AN EVOLUTIONARY MODEL OF PROBLEMS AND SOLUTIONS

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ABSTRACT

We develop the idea that problem solving is a bidirectional process in which problems can find solutions and solutions can find problems. We argue that problems and solutions in a given population are not optimally distributed due to path dependence, such that the best problem-solution matches are often split apart in faraway domains. This paper consists of two parts: in Part I we present theoretical reasoning on the bidirectionality of problem solving; in Part II we present an agent-based model of problem solving based on the theories discussed in Part I.

PART I: THEORY AND PROPOSITIONS

Problem solving is conventionally depicted as a process that begins with the identification of a problem and ends with a solution. We argue that while this view is useful for examining certain isolated, micro instances of problem solving (e.g., how to locate a misplaced item), it is unsuitable for describing problem solving at the systems level. In reality, not only do problems find solutions, solutions also find problems. Furthermore, a problem may have many solutions, and conversely, a solution may solve many problems. Occasionally, a solution developed for a particular problem ends up being utilized to solve another problem. Similarly, a previously solved problem may find better solutions in a field far from its original domain. Thus, when examined at the systems level, problem solving is a complex and dynamic process.

Scholars in organization studies have recognized the fact that problem solving is bidirectional. Most notably, Cohen, March, and Olsen (1972) proposed the Garbage Can Model of organization theory to depict problem solving and decision-making as the outcome of interrelations among four distinct streams of elements: problems, solutions, participants, and choice opportunities. It is at the collision of these four streams that problem solving and decision-making occur.

Solutions can be independent of problems

Can a solution exist in the absence of a problem? According to Cohen et al. (1972), "A solution is somebody's product... It is an answer actively looking for a question... Despite the dictum that you cannot find the answer until you have formulated the question well, *you often do not know what the question is in organizational problem solving until you know the answer*" [emphasis ours]. This last bit of Cohen et al.'s definition of a solution is important to note because we are accustomed to thinking that whether something counts as a solution depends on its suitability for a problem. In other words, the problem creates a context which determines whether something is a solution. As Cohen et al. (1972) pointed out, however, sometimes a problem only becomes apparent after its solution is known.

Examples of problems being defined by solutions rather than the opposite can be illustrated through stories of serendipitous breakthrough. Throughout the history of science, numerous accounts describe inventions or discoveries that were triggered by "accidents." Some of the most important solutions in science were not found through *a priori* problem definition, but rather through the identification of the solutions themselves. Alexander Fleming's discovery of penicillin is one of the best-known examples of serendipitous breakthrough (Brown, 2004). One day in 1928, while cleaning out bacterial culture dishes that had been contaminated with fungus, Fleming noticed a zone around an invading fungus where bacteria could not seem to grow. Fleming proceeded to isolate an extract of the fungus, correctly identified it as belonging to the *Penicillium* genus, and subsequently named the agent penicillin. Austin, Devin, and Sullivan (2008) used the term *accidental innovation* to describe similar stories, such as Louis Daguerre's discovery of photography in the 1830s after he noticed that drops of mercury from a shattered thermometer produced a photographic image, and Percy Spender's discovery of the microwave after he noticed that a lolly bar in his pocket had melted while he was testing a new vacuum tube. Austin et al. (2008) also described the discovery of saccharin as the accidental result of a scientist's work on a treatment for gastric ulcers, the invention of Post-it Notes at 3M after a researcher named Art Fry used bits of 3M adhesive paper that could be easily lifted off the page to replace the scrap paper bookmarks that kept falling out of his hymn book, and Pfizer's discovery of Viagra during its research program on anti-angina medication.

Solutions also have the potential for unveiling non-technological problems. For example, a company might offer new ways of doing things that alter a society's lifestyle or expectations. Starbucks's mass introduction of espresso coffee in the United States has elevated the American people's expectation of coffee quality (Schultz and Yang, 1997). Who knew the US had a coffee problem? FedEx's introduction of fast, reliable shipment (Frock, 2006) and Netflix's introduction of online DVD rental also produced similar effects. Because of the services offered by FedEx and Netflix, anything less convenient is gradually perceived to be bothersome. The fact that shipment used to require more time and movie rental used to require a trip to the video store was not really a problem until its solutions came along.

