Supporting Innovation by Promoting Analogical Reasoning[1]

While there are many roads to innovation, there is good reason to believe that it often arises from the adaptation of known solutions in new problem domains.

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Human behaviour contains a striking mix of habit and creativity. On the one hand, much of what we do in life is routine: we tend to take the same route to work each day; we sit in the same seats in classes and meetings; and we purchase the same products at the supermarket each week. On the other hand, our daily life is marked by language use in which we produce novel sentences in new contexts, communicating our thoughts with sequences of words that we have never uttered before.

Much of our everyday behaviour—both the habitual and the productive—feels effortless. In contrast, innovation settings often feel *effortful* and frustrating. Consequently, we are prone to think that innovation requires cognitive processes quite different from those involved in our daily behaviour.

We suggest that feelings of frustration and effort involved in innovation settings arise from an inability to retrieve relevant knowledge that suggests a solution to the current problem. That is, a critical bottleneck in innovative problem solving is the ability of a problem solver (or team) to identify prior instances or principles that facilitate problem solving. Once we understand people's strengths and weaknesses in their ability to retrieve background knowledge, we can develop tools that improve these abilities.

Cognitive Science typically takes one of two approaches to studying problem solving:

The problem space view, whereby problems arise when people have a goal that they must achieve and a set of steps or operations that are available to solve

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the problem, but the sequence of steps or the set of relevant operations is not known *a priori*; and

The background knowledge view, whereby a central method for solving a new problem is to find a prior problem that bears important similarities to the current problem and then to adapt the solution to the old problem to the new situation. The background knowledge might be an analogous situation, or it might be a known specific case from a similar domain.

It is often easy to see the role of background knowledge in innovations retrospectively. For example, barbed wire was modeled on briar bushes that were grown in the west to provide livestock barriers, and **George De Mestral** invented Velcro after noticing burrs sticking to the fur of his dog. The critical issue for promoting innovation, however, is to understand how people come to recognize that knowledge they have in one domain could be useful to solve a current problem. That is, how can we use analogy proactively? To address this question, we first have to give a brief summary of what we know about analogy.

Analogical Reasoning

Analogies involve parallel sets of relationships between domains. We can illustrate this idea with the analogy between an inflatable mattress and water weights described in **Figure One**. An inflatable mattress is used by campers to provide a comfortable surface for sleeping. The mattress is a plastic shell that is inflated with air when it is set up. Water weights are a workout set consisting of inflatable plastic pouches connected to bars. The plastic pouches are empty when packed, but can be filled with water to allow travelers to lift weights on a trip.

These devices are not particularly similar either in the way they look, their specific functions, or the way they operate: an inflatable mattress is large, water weights are small; mattresses are for sleeping on, while weights are for lifting; an inflatable mattress is filled with an air pump, water weights are filled with a faucet. However, these products are analogous, *because they preserve a common set of relationships*: mattresses are hard to travel with because they are heavy, so an inflatable mattress removes the heavy component and replaces it with a resource (air) that provides the same functionality and is available at the location where the mattress is to be set up. Likewise, water weights are hard to travel with because they are heavy. The water weights replace the heavy component with a resource (water) that provides the same functionality and is available at the location where the weights are to be used.

People have a remarkable facility to notice similarities between domains that are not alike on the surface. Analogies also allow people to extend their knowledge of one domain by virtue of its similarity to another. This ability to make analogical inferences is crucial to problem solving. When solving a new problem, the problem statement is only a partial match to the known solutions;

the key to analogical problem solving is to find known problems that have the same structure as the problem being solved.

For example, if someone were trying to create a set of weights that could be used during travel, then the representation of that domain would not contain any information about potential solutions. Solving this problem by analogy requires matching the *problem statement* and the *obstacles to problem solution* (create weights that can be used for travel, because regular weights are heavy) against known problems that have solutions (such as the inflatable mattress). The problem solver can then try to adapt the solution to the new domain.

