001), technological inventions (Fabrizio, 2009; Rosenkopf and Nerkar, 2001; He and Wong, 2004), and product competition (Greve and Taylor, 2000). Researchers in this area argue that firms search for information to generate potential alternatives in their quest to innovate (Rosenkopf and Nerkar, 2001), solve problems, and reduce organizational performance gaps (Huber, 1991; March, 1991). In his seminal paper, March (1991) argued that firms must balance their far reaching exploratory search with exploitative search, the latter of which more closely utilizes their current knowledge, in order to maximize their learning and the opportunities they discover from this learning (Gupta et al., 2006). Others have expanded on this notion to include a more varied set of locations or terrains (Rivkin and Siggelkow, 2007). For example, search can deviate in topography (Nelson and Winter, 1982), depth and scope (Katila and Ahuja, 2002) and in organizational and technological boundary spanning characteristics (Rosenkopf and Nerkar, 2001).

While research in the organizations literature has focused on the search terrain, search context, and the importance of search at the organizational level, there has been less attention to the actual search processes and the underlying routines that organizations or individual organization members use to search. One reason why it has been difficult to study individual search processes is that search oftentimes occurs over a long period of time, in the case of the search for new technological inventions this can mean a decade or more. As a consequence, existing individual level search process research generally falls into two categories: one claiming that search is illusory and needs no explanation and the other claiming that it is mysterious and permits no explanation (Schon, 1963).

In this study, we utilize an extensive historical content analysis of notable technology inventors to inductively develop theory about the search process and propose a model of search routines and processes at the level of the individual inventor. While there exists a conceptual literature on search process, we are unaware of other empirical attempts to inductively model the search process. Thus, in the discussion section, we compare our induced model of individual search to conceptual models of invention as well as related areas of creativity, decision-making, and problem solving. We identify common elements and important differences between our model of search and these conceptual models in an effort to further our understanding of the process of search used in the discovery of inventions.

## 3. Method

Because of the dearth of empirical efforts to model the search process, it was necessary to undertake a grounded, theory building approach. Thus, the methodology used in this study is a qualitative, inductive, archival, content analysis of historical first-person documents and quotations of ten notable inventors. According to Smith (2000), this type of approach allows categories (stages) to emerge from material without the influence of preconceptions. Throughout our study, we closely followed the guidelines for content-analytic research proposed by Smith (2000) and Eisenhardt (1989).

Content analysis is used to extract information from qualitative material. It can be performed in a variety of situations including when participants are aware they are being studied and also when they are not. It can also be used with both verbal or written materials and documents. The content material is analyzed systematically and objectively to identify the characteristics of interest (Smith, 2000). In this study, we analyzed historical documents in an attempt to elicit any recurring patterns of activity as it applies to the search and discovery process of invention. These patterns will be used to develop a model of the search process.

More specifically, we employed archival reading and content analysis of first person accounts of the invention process of ten notable inventors. In an effort to keep the data collection manageable yet ensure an appropriate level of first person documentation, we randomly selected ten of the inventors interviewed and quoted by Brown (1988) in his well-known book *Inventors at Work*. These individuals are: Marvin Camras (inventor of magnetic recording tape), Gordon Gould (inventor of the Laser), Wilson Greatbatch (inventor of the implantable pacemaker), Marcian E. "Ted" Hoff (inventor of the microprocessor), Raymond Kurzweil (inventor of the first commercial application of artificial intelligence, the piano/synthesizer), Paul MacCready (inventor of the Gossamer Condor, the first vehicle to fly on human power), Stanford Ovshinsky (inventor of Ovonic devices), Harold Rosen (inventor of the spin stabilized geo-synchronous satellite), Steve Wozniak (inventor of the first truly personal computer, the Apple II), and Nat Wyeth (inventor of the ubiquitous plastic soda bottle).

We performed an exhaustive library search on the ten inventors to ensure replication, completeness, and corroboration of our

data collection (Yin, 1984). In particular, we searched for all published material that included first-person documentation from each inventor regarding their process of search and discovery. In total, we identified and examined 155 such documents, an average of 15.5 per inventor in our study.

We focused on first-person documentation for two main reasons. First, we believed that non first-person accounts would not yield the type of language data that would capture the internal cognitive processes and subjective experience of each inventor that can be garnered from first-person accounts (Smith, 2000; Csikszentmihalyi, 1997). Second, non-first-person sources were eliminated in an effort to diminish the amount of bias that could be associated with a particular biographer's interpretation. Unfortunately, it may be impossible to completely eliminate the bias of editors and interviewers even in first-person accounts. However, this bias should be minimized in comparison to the problems associated with third person interpretation of the sample inventors' processes. Archival material not in the first person such as patent records was used to validate the first person.

Our inductive approach to modeling the search and discovery process involved a number of steps. First, the archival material pertaining to the ten inventors was reviewed and an individual case study was assembled for each inventor. While reviewing the material, a record of statements made by the inventors regarding the search and discovery process was kept. Quotations of similar themes and patterns, that were observed to replicate across inventors, were grouped into a table (Eisenhardt, 1989). We then compared and contrasted our data in an effort to reach a consensus on the themes uncovered during the archival analysis. In an effort to ensure that the themes we identified were repeated across inventors and not just idiosyncratic, we established an arbitrary decision rule to consider only those themes that were repeated and supported with quotations from at least six of the ten inventors. This data integration yielded eight themes pertaining to the search and discovery process.

In the next phase of the study, we assembled the data into tables to facilitate comparisons in an iterative pattern-matching fashion. Together, our team continued to revisit the data for clarification and accuracy (Brown and Eisenhardt, 1997). Through this method we split the data into two categories. The first category consisted of five themes that emerged to constitute a number of emergent stages or routines the inventors experienced or undertook during the search process. Using these stages, we initially arrived at a basic linear model of the search process (see Section 4.1).