Loose solutions are scattered throughout the society

The society is imperfectly structured for organizing all the solutions that reside within it. It is possible that the world is lacking not of solutions but rather of problems. There are at least two reasons why loose solutions are pervasive. First, a person is likely to have more talents, interests, and qualifications—all of which are sources of solutions—than there are immediate opportunities to put them to use. Even when a person's skills and knowledge are already utilized in their occupations, there are usually other ways to apply them. A solution can solve more than one problem. For example, a computer programmer whose job is solely to write Internet security applications may be perfectly capable of writing computer games using the same skill-set. People also rarely have perfectly linear and coherent training or experiences. For example, a neurologist may have majored in music as an undergraduate. Thus, most people are either overqualified for or imperfectly matched to their occupations. People generally have excess knowledge that is peripheral to their core functions. In effect, each person represents a set of solutions looking for problems.

Second, when people try to solve problems, they do not usually arrive at the desired solutions at first try. In the process, many solutions that are considered unsatisfactory get discarded or forgotten. This is unfortunate because while those solutions do not match the problem at hand, they may be useful for solving other problems. Creative people have indeed recognized the value of these "scrap" solutions and have taken the steps to prevent them from dissipating away. As explained by Austin et al. (2008), "Innovators squirrel away things they don't know how to use. Designers and sculptors collect photos and keep warehouses or cabinets full of things they can't use (yet). Painters and product developers keep sketchbooks. Innovators of all stripes keep 'junk,' as one designer called it, against the day when, leafing through a notebook or tidying a shelf, they have an 'Aha!' moment." If mechanisms exist for collectively rather than individually squirreling away scrap solutions, perhaps such 'Aha!' moments can be induced to occur more frequently.

Lakhani et al. (2007) found evidence that there are indeed loose solutions in the society. Furthermore, they showed that solutions were often found outside the disciplinary boundary of problems and from unpredictable or unconventional sources. This suggests that harnessing solutions prior to problems is useful because it is often difficult to see in advance which problems a solution is capable of solving. Lakhani et al. studied InnoCentive, a company that broadcasts unsolved scientific problems from firms in the agrochemicals, biotechnology, chemicals, consumer products, and pharmaceuticals, to an online community of potential solvers. Their study revealed that the broadcast of problem information to the online community resulted in a 29.5 percent resolution rate. This is remarkable considering that most firms had spent a few years trying to solve the problems in their own laboratories, using significant brainpower and monetary resources. Most interestingly, Lakhani et al. (2007) found that the odds of a solver's success increased in fields in which they had no formal expertise. The farther the problem was from their specialized knowledge, the more likely it was to be solved (Howe, 2008: 151). Furthermore, Lakhani et al. (2007) found that 75 percent of successful solvers relied on information from previously developed solutions, thereby reiterating the idea that existing solutions can have numerous applications.

To appreciate the circumstances under which InnoCentive solvers perform, let us consider the following profile of an InnoCentive solver (Howe, 2008: 148-150):