Adapting solutions is itself not a trivial process. For example, to adapt the inflatable mattress solution to water weights, the weight must be reconceptualized as 'a container that can be deflated.' Then, rather than filling the weights with air, they must be filled with something easily available and heavy, and so water is substituted for air. This process of adapting a solution may itself be accomplished by drawing on further analogies.

It turns out that retrieving analogous problems is not nearly as easy as recognizing an analogy between two domains that are already being compared. A classic demonstration of this point came from a study where researchers told people a story about a general who split his army into groups and had them attack a fortress from a variety of directions, because the main road leading to the fortress had been mined. Later, people tried to solve a radiation problem in which they must treat a patient with an inoperable tumor with radiation. The problem: radiation sufficient to kill the tumor will also kill the healthy tissue surrounding it. The solution is to split the radiation into weaker rays and converge them on the tumor so that the tumor is the only area of tissue that receives enough radiation to be destroyed. Despite having seen the story about the general earlier in the experiment, few people in this study recognized the similarity between this story and the radiation problem.

More generally, research on analogical retrieval suggests that people tend to retrieve information from the same domain as the current situation rather than information that is analogous to the current situation. For example, when solving a problem about oncology (as in the radiation problem), people are likely to think of other medical solutions, or perhaps other solutions involving radiation. Military solutions are unlikely to come to mind.

Improving Analogical Retrieval

Some research has explored factors that affect people's ability to retrieve prior knowledge on the basis of analogical similarity. One study demonstrated that the way that relations are described in the *base* and *target* domains affects analogical retrieval.

In this study, participants were asked to read short passages and then, a few days later, they were asked to read other passages. The passages presented later told similar stories, but using quite different characters. For example, one passage might have been about alien creatures and a second might be about satellites. Thus, the analogous passages were different in their surface information.

Given this setup, people were better able to retrieve the earlier passage they read when the relations were described using general language than when they were described using specific language. For example, the specific relations might have involved 'the alien creatures eating rocks and the satellites taking photographs', while the more general relational language might refer to 'gathering rocks and collecting photographs'. These more 'domain-general' relations made it easier for people to retrieve stories with relational similarities, despite the difference in story domains. Thus, the study demonstrates that the content of the stories had an important influence on the likelihood of analogical retrieval.

Recently, research has begun to examine analogical retrieval abilities in the context of innovative design. In one set of studies, mechanical engineering students with some background in design were given descriptions of products that would be useful in later design projects. For example, the participants might have read about an inflatable mattress like the one described earlier. Later, they were given difficult design problems to solve (e.g., design weights that can be used for travel). Researchers varied the level of abstractness of the description of both the base analogy in memory as well as the abstractness of the description of the design problem. For example, the air mattress might have been described as being filled with a substance at the location where it would be used (a domain-general description) or as being inflated with air in the home where it would be slept on (a domain-specific description).

The results of this study supported previous work in that the domain-general description was more likely to be used than was the domain-specific description of the analogous solution. Interestingly, people were much better at solving the new problem using the analogous solution when the new problem was described in domain-specific language than when it was described in domain-general language. In addition, people in all conditions including the domain-general problem statements produced numerous additional solutions that were not based on the presented analogous solution.

The structure of this study also suggests another factor that may be important for improving analogical retrieval: participants solved the problem in phases. In a late phase of the study, designers were given a 'function structure' that described the problem. Function structures are representations drawn by designers to convey the abstract functional relationships of a design. While they do involve some process choices about the design, they are more abstract than

most descriptions of a design problem are likely to be. Giving participants a function structure that is consistent with a solution to a problem suggested by an analogy also increased people's likelihood of finding the analogous solution. This study did not ask participants to draw their own function structure, and so it does not address the question of what kinds of function structures people would draw on their own given a particular problem statement. This study indicates that engineers should re-describe their design problems in a multitude of representations and that other representations of the design problem are likely candidates for facilitating the innovation.