We then began to closely analyze the remaining themes. In iterative fashion, and through our examination of the underlying data, we found that these themes had an influence on the stage of invention rather than being part of the process themselves. Thus, we were left with three themes that had an influencing impact on which stage of invention was occurring.

To summarize, through our analyses we identified eight themes pertaining to the search and discovery process. Five of the themes were determined to directly constitute stages the inventors went through during the search and discovery process. We labeled these stage themes. The remaining three themes appeared to influence the manner in which inventors progressed through the five routines or stages. We label them influencing themes, as a result (Table 1).

## 4. Results

### 4.1. Initial results

Our grounded methodology required us to ignore prior knowledge we had of conceptual process models of invention (Rossman, 1931) and related concepts such as creativity (Amabile, 1983, 1996;

Perkins, 1981) and decision-making (Bazerman, 2002). However, it is interesting to note that our initial results identified a straightforward linear process model reminiscent of this prior literature. For example, Nelson and Winter (1982): "There is a set of activities that may be used for finding out more about the technological and economic attributes of a technology or making a study" (p. 249). They label this process as a "search strategy" which essentially involves the process of updating information so as to make a discovery (see Fig. 1). Thus, while we undertook an inductive methodology, our findings had clear linkages to several literatures. In what follows, we present our grounded findings along with existing, related literatures in an effort to highlight those linkages and demonstrate how our study extends and contributes to this prior work.

Our initial model thus involves five linear and sequential steps. The first step in the process is *Stimulus*. Stimulus is the identification of a problem, opportunity or reverse salient (Hughes, 1978). In this step, the inventor realizes that a need exists. For example, when his cousin wanted to practice his singing, Marvin Camras thought, "it was a waste of good records to record something only for practice. You would make a record and probably listen to it once before you threw it out." This stimulated Camras to invent the magnetic recording head, the precursor to recording tape, videotape and floppy discs. The stimulus can be even simpler, however. For example, Harold Rosen's interest was piqued when, "in discussions with some of my colleagues here at Hughes that I first heard about the geostationary orbit." Others are stimulated by everyday occurrences in their lives. For example, Nat Wyeth observed problems in the manufacturing processes at the Du Pont plant in which he worked. Such problems were the stimulus for many of his inventions. Raymond Kurzweil was stimulated by needs he observed, "I would say that I help develop technology to solve some previously unsolved human problem." Paul MacCready's stimulus for designing the Gossamer Condor was largely the elusive \$50,000 Kremer Prize for man-powered flight established by British Industrialist, Henry Kremer, nearly 18 years earlier. MacCready stated, "One of the main points behind the Gossamer Condor was the prize money. I had the debt of a relative that I had to handle." While all the inventors appeared to cite the stimulus for their search, it is interesting to note those stimuli were quite varied.

The second step in the search process we call *Net Casting*. During this stage, the inventors gathered information that pertained not only to the domain of direct interest to them but in areas outside that domain as well. Multiplexity is imbedded in this component of the search process suggesting that the information gathering can proceed along multiple paths and include various sources (Brass and Butterfield, 1998; Burt, 1983). For instance, Stanford Ovshinsky said, "My way of reaching a conclusion is based on my own logic, with many parallel paths operating simultaneously, perhaps subconsciously, based on a lot of information that I have already gathered." Hoff also said, "The only way to do it is to keep reading as much as possible and try your best to keep up with everything that's happening." Other inventors' quotations also led to this finding. For example, MacCready states, "you keep filling in the pieces as you read something new or do some new calculation." The inventors often spoke to third parties to gather particular knowledge and read material on the subject at hand. For example, Ted Hoff said, "There are libraries and books around, but that takes a lot of self-discipline. It's probably easier to learn if you have someone pounding it into you. Certainly, some inventions can be done with very little training, but others take a great deal. It depends on the invention." Hoff also said, "The whole process was one about asking the right questions and finding out that nobody had ever looked at this piece of information before."

There are two important aspects of net casting that emerge from our data. First, we were surprised by level of individual motivation and persistence required in the net casting process. Our inventors