> The future of corporate R&D can be found above Kelly's Auto Body on Shanty Bay Road in Barrie, Ontario. This is where Ed Melcarek, one of InnoCentive's most successful solvers, keeps his "weekend crash pad," a one-bedroom apartment littered with amplifiers, a guitar, electrical transducers, two desktop computers, a trumpet, half of a pontoon boat, and enough electric gizmos to stock a Radio Shack. On most Saturdays, Melcarek comes in, pours himself a Saint-Rémy, lights a Player cigarette, and attacks problems that have stumped some of the best corporate scientists at Fortune 500 companies.
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> … While most of InnoCentive's solvers are full-fledged scientists, many are hobbyists working from their proverbial garage… in Melcarek's case, a mildly eccentric electrical engineer whose lab doubles as a music studio. Yet Melcarek solved a problem that had stumped the in-house researchers at Colgate-Palmolive. The giant packaged goods company needed a way to inject fluoride powder into a toothpaste tube without it dispersing into the surrounding air. Melcarek knew he had a solution by the time he'd finished reading the challenge: Impart an electric charge to the powder while grounding the tube. The positively charged fluoride particles would be attracted to the tube without any significant dispersion.
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> "It was a very simple solution," says Melcarek. Why hadn't Colgate thought of it? "They're probably test-tube guys without any training in physics." Melcarek earned $25,000 for his efforts. Paying Colgate-Palmolive's R&D staff to produce the same solution could have cost several times that amount—if they even had solved it at all. Melcarek says he was elated to win. "These are rocket-science challenges," he says. "It really reinforced my confidence in what I can do."
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> Melcarek has charted an unconventional course through the sciences. He spent four years earning his master's degree at the world-class particle accelerator in Vancouver, British Columbia, but decided against pursuing a Ph.D. "I had an offer from the private sector," he says, then pauses, "I really needed the money." A succession of "unsatisfying" engineering jobs followed, none of which fully exploited Melcarek's scientific training or his need to tinker. "I'm not at my best in a nine-to-five environment," he says. Working sporadically, he has designed products such as heating vents and industrial spray-painting robots. Not every quick and curious intellect can land a plum research post at a university or privately funded lab. Some must make HVAC systems.
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> … Melcarek has discovered something of a winning formula: find chemistry or biology problems that he can crack using his background in physics and electrical engineering. In 2007, InnoCentive launched a category for engineering challenges, but Melcarek doesn't bother with it. All seven of the problems Melcarek has solved were in other fields.

Melcarek's story captures some of the arguments that we previously advanced for why there are loose solutions in the world. The society is not structured to allow perfectly efficient pairing of solutions to problems. Incentives, such as salary, are often misaligned with people's best abilities and interests. Routine and time commitments in occupations limit mobility and therefore allow only a subset of one's potential to be expressed. Job descriptions often fail to predict and consequently gather the kind of qualifications that are needed for successful problem solving at any given time.

The value of collectively harnessing solutions

Loose solutions, when collectively harnessed, provide a fertile ground on which breakthroughs can be cultivated through two mechanisms: recombination and exaptation. Both mechanisms point to the infinite new possibilities that collective harnessing of solutions can generate. Within these infinite new possibilities lies a high probability that problems are uncovered and solved.

The enormous diversity of solutions that is generated through people's unique life experiences can stimulate recombination, i.e., the new combination of existing components. Recombination has been extensively shown in the literature to be an important constituent of creativity and innovation that lead to breakthroughs. Gilfillan (1935) and Usher (1954) argued that recombination provides the ultimate source of novelty. Similarly, Schumpeter (1939: 88) observed that "innovation combines components in a new way," and Weick (1979: 252) defined creativity as "putting new things in old combinations and old things in new combinations." Recent work on patent citation data (Fleming, 2001; Fleming et al., 2007) suggests that experimentation with new components and combinations creates variation which in turn can lead to breakthroughs.

Breakthroughs can also result from a shift in the functional interpretation of an existing solution without involving combination. We refer to this mechanism as 'exaptation.' The concept of exaptation originated from evolutionary biology and was first explained by Gould and Vrba (1982) to describe a process in which a characteristic previously shaped for another function is co-opted for new use. Exaptation has recently been adopted in the economics and management literature to describe technical innovation in which existing technology is connected to a new domain of use (Dew et al., 2004; Grandori, 2007; Villani et al, 2007). An important implication of exaptation on problem solving is highlighted by Villani et al. (2007): "Exaptation can provide a key to interpret the serendipity that characterizes the generation of new products. Exaptation emphasizes that the functionalities for which a technology has been selected are only a subset for the consequences generated by its introduction. In many cases, the number of consequences generated by a new technology, a product, or a process can be incredibly large and thus, its exaptive potential practically unbounded."

