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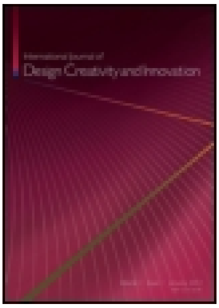

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The Obscure Features Hypothesis in design innovation

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A new cognitive theory of innovation, the Obscure Features Hypothesis (OFH), is applied to the area of engineering design innovation. The OFH states that all innovative solutions are built upon at least one overlooked (i.e., obscure) feature of the problem at hand. In this paper, we first highlight the types of features that exist and the cognitive obstacles that hinder people's ability to notice the obscure members of various feature types. We then detail five innovation techniques we have developed to help designers search the obscure realms of the space of features. Each of these techniques counteracts a specific cognitive obstacle to innovation: *design fixation*, *functional fixedness*, *narrow verb associations*, *assumption blindness*, and *analogy blindness*. We compare our approach with other approaches to innovation in psychology (the *representation change view* and the *distant association view*) and engineering (theory of inventive problem solving and C–K theory). Finally, we show how the innovation techniques can be implemented in software to assist users in the design process.

Keywords: creative process; computational creativity; design methodology; problem-solving

1. Introduction

The aim of this paper was to present to the design community five known cognitive obstacles to innovation (i.e., *design fixation*, *functional fixedness*, *narrow verb associations*, *assumption blindness*, and *analogy blindness*) and concrete techniques that counteract each cognitive obstacle. These counter techniques all flow from our new psychological theory of innovation: the Obscure Features Hypothesis (OFH: McCaffrey, 2012). For each counter technique, we present the best real-world example of its use that is currently available. To counter the cognitive obstacle *assumption blindness*, for example, we have a sophisticated engineering problem that the technique helped to solve: *how to adhere a coating to Teflon*. In contrast, for the classic cognitive obstacle *functional fixedness*, we currently do not have a complex real-world example and so we illustrate it using a "toy" laboratory problem from psychology experiments. Although each cognitive obstacle is an established psychological phenomenon that most likely hinders real-world design innovation, our counter techniques are young (i.e., created in 2011) and are still in the process of being applied to real-world problems. As our new theory continues to mature and be moved out of the psychology laboratory to the real world, we will continue

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*Corresponding author. Email: tony@innovationaccelerator.com to assess how much each cognitive obstacle actually hampers efforts at real-world design innovation.

Innovative designs are so important for leading UK companies that 75% of their profits come from products that were not in existence just 5 years prior (Cox, 2005). But where do innovative designs come from? A possible answer: Innovative designs are built upon the overlooked (i.e., obscure) features of the problem at hand. Overall, innovation is putting the obscure to work for something useful. In this article, we justify our characterizations of these concepts and demonstrate how they lead to a systematic approach to innovation. We make our approach systematic by following three steps: categorizing the possible types of features of a design problem, articulating the cognitive obstacles to noticing the obscure members of each feature type, and devising a counter technique to each cognitive obstacle so that the obscure members can be noticed.

We will compare and contrast the OFH approach with other approaches to innovation in psychology (i.e., the *representation change view*: Ohlsson, 1992; Knoblich, Ohlsson, Raney, Haider, & Rhenius, 1999; and the *distant association view*: Mednick, 1962) and engineering (theory of inventive problem solving (TRIZ): Altshuller, 1996; and C–K theory: Hatchuel & Weil, 2009). Next, we will present effective counter techniques to three well-known cognitive obstacles (i.e., *design fixation*: Jansson & Smith, 1991; Purcell & Gero, 1996; Smith, 1995; *functional fixedness*: Duncker, 1945; and *analogy blindness*: Gick & Holyoak, 1980, 1983) and two new cognitive obstacles that became visible under the OFH approach (i.e., *narrow verb associations* and *assumption blindness*). For each counter technique, we show how software can assist designers in using the technique.