**Table 1**  
Search process emergent themes, definitions, and summary of quotes in text.

	Definition	Representative quotes
<b>Process stage themes</b>		
Stimulus	Identification of a problem or opportunity	Marvin Camras, “it was a waste of good records to record something only for practice. You would make a record and probably listen to it once before you threw it out.” Harold Rosen, “in discussions with some of my colleagues here at Hughes that I first heard about the geostationary orbit.” Raymond Kurzweil, “I would say that I help develop technology to solve some previously unsolved human problem.” Paul MacCready, “One of the main points behind the Gossamer Condor was the prize money. I had the debt of a relative that I had to handle.”
Net casting	Gathering of information both within and outside of the domain of interest. Searcher persists and gains perspective by zooming in and out on details.	Stanford Ovshinsk, “My way of reaching a conclusion is based on my own logic, with many parallel paths operating simultaneously, perhaps subconsciously, based on a lot of information that I have already gathered.” Ted Hoff, “The only way to do it is to keep reading as much as possible and try your best to keep up with everything that’s happening.” Paul MacCready, “you keep filling in the pieces as you read something new or do some new calculation.” Ted Hoff, “The whole process was one about asking the right questions and finding out that nobody had ever looked at this piece of information before.”
Categorizing	Filtering of information and alternatives revealed from net casting stage. Searcher places information in mental schema organized into macro or micro hierarchies that affect the number of alternatives they consider.	Marvin Camras, “I tested thousands of different materials trying to find the best material for magnetic recording.” Gordon Gould, “You have to be able to look critically at what you’ve thought up and refine it to only those things that work.” Stanford Ovshinsky, “I had a complete picture in my mind of how Ovonic materials were going to work and be applied, although I certainly didn’t have all the details that I see now. I knew we were going to build computers from these materials.” Steve Wozniak, “Here’s a few categories of technology we’re going to pursue because they make good sense, and that’s where the money will be spent.” Raymond Kurzweil, “We finally found five different Steinways that, together, gave us really beautiful sections across the entire keyboard.”
Linking	Searcher integrates ideas from seemingly different disciplines to arrive at their discovery.	Gordon Gould, “That flash of insight required the twenty years of work I had done in physics and optics to put all the ‘brick’ of that invention in there.” Ted Hoff, “Most of the inventions I’ve patented have been in areas that fall between disciplines.” Raymond Kurzweil, “I find that the projects I get involved with are increasingly interdisciplinary some of the technologies include linguistics, signal processing experts, very large scale integration designers, psycho-acoustic experts, speech scientists, computer scientists, computer scientists, human-factor designers, experts in artificial intelligence and pattern recognition, and so on.” Stanford Ovshinsky, “I started developing my theories about amorphous materials by thinking about the relationships between the surfaces of neurons in the brain and the storage and encoding of information.”
Discovery	Searcher tests and validates the notion or idea arrived at through linking.	Nathaniel Wyeth, “I will never forget the great pleasure I had in watching that machine go through its paces without missing a trick. I could see he was happy with it and that the other guy was impressed too.” Paul MacCready, “Suddenly, I had found the last piece of this jigsaw puzzle of man-powered flight and put it in and the problem was solved.”
<b>Process influencing themes</b>		
System complexity	Situation in which a large number and increasing number of components and interdependencies exists.	Marvin Camra, “An inventor may try hundreds of things that don’t work.” Raymond Kurzweil, “the projects very quickly get complex enough that different people’s expertise is required” Harold Rosen, “All those elements have been evolving since then. . .In the beginning, we didn’t know that attitude control would be required continuously throughout the life of the satellite.”
Search context	Dynamic environment in which search takes place. Can be general, based on technology, rooted in organizational context, search-specific, etc. The ruggedness of the context/landscape in which search takes place influences the process.	Paul MacCready, “more challenges and solutions appear all the time but you have to be realistic in selecting goals.” Stanford Ovshinsky, “A new idea has to win its place against normal skepticism, a lack of desire to change, and even jealousy.” Harold Rosen, “I’m not saying it couldn’t have happened elsewhere, but it would have taken a rare combination of talents.” Ted Hoff, “It’s a challenge as you progress in years and try to remain creative. The only way to do it is to keep reading as much as possible and try your best to keep up with everything that is happening.”
Searcher knowledge, experience, and motivation	Ever-changing characteristics of the individual searcher that influences the search process.	Steve Wozniak, “In my case, I would say that what I did was in some ways inevitable. All my life, all the little steps, all the right experiences in TV, video, circuits, building my own terminals, working at Atari, working at Hewlett-Packard – all these things converged. If you combine them all at that point in time, they were definitely going to be the Apple II.” Paul MacCready, “My background may not be right for some challenges, but for this one it was just right.” Gordon Gould, “I certainly had no idea that was what I was heading for, but I think that background – and I’m talking about experimental experience, not theoretical – enabled me to pull everything together into what’s called the laser.” Raymond Kurzweil, “There’s no substitute for practical experience when it comes to being an inventor or an entrepreneur. Practical experience is really the essence of learning in these fields.” Steve Wozniak, “The process sort of starts, and then it may continue over several days. I’ll scrap things together, try this, try this – with no one around.” Wilson Greatbatch, “I can completely reverse a project midstream and say, ‘Well, I’ve been going the wrong way. I’ve got to go back and go the other way’.”



Fig. 1. Initial model: linear process of search and discovery of invention.

describe this as ongoing and effortful. Prior research on search terrains has often emphasized terrain landscapes and locations, including dimensions of familiarity, distance (local versus distant), and depth (Katila and Ahuja, 2002). For example, Rosenkopf and Almeida (2001) study on semiconductor firms suggests that technological familiarity and geographic proximity or distance are antecedents of local search. Inventors in our study, however, did not often make these types of landscape distinctions. Instead they emphasized individual discipline, information comprehensiveness, and acquisition of up-to-date knowledge as ongoing.

Second, it is also important to point out that net casting is dynamic involving switching from fine-grained nets to coarse-grained nets and vice versa so as to make sense of the search terrain. We describe this as being very similar to zooming (Berthold et al., 2008). In other words, the inventors in our study appear capable of switching nets for fine casting to more coarse grained casting and vice versa. We speculate that by engaging in zooming, our inventors achieve greater perspective of relationships and greater understanding of the importance of the detail information they obtained. One may think of zooming in, as for example, as dynamically comparing the detail of an object on the horizon with normal eyesight, and then zooming in closer with a pair of binoculars. Similarly, zooming can be thought of in terms of Global Positioning Systems (GPS). When viewing a tightly zoomed 1/8-mile screen on a GPS, the viewer can see many details but may not have perspective of the overall context. By zooming out, to a five-mile view, the searcher may miss details but has a better perspective of the total information landscape. Both views are important but reveal different levels of specificity and relationships in the field of view. Thus, zooming out provides greater overall perspective of relationships, but often at the cost of specificity, whereas zooming in provides greater specificity. Our findings suggest effort and persistence play an important role in zooming because it can be a tedious and time-consuming activity.