Mechanisms for collectively harnessing solutions prior to problems

Some of the most elegant mechanisms for organizing complexity can be found in nature. The human immune system has tackled a particularly profound challenge that requires it to harness solutions prior to problems. When a baby is born, it must prepare to neutralize millions of potentially harmful antigens that it will encounter during the course of its anticipated long duration of lifetime. There are, however, approximately only 20,000 coding genes in the human genome (Pennisi, 2007). Given that most of them are dedicated to functions other than immunity, the immune system is left with a relatively small number of genes from which it must devise a way of identifying and subsequently conquering an extremely diverse array of potential intruders. Most importantly, the immune system must do so *before* it is exposed to any antigen. As such, the immune system must be anticipative rather than reflexive. Because of the small number of genetic templates available to it, it cannot rely solely on hereditary mechanisms to generate a large enough repertoire capable of recognizing most antigens (Tonegawa, 1987). Instead, it brilliantly overcomes this challenge using a recombination mechanism that is later enhanced by a high rate of mutation (Tonegawa, 1983; Alt et al., 1992). The immune system randomly rearranges segments of DNA—a mechanism called VDJ recombination—then mutates them to generate an enormously diverse repertoire of immune cell receptors and antibodies capable of recognizing a similarly large and diverse array of antigens. Most of this process is completed during fetal development (Goldsby et al., 2000). Thus, by the time a baby is born, it is already equipped with the solutions to problems it has not even encountered yet.

If the immune system had to develop a response from scratch every time it is challenged, not only would it have been inefficient, it would have likely been unsustainable. Yet in problem solving, people often intuitively want to develop new solutions rather than simply find an existing one. This is certainly not because the world is lacking solutions. Not only are there excess solutions in the society, they are extremely diverse. The collection of solutions in the society constantly undergoes recombination due to the diversity of people's experiences and their interactions. Rather, people often believe that creating solutions is easier than finding existing ones simply because most solutions are scattered and disorganized.

Nevertheless, mechanisms for collectively harnessing solutions prior to problems are not entirely absent in the society. The banking system provides a straightforward example. A bank collects capital from individuals who have no immediate use for it and subsequently make loans to those who need it. The banking system increases the efficiency of capital flow by creating centralized repositories and creating a credit mechanism that is relatively anonymous. Without banks, people who need money, such as to start a business or purchase a home, must either wait until they accumulate enough of their own money or seek loans from people they know, whereas banks allow them to borrow money from depositors whom they most likely have never met. The widespread stagnation in business activities created by the credit crisis in 2008 should allow us to appreciate how little progress our society would have made without the banking system. In the simplest sense, a bank pairs solutions with problems first by harnessing solutions and subsequently allowing problems to find them.

Banks are able to gather and redistribute solutions because the solutions in their context are embodied in a singular and unambiguous medium of exchange: money. (Of course, there can be many derivatives of money, but the important point is that they are all still quantified monetarily.) While this greatly simplifies the problem of harnessing solutions for banks, it points to the challenge of harnessing solutions elsewhere. Solutions are diverse, which makes them collectively valuable but also difficult to quantify and organize. Solutions can be codified, but codification of the same piece of solution can take many forms. Because individuals frame their solutions differently according to the perspectives that they are accustomed to taking or the circumstances in which the solutions are acquired, people may not have a shared understanding of the same piece of solution. Furthermore, borrowing Simon's (1962; 1973) terminology of problem characteristics, solutions may be decomposable, non-decomposable, nearly decomposable, and ill- or well-structured, thereby complicating attempts to determine the unit of solutions.

There are two possible ways to overcome this difficulty. The first is to find ways of creating a universal taxonomy for solutions. However, this is clearly unrealistic. Because a solution is somebody's product, it is always subjectively represented. Therefore, it is unlikely that people are ever able to agree on a universal taxonomy of solutions. The second possible approach is based on a famous adage in open source software development: "Given enough eyeballs, all bugs are shallow" (Raymond, 2001). This is known as Linus's Law, named after Linus Torvalds, the chief architect of

Linux. What it originally means is that the more widely available a software source code is for public testing, scrutiny, and experimentation, the more rapidly all forms of bugs (i.e., errors in the source code) will be discovered (Raymond, 2001). The underlying idea is that diversity (of errors) is best countered using diversity (of eyeballs). This premise is indeed similar to the immune system's strategy of anticipating diverse antigens using randomly generated diverse antibodies and immune cell receptors. As such, the proper way of collectively harnessing solutions is counterintuitive. It is not achieved by sequestering solutions and putting them onto a shelf for people to find—which would actually be consistent with the conventional definition of harnessing—but rather by broadcasting them as freely and as widely as possible. If a solution *can* exist in several forms, chances are it already does. The task is not so much to identify all the different forms in which a solution exists, but to expose these forms as widely as possible so that people with the right problems have a high probability of recognizing the solution as it is presented to them.