2. Obscure features and innovative solutions

If an unsolved problem ultimately has a solution, then something is being overlooked. If a problem has been unsolved for an extended period of time, then that which is overlooked is most likely not commonly noticed; for if it were commonly noticed, the problem would most likely have been solved by now. From this reasoning, we hypothesize that an innovative solution comes after uncovering something about the problem that is either infrequently noticed or never-before noticed (i.e., *obscure*). We characterize all possible *somethings* of a problem using the umbrella term *features*. Other researchers may refer to them using various other terms: properties, components, attributes, behaviors (Gero, 1990), resources (Altshuller, 1996), relations, effects, facets, aspects, or any other related term.

Based on this terminology, the OFH, in brief, states that the solution to a solvable problem that has been unsolved for an extended period of time is most likely built upon at least one obscure feature of the problem. The reasoning goes that uncovering obscure features of the problem increases the probability of noticing the key obscure feature(s) that ground a novel solution.

Up until now, the notion of *obscure feature* has been presented in a metaphorical manner. We will make both the concepts *obscure* and *feature* more rigorous. In this section, we will focus on the concept *obscure*. We will wait until Section 4, however, to make the concept of *feature* more rigorous – using an extended example in Section 3 to build up the reader's intuition before actually defining it.

A feature can be considered *obscure* if it is listed by fewer than some specific percent (e.g., 10%) of subjects in a feature-listing task. During a feature-listing task, subjects are usually given a time limit (e.g., 4 min) to list out all of the items of an object that they understand to be either an association of that item, a feature, a property, an attribute, or any other related term (e.g., component, facet, and relation). Because subjects often differ in their understanding of a feature, we give them a cluster of terms that are considered to overlap in meaning. A feature-listing task in conjunction with a specific cutoff (e.g., 10%) allows us to quantify what it means for a listed item to be obscure.

3. Where obscure features live

We now layout the various locations where obscure features might reside. A standard way to conceptualize design innovation is to view it as an iterative process between top-down *problem framing* and bottom-up *problem solving* (Rittel & Webber, 1984; Simon, 1995). *Problem framing* involves refining the goal by doing things such as altering the expression of the goal. *Problem solving* involves unearthing features of the available objects and materials, and then interacting them in order to produce effects that help satisfy the goal. We will break up the *problem solving* process into two components: unearthing features and crafting interactions. We find that this tripartite division is more advantageous for several reasons. First, it specifies three distinct locations where obscure features may reside. Obscure features may reside in the expression of the goal, in the available objects and materials, and in the interactions among the available items.

Second, the three-way division is more compatible with the Function–Behavior–Structure (FBS) model (Gero, 1990; Gero & Kannengiesser, 2004) than a two-way division. From the perspective of an object, Function tells us what the object is for; Behavior tells us what the object does; and Structure tells us what the object is (Gero & Kannengiesser, 2004). Switching focus from a completed object to the activity of designing an as yet unknown object reveals the following correspondences: Function now corresponds to what the desired object is for; Behavior corresponds to what the desired object will do; and Structure corresponds to what the desired object is. Figure 1 shows a general picture of the three zones of the design activity network.

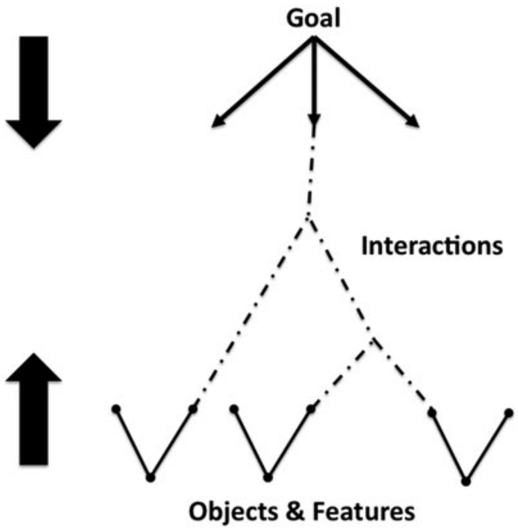

Figure 1. Three zones of the design activity network.

The goal grows down as it is refined and reframed. The objects grow upward as more of their features are uncovered. Objects interact to produce effects that satisfy the design goal.

To illustrate our three-zone approach to design innovation, we will use an insight problem used in psychology experiments that test innovation. The problem is simple enough to keep our figures and descriptions manageable, while complex enough to present the dynamics involved in all three zones of our proposed network.