In the third step, *Categorizing*, the inventor filters out information and alternatives revealed from net casting stage. Categorizing has been alluded to by others as an important component of search. For example, Baron (2004) contends that how entrepreneurs search is affected by how they access, manage, store, convert and use information they find. In other words, he suggests that the cognitive mental process of the searcher drives the search process.

Similar to net casting, categorizing can be either organized into macro or micro hierarchies of information, greatly affecting the number of alternatives that will continue to be considered. We found variation in alternative considered varied both within and across our inventors. For example, Wilson Greatbatch initially evaluated three alternatives to sealing the pacemaker from the body's internal environment. First, he attempted to use electrical tape to seal the pacemaker. He next tested epoxy and eventually decided a metal encasement of some kind would be needed to accomplish the task. Camras, on the other hand, considered a large number of alternatives. He said, "I tested thousands of different materials trying to find the best material for magnetic recording." He rejected nearly all of these materials and performed future experiments on just a few in order to identify the best.

Gordon Gould also illustrates the screening process and rejection of alternatives that do not work. He noted, "You have to be able to look critically at what you've thought up and refine it to only those things that work." Ovshinsky believed he had the correct materials but needed to close in on the selection of the optimal solution, "I had a complete picture in my mind of how Ovonic materials were going to work and be applied, although I certainly didn't have

all the details that I see now. I knew we were going to build computers from these materials." Steve Wozniak narrowed down his options too, "Here's a few categories of technology we're going to pursue because they make good sense, and that's where the money will be spent." Kurzweil, likewise, rejected all piano manufacturers except Steinway as acceptable for sampling sounds for his synthesizer. He then tested numerous Steinway pianos in order to identify one that had an acceptable sound across its entire range, "Some had a beautiful, deep, resonant bass, but were tinny in the treble or had a weak middle. We finally found five different Steinways that, together, gave us really beautiful sections across the entire keyboard."

We contend that the dynamic stage of categorizing involves the integration of new information obtained by net casting into the existing knowledge structures (schema) of the inventors. Categorization theory suggests an individual's schema represents the existing knowledge structure of an individual based on prior experiences organized into categories (Rosch et al., 1976). These categories are often structured based on an understanding of prototypes, exemplars or beliefs of connection of cause effect relationships in the perceived world (Loken et al., 2008). From this perspective, categories are arranged into a hierarchy based on levels of analysis or specificity, from broad, macro and fuzzy to more specific and concrete. For example, an individual may have a broad category on the subject such as automobiles, followed by more micro and connected sub-categories such as alternative manufacturers, brands, styles (coupe or sedan), and then features such as horsepower, color, and GPS.

An individual's knowledge structure or schema may be strongly ingrained and difficult to change, or it may be more malleable and subject to adjustment (Barsalou, 1982). It is also possible that inventors discard certain new information and knowledge when it is discrepant with strongly held exemplars, prototypes and connections (Loken and Ward, 1990). We suspect that our inventor's knowledge structures were quite malleable – subject to revision as they pass through the categorization process. In other words, as they attempt to sort, classify, and integrate what they learned from net casting, they seek to store this information into existing knowledge categories or update their knowledge categories as they proceed through categorizing. A key point however is the inventors must in some way have updated their mental categories and knowledge structure in order to proceed to the next step.

During the fourth step, *linking*, the inventors integrate ideas from seemingly different disciplines in order to make their discovery. This finding appears to directly relate to the bisociative theory of creativity, that is, the deliberate connecting of two previously unrelated thoughts to produce a new insight or invention (Koestler, 1964; Maggitti and Smith, 2005). For example, Gould elaborated about how he brought together ideas from two different disciplines to arrive at his discovery of the laser, "That flash of insight required the twenty years of work I had done in physics and optics to put all the 'brick' of that invention in there." Hoff makes a similar statement, "Most of the inventions I've patented have been in areas that fall between disciplines." Other inventors also appear to believe that the marriage of more than one discipline was essential to their discovery. Kurzweil stated, "I find that the projects I get involved with are increasingly interdisciplinary some of the technologies include linguistics, signal processing experts, very large scale integration designers, psycho-acoustic experts, speech scientists, computer scientists, human-factor designers, experts in artificial intelligence and pattern recognition, and so on." Ovshinsky provides additional interdisciplinary support, "I

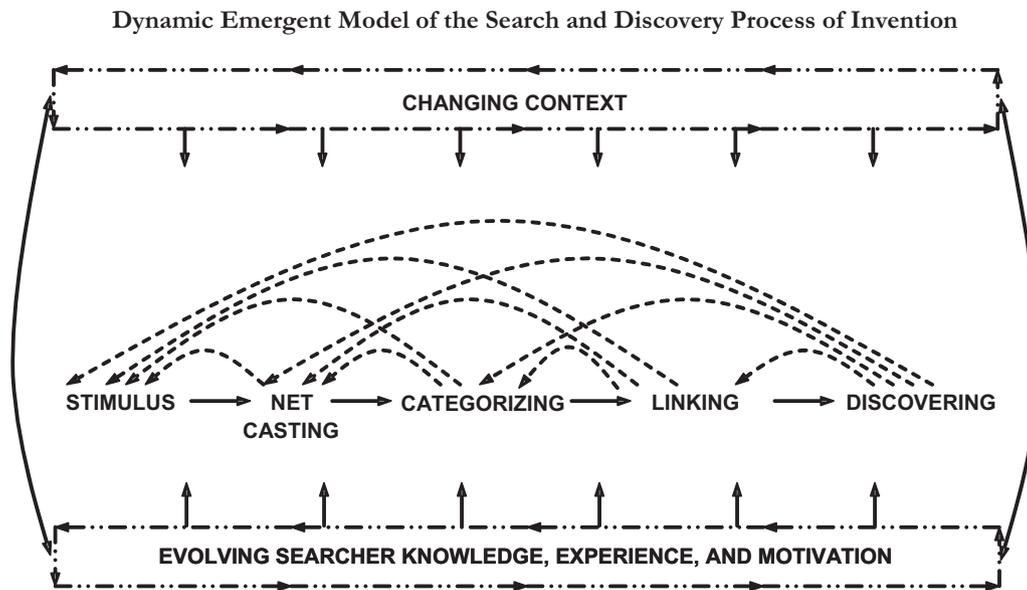


Fig. 2. Dynamic emergent model of the search and discovery process of invention.

started developing my theories about amorphous materials by thinking about the relationships between the surfaces of neurons in the brain and the storage and encoding of information.”