Before solutions can be broadcasted, they must first be expressed. This can happen in two ways. First, a person can describe a solution as it is. For example, a person who knows how to fix a broken radio can simply write about it and post it on a website. However, some solutions are too complex to codify and therefore can only be effectively communicated through personal interactions (Haas and Hansen, 2007). Thus, the second mechanism in which a person can express solutions is by revealing his or her "type" (Spence, 1973). For example, a person who lets it be known that he or she is a nuclear physicist is inviting inferences about the types of solutions he or she possesses. There are indications that people are intrinsically and socially motivated to express solutions using either one or both of these mechanisms. An example of the first mechanism can be seen in Wikipedia. Its success in amassing a large amount of knowledge despite a low requirement for participation and lack of monetary reward not only is a testament to the ubiquity of excess solutions in the society, but also to the desire of individuals to "donate" their knowledge. Raymond (2001) documented that computer programmers participated in open source projects without pay because they were motivated to enhance their reputation and feel a sense of community. Lakhani et al. (2007) found that successful InnoCentive solvers were primarily driven not by financial incentives but by intrinsic motivation, such as enjoying problem solving and cracking tough problems. Meanwhile, evidence of people's willingness to reveal their type can be found in social networking sites. Within a short period of time, these sites have attracted and retained a large number of users. For example, in 2007, only three years after its conception, Facebook was reported to have more than 21 million registered members generating 1.6 billion page views each day (Ellison et al., 2007; Needham & Company, 2007). Each social networking site typically requires a profile to be filled out by its users. People appear to happily comply, suggesting that social networking sites successfully tap into people's motivation to reveal their type, be it self expression or desire to expand social connections.

Summary of propositions and research questions

Thus far, we have made a series of ten propositions, each building on a previous one:

1) Solutions can exist independently of problems.

2) Each solution can solve more than one problem.

3) The society is imperfectly structured to maximally utilize all solutions.

4) Most solutions are therefore underutilized.

5) Consequently, the society is awash in loose solutions.

6) Loose solutions can uncover and solve problems through recombination and exaptation.

7) As such, there is value in collectively harnessing loose solutions.

8) Collective harnessing of solutions is possible because people are willing to express their solutions.

9) Solutions are subjectively represented.

10) Thus, the way to collectively harness solutions and increase the probability of their utilization is by maximizing their exposure through broadcast.

The last proposition leads to an interesting research question: What are the conditions in which the maximization of solution exposure through broadcast is especially useful for increasing the probability of solution utilization? In considering this question, it is useful to note two important characteristics of broadcast: omnidirectionality and capacity for quickly achieving saturation.

First, let us consider the four possible situations underlying the pairing of solutions to problems (Table 1). The person carrying a solution may or may not actively seek a problem, and vice versa. Assuming that solutions and problems travel through social networks, the combination of their search behaviors result in varying levels of mobility through the network. When both the solution and the problem are actively searching for each other, there is a high level of mobility through the network. When only either the problem or the solution is actively searching for its counterpart, there is a moderate level of mobility. Finally, when neither the problem nor the solution is active, there is no mobility. Given a fixed amount of time, the situation in which both the solution and the problem are actively searching for each other will result in the largest number of nodes 'sampled' in the network.

Table 1: Four possible situations in which problem solving occurs

Solution / Problem	Active	Passive
Active	High network mobility	Moderate network mobility
Passive	Moderate network mobility	No network mobility

The broadcast of solutions likely serves as a compensatory mechanism for search activities within the network. Therefore, broadcast is likely to be most marginally useful in a situation in which neither the solution nor the problem is active and least marginally useful in a situation in which both the solution and the problem are active.

Hypothesis 1: The marginal utility of broadcast diminishes with increasing network mobility.