Tools for Analogical Innovation

This analysis of the role of analogy in innovation suggests that there are two fundamental limitations on the ability of a team to use analogy to solve a new problem. First, the team is limited to the knowledge possessed by its members. Second, even if a relevant analogous solution is within the knowledge base of its members, the people with that knowledge may fail to retrieve it. Thus, tools for analogical innovation must address these two limitations.

Often, teams are constructed by making guesses about the relevant expertise required for that team. For example, a team may have an expert in customer research who has done empirical work on customer needs as well as experts in the particular area of expertise required to create the product (e.g., Mechanical Engineering, Chemistry or Software Design). In addition, the team may have representatives from management and marketing.

A potential problem is that the analogy necessary to create an innovative solution to a problem may not exist in the heads of this group. Typically, design teams are set up at the start of the innovation process based on the domains known to be relevant to the problem. Obviously, it is not possible to foresee the domains for which there are analogous solutions, and consequently, experts in domains that have potentially- innovative solutions to a new problem may not be represented on the team. This suggests that when a design team is created, individuals with expertise *outside of the obvious areas* might also be included to provide a perspective on other potential solutions to a problem that might not be obvious to those within the domains of expertise in which the problem is set. It also suggests that individuals with broader backgrounds, interests and preferences, perhaps termed as 'design generalists,' may facilitate the exploration of potential solutions that may not be readily apparent to a group composed solely of highly specialized individuals.

Developing a Problem Statement

Helping people retrieve analogous examples from other domains requires providing them with techniques for formulating problem descriptions that will capture the 'relational essence' of the problem. Tools must be provided to create a 'scaffold' for devising a *problem representation* that will support finding analogies.

The first element of this scaffold entails ensuring that designers have a clear understanding and representation of the problem to be solved, or, indeed, multiple understandings and representations. This element of problem solving might seem trivial, but there are two reasons why it is not. First, research on causal reasoning suggests that people often believe that they can give a causal explanation for more things than they are actually capable of explaining. This is called 'the illusion of explanatory depth.' Similarly, designers may believe that they have a better understanding of the problem to be solved than they actually do. Thus, as a first step, teams should be encouraged to restate the problem-at-hand as explicitly as possible from multiple perspectives and contexts. This step will root out aspects of the problem that are actually unclear.

Second, many design teams are confronted with problem statements that are initially vague. For example, in one study, researchers gave teams the simple problem of designing 'a spill-proof coffee cup.' Even in real design settings, the problem statement is often not much more specific than that, and as a result, members of a design team may not agree about what problem they are trying to solve.

While at the outset of the design process, it can be useful for team members to consider a variety of problems that they might be solving, as the process progresses, the team must begin to agree on the problem being solved. Thus, the scaffolding created by innovation tools should begin by ensuring that each member of the design team is trying to solve a specific problem. The members of the group should then share their statements of the problem in order to find points of divergence. The group may choose to consider a variety of different potential problem statements, but it is important that they agree on the set of problems that they are solving.

The problem-statement process begins with each member of the design team being given the problem statement as it has been formulated initially. Each team member is then encouraged to provide a detailed description of the problem on their own. They should be explicit about where the problem lies (particular when redesigning existing products), and what methods are to be brought to bear on solving this problem. Designers must also be explicit about the *critical* constraints on the problem to be solved. For example, there are often cost or energy constraints on solutions. If those constraints are not made explicit initially, then teams may develop innovative solutions that cannot be made practical, because they violate fundamental constraints on the problem.

Before settling on a problem statement, the group should also evaluate the degree to which that statement is focused on existing solutions for this problem (if any). For example, a company that made film-based cameras in the 1990s might have wanted to make film 'less expensive to produce'. Such an endeavor would likely have focused on the chemicals in film that lead to the expense and

a search for alternatives. An alternative, however, is to focus on whether there are less expensive mechanisms for capturing images. This formulation of the problem might allow the group to consider alternatives to image storage beyond film.

Once the team agrees on the problem to be solved, the next element of the problem-solving process is finding similar problems with known solutions; that is, the retrieval of analogous problems.