We speculate that linking or bisociation can occur when the inventors connect two previous unconnected categories in his/her schema or it may occur when the inventor connects two previously unconnected bits of information obtained from net casting the landscape. Finally, it may also involve a combination of “in the mind” knowledge to observations from the net casting landscape. The key outcome of bisociation is an insight that may take the form of a hypothesis that leads to testing, which we describe in the next step (Nelson and Winter, 1982).

The fifth step is *Discovery*. In this step, the searcher tests and validates the bisociative hypotheses developed in the fourth stage. Wyeth spoke about one of his inventions performing to expectations in front of his boss and a co-worker, “I will never forget the great pleasure I had in watching that machine go through its paces without missing a trick. I could see he was happy with it and that the other guy was impressed too.” Another example is offered by MacCready after he reflected on the flight of a turkey vulture soaring in the sky, “Suddenly, I had found the last piece of this jigsaw puzzle of man-powered flight and put it in and the problem was solved.” While clearly not a necessary for discovery to have occurred, in many cases of technological invention, the final discovery is validated through the acquisition of a patent.

#### 4.2. A more comprehensive model

Our initial model did not address the full set of themes we identified upon further and deeper analysis. In addition, we found that the stages in this initial model rarely, if ever, occurred in a neat, sequential, and linear fashion as the model suggests. In fact, our temporal examination of the inventors’ process showed it to be disjointed and inconsistent both from inventor to inventor as well as within individual inventors themselves, depending on the invention in which they were engaged. Indeed, we found a complex network of feedback loops, connecting later stages in the process back to earlier steps and vice versa. In many cases, it appeared that the searcher continually revisited and reevaluated earlier stages in the process to make adjustments and modifications to his or her

thinking. In all cases, these changes, adjustments, and feedback resulted from one of the three influencing themes we identified in our analysis: (1) system complexity; (2) search context; and (3) searcher knowledge and experience (Fig. 2).

##### 4.2.1. System complexity

One of the simplest definitions of technological complexity holds that the larger the number of components, the more complex the product (Rycroft and Kash, 1999). In this study, nearly all the inventors were working on technological projects that included a large number of components or required the investigation of a large number of components and managing increasing levels of interdependencies in general as well as those that were organizational or search-specific. This level of complexity appeared to increase as the search process developed and unfolded. For example, Camras said, “An inventor may try hundreds of things that don’t work.” Of course, Camras need only look at himself as an example of this. In fact, as mentioned earlier, he claimed to have tried thousands of different materials during the invention of the magnetic tape. Several of the inventors indicate that their invention changes and becomes more complex as it is improved. Kurzweil spoke about his synthesizer projects, “the projects very quickly get complex enough that different people’s expertise is required”. Likewise, Rosen discussed the first version of his spin-stabilized satellite, “All those elements have been evolving since then. . . In the beginning, we didn’t know that attitude control would be required continuously throughout the life of the satellite.”

How do our inventors manage this complexity? In the prior section of this paper we outlined five linear stages. Beyond the initial stimulus, we conceive of a much more complicated process where the stages are iterative, recursive and updated and where the searchers’ effort, motivation, and persistence play a major role. In describing net casting we emphasized the dynamics of zooming in and out. And in the categorization stage we featured the notion of refining mental schema as a result of net casting. However, it is likely that the searchers’ mental schema and categories influences the nature of net casting, perhaps determining breath and scope of net casting. Similarly, zooming in and out while net casting leads to new insights, mental schema updates, and refinements that may promote more net casting and zooming. In this

regard, Fiske and Taylor (1991) describe two different approaches for schema change. First, they suggest that individuals use theory driven models whereby a process, such as search, is driven by the searchers' mental representation of information and knowledge. Alternatively, they suggest that individuals can use data driven processes, in which, context salience of new information attracts the searchers' attention. We see evidence of both models in simultaneous use by our inventors.

This iterative updating process, either theory or data driven, must be combined with the linking or bisociative capabilities of the searcher where the searcher combines seemingly unrelated information to form hypotheses. We predict that the seemingly unrelated information is drawn from the formation of new mental representative categories of the searcher, both at a micro and macro level, and the actual net casting zooming process leading to potential insights and intuitions. At any one point in time and through a single lens, an observer may construe net casting and zooming as a two step sequential process, but when observed overtime and at a different level of analysis, the process of categorization iterates back to initiate a new net casting process as the searcher attempts to make meaning of net casting and net casting is further engaged as a result of new mental categories of knowledge and information. Linking of information can occur at any point where the searcher learns to form a new intuition or hypothesis.

Complexity is not only inherent in the components of the technologies being developed. The search process is complex as represented by the dynamic and fluid nature of the final two themes, the ever-changing search contextual environment as well as the dynamic nature of the searcher's own knowledge, experience, and perceptions thereof. Both the changing context (landscape) and the changing searcher knowledge (schemata) influence complexity (e.g. Katila and Chen, 2009; Chen et al., 2010). Indeed, every stage in the process may be affected by both of these dynamic and ever-changing variations.