This hypothesis can be tested using computer simulation. Some of the important parameters to be specified are: network size (number of nodes and ties), number of disparate clusters, and the distance between solutions and problems. These parameters will likely affect search efficiency, thereby affecting the compensatory value of broadcast. Several additional hypotheses can be generated based on these parameters. For example, more nodes are likely to create more noise in the search activity:

> *Hypothesis 2: The number of nodes is negatively correlated with search efficiency and positively correlated with the marginal utility of broadcast.*

However, more ties in the network mean that it is easier to reach nodes:

> *Hypothesis 3: The number of ties is positively correlated with search efficiency and negatively correlated with the marginal utility of broadcast.*

A network with disparate clusters is marked by a low number of ties. Therefore, consistent with the argument for hypothesis 3, disparate clusters is likely to complicate the search process:

> *Hypothesis 4: The number of disparate clusters is negatively correlated with search efficiency and positively correlated with the marginal utility of broadcast.*

The degree of separation between a solution and a problem increases the search time:

> *Hypothesis 5: The degree of separation between the solution and the problem is negatively correlated with search efficiency and positively correlated with broadcast.*

Future directions

Results from computer simulation can inform the design and viability of a real world broadcast model. The Internet as a massive global network provides a platform on which solutions can travel quickly at very low communication cost. Nevertheless, several important challenges must be addressed first. For example, the source of solutions that are likely to create breakthroughs is unpredictable, and therefore solutions should be broadcasted without *a priori* classification. However, people have limited time, attention span, and mental agility, and therefore can only attend to a limited number and type of solutions that cross their paths (Hansen and Haas, 2001; Simon, 1997:40). Another source of challenge is the problem of social cues. Theoretically, recombination and exaptation are promising mechanisms for translating diverse solutions into breakthroughs. However, in reality these mechanisms have complicating social components. People use social cues, such as status and reputation, to augment their cognitive judgments. In recombination or exaptation, which often necessitates the straddling of traditional boundaries, the problem of status and reputation can be especially salient (Stonequist, 1961). For example, because some disciplines are perceived as more prestigious than others, people may have trouble transplanting an idea from a lower- to higher-status discipline. The Internet fortunately enables mechanisms of anonymity, thereby alleviating this problem. However, the removal of identity can also raise concerns about the legitimacy of an idea.

Conclusion

We have advanced several reasons for why there are excess solutions in the society, argued for the value of collectively harnessing solutions prior to problems, and discussed possible mechanisms for doing so. Our underlying belief is that the solutions to many problems already exist and that they are scattered throughout the society. In Part II below, we present a basic agent-based model that captures the key attributes of problem-solution dynamics. We hope this model can become a robust platform on which to examine various questions raised in Part I.

PART II: AGENT-BASED MODEL

To explore the ideas discussed in Part I, we built an agent-based model of problems and solutions. We opted to create an elementary model in which problems and solutions themselves are the agents (as opposed to some higher level entity such as actors or organizations). This approach forced us to construct a careful and accurate definition of problems and solutions, which is an undoubtedly important prerequisite for any tool designed to probe problem-solution dynamics.

Defining problems and solutions

Our first challenge was to differentiate between information (or knowledge), problems, and solutions. This is a nontrivial challenge since there is no obvious rule to determine at what point information turns into problems or solutions. Something can usually be defined as a problem, a solution, or simply information depending on the relevant circumstances. While it is possible to treat the definition of problems and solutions as circumstantial, we attempted to find a simpler, crisper approach.

At the most basic level, all information can be conceptually defined as solutions, whether potential or realized. Based on this conceptualization, it is reasonable to designate all agents in an agent-based model as solutions. At this point, we have removed the need to distinguish information from solutions. Next, instead of defining problems as structurally distinct from solutions, we define a problem as *an incomplete set of solutions.* (It is important to note here that a problem is never a total absence of solutions – knowing that there is a problem is in itself part of the solution set.)Thus, we are able to collapse three apparently distinct concepts (information, problems, and solutions) into a single mode of representation.

We built our model using NetLogo. [To be continued]

Interactions and evolution

Time required to solve problems

Future directions

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