The Next Steps: Creating the Scaffolding

Human memory retrieval is effortless. That is, humans are designed so that information that is active serves as a partial pattern that is completed by other information from memory. A core principle of memory retrieval is *encoding specificity*, which states that information will be retrieved from memory to the degree that the context at the time of retrieval is similar to the context at the time the information was put into memory.

So, what can be done to help people retrieve information? The knowledge people have has already been learned, and so there is no way to influence that. Thus, the only lever at the disposal of the tool designer is to influence the representation of the current problem in a way that will be maximally likely to help group members retrieve prior problems that are analogous to the current problem.

There are three things that designers must be encouraged to do in order to maximize the likelihood of retrieving analogous problems. First, they must be encouraged to focus on the *causal* and *relational* aspects of the problem rather than the *surface contextual elements* of the problem. For example, a team thinking about 'how to make photographic film less expensive' could begin by thinking about improving image-storage media rather than film itself. By recasting the terms of the problem into 'image storage,' team members can then be reminded of many different methods for storing images (including photocopies and digital scanning).

A second and related aspect of this tool, or set of tools, is that it should encourage the use of abstract relational terms to describe the problem. Many of the relational terms we use to describe problems are verbs and 'gerunds' (nouns derived from verbs). Often in technical situations, we use precise language. For example, when describing film, we may refer to particular chemical reactions brought about by exposure of chemicals to light. In the previous paragraph, however, photographic film was described as 'an image-storage medium.' 'Storage' is a more abstract relation than a description of a chemical reaction. There are many tools that can be used to promote more abstract re-descriptions of problems. For example, online language databases like WordNet can be used to find more abstract terms to describe a problem, which are useful for analogical retrieval.

Third, there is a tendency for tools that support innovation to present information in written format. Because there is some reason to believe that analogical retrieval is easier when information is presented in other modalities, the tools for innovation should encourage discussion during design sessions to make the conditions more conducive to analogy finding.

In many cases of innovation, the relevant domains required for solving a problem may not be familiar to members of the team. In this case, it can be useful to have tools to search broader databases for potential solutions to problems. There are many possible sources for solutions, including the patent databases and the broader Internet. For example, we can examine the concept 'carry' in the library of generic concepts developed by the University of Texas at Austin's **Ken Barker** and **Bruce Porter** and **Boeing**'s **Peter Clark**. In this library, the specific event of 'carrying' is broken into the concepts of 'moving', 'locomoting' and 'holding.' Thus, an innovation team could focus on making any of these steps easier to carry out.

Another avenue for developing analogy search tools utilizes the concept of 'functional decomposition' to re-describe the design problem or concepts. The problem can be transcribed into a set of high level, domain-independent terms that address the issue of solution-domain fixation by eliminating causal and structural relationships that are specific to the current process for solving a problem. For example, the concept of 'filtering' can be abstracted to 'separating.' While these kinds of knowledge bases have not yet been applied to innovation tools, they are a promising direction for future research.

In closing

It has long been known that analogies are important for solving new and seemingly-intractable problems. The difficulty lies in finding the relevant analogous domain.

In many cases, analogies between domains are only obvious in retrospect. At the time that the problem is still unsolved, it may not even be clear what kind of problem is actually being solved. Thus, finding the relevant domain requires agreement about the nature of the problem being solved. Once this is achieved, the 'scaffolding' we describe herein can enable innovation teams to embrace analogy and solve new problems.

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FIGURE ONE: Inflatable Mattress vs. Water Weights

Inflatable Mattress:	Water Weights:
Goal: Mattress that can be easily packed	*Goal*: Weights that can be easily packed
Obstacle: Regular mattress is heavy	*Obstacle*: Weight sets are heavy
Solution: Replace mattress filling with air	*Solution*: Replace weights with water-filled bag
Air-filled mattress supports body	Water is heavy
Mattress can be filled on-site	Weights can be filled on site

Figure 1: Analogy between an inflatable mattress and water-filled weights.