#### 4.2.2. Search context

The search process can be greatly influenced by the nature of the context in which it takes place. This is especially true and impactful when searchers face dynamic environments and experience dramatic change. An ever changing context can complicate or enrich the searcher's evaluation and reevaluation of new information and knowledge as they progress through the process, influencing progression and iteration through the different stages. The searcher must not only feed back to earlier steps in the process, but must also be cognizant of changes that have occurred within the parameters at that earlier step in the process. These issues can be related to the technology at hand but also to a myriad of other outside pressures, time limitations, financial constraints, etc. These contextual factors may be general in nature for the sole inventor and/or organization-specific for searches taking place in an organizational context. In addition, these contextual changes can vary in their salience in relation to the relative terrain that is encountered. This largely affects the ability of the searcher to detect change and identify novelty in the terrain and how that change interacts with the search process. A quote from MacCready illustrates this point, "more challenges and solutions appear all the time but you have to be realistic in selecting goals." Ovshinsky spoke about context with respect to social pressures facing the inventor, "A new idea has to win its place against normal skepticism, a lack of desire to change, and even jealousy." Similarly, Rosen opines that the context of the people with whom he worked had much to do with his discovery, "I'm not saying it couldn't have happened elsewhere, but it would have taken a rare combination of talents." Hoff makes a statement that relates to the importance of keeping abreast of the ever-changing terrain, "It's a challenge as you progress in years and try to remain creative. The only way to do it is to keep reading as much as possible and try

your best to keep up with everything that is happening." Indeed, a continual updating of context appears to very important to our inventor's success.

It is quite possible as the fluid context changes, inventors are forced to iterate updating their netcasting and categorization process. By the time they return, the context may have changed further requiring additional iteration perhaps leading to new hypotheses and discovery. In such a dynamic, it may be unclear where the process of invention should finally end, suggesting that inventors must be willing to satisfice and prematurely end the process because of the endless changing context.

#### 4.2.3. Searcher background, experience, and motivation

The inventors in our sample appear to share significant interest, curiosity, endurance, and enjoyment in what they do. They also seem to believe that their background, knowledge, and experiences come together at exactly the right moment in time during the search to make them uniquely qualified for their discovery. The influence of these individual characteristics can be seen in a number of instances. For example, Wozniak said, "In my case, I would say that what I did was in some ways inevitable. All my life, all the little steps, all the right experiences in TV, video, circuits, building my own terminals, working at Atari, working at Hewlett-Packard – all these things converged. If you combine them all at that point in time, they were definitely going to be the Apple II." MacCready appears to believe the same is true in his case, "My background may not be right for some challenges, but for this one it was just right." Gould credits his knowledge and experiences in much the same way, "I certainly had no idea that was what I was heading for, but I think that background – and I'm talking about experimental experience, not theoretical – enabled me to pull everything together into what's called the laser."

Research from categorization theory suggests that ability and experience are positively related to flexibility in categorization process (Cowley and Mitchell, 2003). Specifically, experts as opposed to novices have been found to organize and store information and knowledge in ways that provided greater range and depth of categories and a greater ability to update categories (Cowley and Mitchell, 2003). Most of our inventors enjoyed both technological and practical experience in developing new inventions. Thus categorization theory suggests that this experience was important in allowing our inventors to update and revise their knowledge as the search process progressed. For example, a quote from Kurzweil captures the importance of experience, "There's no substitute for practical experience when it comes to being an inventor or an entrepreneur. Practical experience is really the essence of learning in these fields."

Our inventors also display high levels of motivation, effort, and persistence. Motivation levels have been found to be important to the process of cause and effect inference (Fiske and Taylor, 1991). For example, both data-gathering and the schema categorization process, while influenced by individual cognitive search strategies, have also been found to be affected by individual needs that motivate these processes. High levels of effort and persistence affect the searchers' need for keeping options open as search progresses and it may also influence the directions of future search (Fiske and Taylor, 1991). It appears high levels of effort and persistence enable our inventors to constantly reevaluate prior actions and revisit earlier stages in the process in order to refine and redefine the choices made at each step. A quote from Steve Wozniak illustrates this point as well as the existence of feedback and re-evaluation, "The process sort of starts, and then it may continue over several days. I'll scrap things together, try this, try this – with no one around." In further support of this notion, he said he, "laid out a whole board, and then I got an idea to save one feed-through. So I took the board apart, I trashed maybe a week's worth of work, and then started over."

Greatbatch's statements also suggest that, even after experiencing failure, he was sufficiently motivated to persist even when it meant he had to return to earlier stages in the process over again, "I can completely reverse a project midstream and say, 'Well, I've been going the wrong way. I've got to go back and go the other way'." Perhaps the most straightforward support for searchers exhibiting a willingness and motivation to persist despite the need for an iterative and non-direct process was provided by MacCready who, "at first tried... linear way of approaching problem" and then had to change to a more iterative approach. The implication in these quotes is that high levels of motivation, effort, and persistence drive a non-linear approach to search.

## 5. Discussion

We performed an inductive investigation of the search routines and discovery process of invention and presented a model of that process. Our findings indicate that the process is more complex than indicated in prior conceptual literature. While we did model five underlying stages of stimulus, net casting, categorization, linking (bisociating), and discovering, we found their occurrence to be non-linear, non-sequential, and involving iterating back and forth to earlier stages. We also identified three factors, system complexity, search context, and individual searcher knowledge, experience, and motivation that influence the sequence through which the inventor progresses through the five stages of the search process.

Several key aspects of the search and discovery process have been brought to the surface by this study. First, the process is largely context-driven. Indeed, the changing search terrain may affect every step in the search process as it evolves. The searcher must be aware of changes that occur in the terrain of the search as well as the context in which search occurs. The changing terrain forces the searcher to revisit earlier steps in the process and reevaluate his/her position along the search process. Contextual factors can include changes in the requirements of a successful search and changes in technology that affect the domain of the search on a daily basis. The changing context in which the search is performed can also have a significant effect on the process. Examples of context factors include institutions (Hargadon and Douglas, 2001), the organization or team within which the searcher is a member (Nerkar and Paruchuri, 2005), the terrain of the search in relation to potential sources of knowledge, including other people, the legal or regulatory environment pertaining to the search, and the competitive environment relating to the search domain. In addition, non-domain changes that impact the range of possible solutions can also have an effect on the search and discovery process.

Secondly, we observe that the knowledge, experiences, and motivation of the searcher have an important impact on the search and discovery process and can also affect each stage of the process. This at first appears to be an obvious point. However, we observed that it is not always the depth of knowledge and experience of the searcher that results in discovery. Rather, it is a unique breadth of these components in addition to the ability to draw from seemingly different terrains and categories to arrive at solutions and discoveries in a dynamic, complex and time sensitive environment. As the searcher's knowledge and experience evolve and new information becomes available he/she is required to feed-back and link earlier steps in the process and reevaluate not only the progress they have made but also how the context of the search has changed at that moment.

Third, this study contributes to the growing body of literature on complexity. Some complexity theorists believe that simple responses to the complexities of technological innovation have been incorrect (Rycroft and Kash, 1999). To an extent, we find that a simple set of routines and stages exist, however, the nature of

the progression through them is very complex. We would agree that this has been the case with the relatively simple linear conceptual models of the invention and related process found in the literature (Anderson, 1999; Meyer et al., 2005). The results of our study indicate that these processes have been overly simplified in the extant conceptual literature which illustrates a linear process, while more recent conceptualizations are more closely representative of our complex model and support the empirical findings in this study (see Table 2). In what follows, we integrate and compare our empirically derived search process model with a number of these conceptualized models.

One way in which the complex systems of search we identify enriches prior conceptualization of search is by introducing the notion of search taking place on a rugged and complex landscape. Specifically, it can be seen that prior models employed some stimulus and generation of alternatives but did not fully model how the complexities of their world would increase potential solutions or make it difficult to explicate plausible from implausible alternatives. This does not diminish the importance of earlier models but, rather, enhances them. Whereas our model of search was derived from a grounded theory approach, we recognize that some conceptual models may prove well-suited to explain the process of search if a dynamic and complex environment is taken into account. For example, similar to our "net casting" stage, Dewey's (1910) model (specifically, step 1: difficulty or problem situation located and problem defined/formulated; step 2: one or more plausible solutions suggested), Bazerman's (2002) model (specifically, step 1: define the problem; step 4: generate alternatives), and Amabile's (1983) model (specifically, step 1: problem or task presentation; step 3: response generation), the complex systems view emphasizes that the complex and rugged landscape can influence how problems are defined and/or formulated. Further, the dynamics inherent in the complex systems model can inform the existing models. For instance, ruggedness of the landscape can increase or decrease over time making feedback loops to re-evaluate context essential.

The complex systems view could also enhance earlier conceptualizations of search by emphasizing the breadth of searchers' knowledge, experience, and perception in search. For example, these searcher-specific characteristics may influence their ability to bisociate insights from seemingly unrelated information domains. Thus, bringing this perspective to bear on evaluative stages of earlier models such as Dewey's (1910) model (specifically, step 4: consequences considered and evaluated), Bazerman's (2002) model (specifically, step 5: rate each alternative on each criterion; step 6: compute the optimal solution), and Amabile's (1983) model (specifically, step 4: response validation) enriches those models by explicating variation among searchers that could influence that portion of their search. Similarly, the dynamically changing and evolving searcher knowledge could again introduce feedback loops to the process.

In 1996, Amabile revised her 1983 componential framework of creativity to reflect a non-linear process. Although the 5-stages of the process do not change significantly, the revised model indicates that these steps do not have to occur sequentially. Nor is each step necessary for a creative outcome to occur. In addition, Amabile adds that the social environment can affect the individual and ultimately, the process.

Similarly, we believe that Root-Bernstein (1989) posited the most accurate theoretical model of the search and discovery process to date. That model of the process of scientific invention presents a conceptualization in which a more cyclical and complex process is involved in invention (Root-Bernstein, 1989). He observes that previous models of the process are either based on the four-step linear approach introduced by Wallas (1926), or ignorant of the people involved in the process. Indeed, his model of invention

**Table 2**  
Sample sequential models of the search and discovery process in various literatures.

Invention/discovery		Problem solving	Decision making	Creativity
Wallas (1926) 4-step (linear)	Bernard (1957) 4-step (linear)	Rossman (1931) 7-step (linear/circular)	Dewey (1910) 5-step (linear)	Amabile (1983) 5-step (linear/circular)
	1. A fact is noted.	1. Observation of a need or difficulty. 2. Analysis of the need.	1. Felt need or difficulty observed. 2. Difficulty or problem situation located and problem defined (formulated).	1. Problem or task presentation.
1. Preparation (information obtained).	2. An idea is born in the mind.	3. A survey of all available information. 4. A formulation of all objective solutions.	2. Identify the criteria. 3. Weight the criteria.	2. Preparation.
2. Incubation (unconscious work occurring).	3. Reason, experimentation, and imagination bring to pass the ideas material conditions. 4. New phenomena results that must be observed, and so on and so forth.	5. A critical analysis of these solutions. 6. The birth of the new idea, the invention.	3. One or more plausible solutions suggested. 4. Consequences considered and evaluated.	3. Response generation.
3. Illumination (one or more solutions emerging).		7. Experimentation to test out the most promising solution, and the selection and perfection of the final embodiment by some or all of the previous steps.	5. Rate each alternative on each criterion.	4. Response Validation.
4. Verification (solutions tested, judged for appropriateness, and elaborated upon).			6. Compute the optimal solution.	5. Outcome (return to step 1 if only some progress is made).

includes not only circular components and feedback loops back and forth between stages but also includes the characteristics of the individual inventor and the context of the technological domain in which the invention exists.