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SUPPORTING INNOVATION BY PROMOTING ANALOGICAL REASONING

by **Arthur Markman, Kristin Wood, Julie Linsey, Jeremy Murphy** and **Jeffrey Laux**

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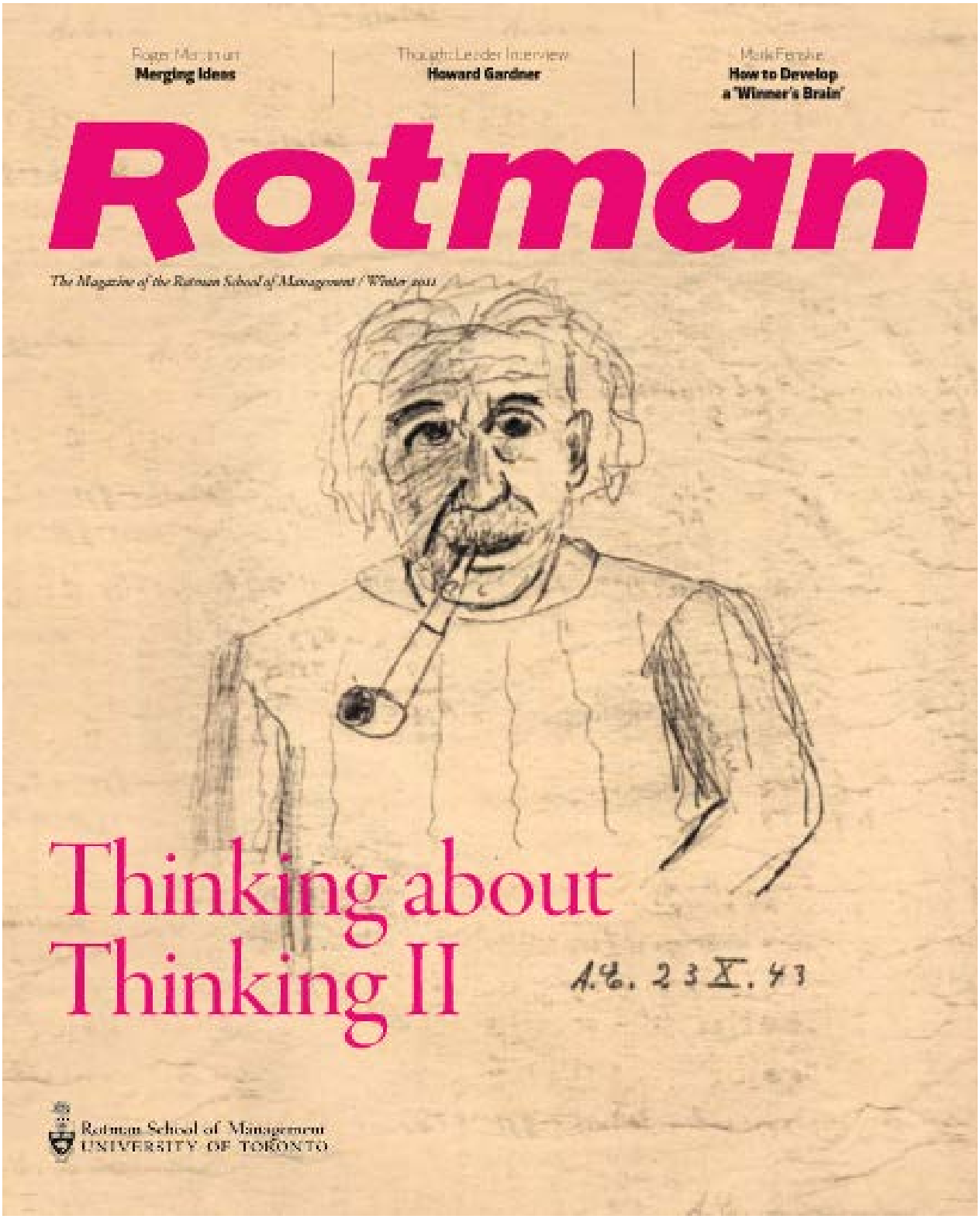
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