Our observations of the search routines and discovery process are partially consistent with Root-Bernstein's conceptual model of search. First, he theorizes that individual skills, proclivities and experiences will have a great effect on the process. In addition, he uses the recursive process of feedback to show how the individual may search in one direction, find the path impossible, find a more inviting detour, or go through a cycle many times before a solution emerges (Root-Bernstein, 1989). Finally, Root-Bernstein presents the idea that the context and environment within which the inventor resides can have a significant influence on the process.

Although Amabile's (1996) updated model and Root-Bernstein's (1989) model of search are improved conceptions of the search process, we argue that neither presents a complete picture. Specifically, Amabile's (1996) componential framework of creativity shows that the social environment affects the individual searcher. She omits the potential effects of the more general contextual environment that may have an influence on the process itself and she doesn't recognize how the context can change as the process unfolds. Root-Bernstein's (1989) theoretical model, on the other hand, presents the process of scientific invention to include the potential environmental context effects on the process as well as the effects of the individual. However, the backbone of the model, for example, the actual stages and the simultaneous roles of increasing complexity,

context and experience differs significantly from previous linear theory and, again, is purely conceptual in nature.

We believe that the findings of our study and our model of the search and discovery process of invention largely rectify both of these issues. Our model consists of a basic linear series of stages coupled with a non-linear process. By using the linear model matrix, our model does not discount the previous linear conceptual models. In addition, our combined model shows that the process is affected by both the evolving search terrain and environmental context, as suggested by Root-Bernstein (1989), and the knowledge and experience of the individual searcher, as suggested by both Amabile (1996) and Root-Bernstein (1989). Finally, our model is empirically grounded and based on our inductive case studies.

Of course, we must be cautious in drawing conclusions from this inductive case study of successful inventors and, like all studies, ours has limitations. The fact that we have exclusively selected successful inventors leads to two potential problems associated with sampling on the dependent variable: failure to establish that the search processes that successful inventors use are not used by unsuccessful inventors, and lack of generalizability. First, because sampling does not vary on the dependent variable, it would appear impossible to establish causality between the search and discovery process and invention. In order to establish causality it is necessary to analyze how the search and discovery process of successful inventors differs from the process used by unsuccessful inventors. Second, our sample of ten successful inventors may not be representative of the overall population of inventors. This implies that conclusions drawn from this study may not be generalizable.

The first problem is difficult to resolve since, by definition, an unsuccessful inventor is not an inventor at all. In order to study the search and discovery process of invention a researcher must draw upon the entire population of inventors, individuals who have invented something. We believe we have partially addressed the potential problem associated with the second issue by selecting a sample of inventors that, although small, consists of a wide range of success levels based on their patented inventions. While this approach is not perfect and differences exist across fields in terms of propensity to patent, it is interesting to note that the inventors in our sample have as little as 3 and as many as 197 patented inventions (mean = 37.8, SD = 58.44). In addition, the inventors in our sample speak of failure at one time or another and, thus, are not always successful. Although future research should attempt to replicate these findings to assess the model's predictive validity with a larger and more generalizable sample, we believe our study provides a foundation for this work. Another potentially valuable future methodological approach would be to examine a "search" as the unit of analysis. By doing so, it might be possible to investigate the characteristics of successful and unsuccessful searchers of an individual. Future studies in this vein might yield valuable insights into how searchers revise their search as they accumulate more experience and information.

Future studies can also explore the relative importance and effects of each variable on the outcome of the search and discovery process of invention. In other words, do inventors feed back between some steps more or less often than others and do these patterns influence the outcome. In addition, it would also be desirable to operationalize the model presented here to see if it has predictive validity. Laboratory study and manipulation of the constructs identified in this study may also prove valuable. For example, one can control elements of the search context environment such as information availability and technological change in a lab. Likewise, the searcher experience can be altered through the use of training in a lab setting. Finally, in this study, the search and discovery process of invention is assumed to be illustrative of other search processes. It would be important to study search utilizing other samples such as entrepreneurs or managers of organizations, and indeed organizations themselves, in order to develop a more robust model of the search process.

## 6. Conclusion

The purpose of our study was to inductively derive a model of search. In contrast to conceptual processes found in prior literature, our approach provides empirical grounding and adds detail not found in those models. Perkins (1981) stated that a creative product could be thought of as a very special selection from a chaos of possibilities. We have shown that the search routines and the discovery process of invention is indeed chaotic and complex. In fact, this study also contributes to the growing body of literature on complexity theory. To date, the focus of the complexity literature has largely been on group (e.g. McCarthy et al., 2006) and organizational systems (e.g. Davis et al., 2009; Sommer et al., 2009), with little focus on the individual level of analysis (Uhl-Bien and Marion, 2009). Complexity theory holds that real world systems are complex and that the actions of the components of a system are highly dependent on the actions of the other components in the system (Anderson, 1999). Our individual level study findings fit within this literature. Namely, that the timing and success of discovery rely not only on the individual searcher's persistence, effort, and motivation but also on his or her ability to continuously reevaluate the system of an ever-changing context landscape in conjunction with their own knowledge and experience.

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