Consider the Two Rings Problem from McCaffrey (2012). Two weighty steel rings must be fastened together in a figure-eight configuration using only a long candle, a match, and a two-inch cube of steel. Melted wax is not strong enough to hold the rings together, so the problem's solution relies on noticing that the wick of the candle is a string which, when extricated from the candle by scraping away the wax on the steel cube, can be used to tie the rings together. In an experiment, when given no assistance, only 4 of the 14 of our subjects, who were undergraduate psychology majors, solved this problem given 8 min to work on it (McCaffrey, 2011). When another group of 15 subjects was told in the problem description that the wick was a string, all 15 subjects easily solved the problem (McCaffrey, 2011). Subjects tend to notice that the candle has a wick, but few notice that the wick is a string. Hence, this feature of the wick can be considered obscure for this particular population of subjects (i.e., undergraduate psychology majors). This problem suffers from *functional fixedness* (Duncker, 1945), which is described as the tendency to fixate on the common use of an object or its parts. In a later section, we will present the first effective technique to counter *functional fixedness*.

As shown in Figure 2, the goal is initially expressed as *fasten ring to ring*. Based on the work of Hirtz, Stone, McAdams, Szykman, and Wood (2002), all engineering goals and operations can be expressed by a verb. Consequently, we will express all goals as verb-leading phrases that have the form *verb noun-phrase prepositional-phrases*. Furthermore, we will express the effects derived from all interactions (i.e., operations) in the middle zone using the same *verb noun-phrase prepositional-phrases* form. The verb describes the change that will satisfy the goal (e.g., *fasten*) or the change that has been enacted through the interaction. The noun phrase (e.g., *ring*) names what needs to be changed and the prepositional phrase (e.g., *to ring*) articulates an important relationship (i.e., one ring fastened to the other).

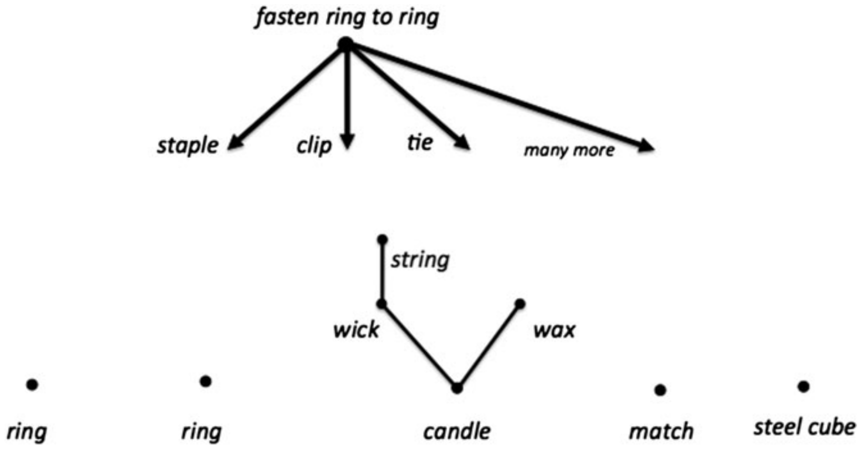

Figure 2. Snapshot of design innovation network for Two Rings Problem.

As the verb *fasten* is very general, one way to refine the goal is to add specific verbs that describe how the fastening might take place. The online thesaurus WordNet (Miller, 1995) lists 61 verbs that express specific ways to fasten things together. Figure 2 shows a small portion of this list. After engaging in this top-down process of goal refinement, people may then switch to the bottom-up portion of the converging networks. The available objects each possess a node at the bottom of Figure 2. As parts and features are added to the representation, they are added above the initial node so that the bottom network grows upward toward the goal. For Figure 2, we only focus on what is necessary to solve this problem. The candle is broken down into its two parts: *wax* and *wick*. The key to the solution is to notice that the wick is also a string, so we added *string* above *wick*. After the string is recognized, people generally need no further assistance so they do not explicitly graph out the interactions necessary to complete the problem. For completeness, however, we will describe the verb-leading phrases that describe the sub-goals and operations to achieve those sub-goals. In order to *free string from the wax*, we need to *scrape wax on the steel cube*. Once the *string* is free, then we can interact the string with the rings in the following manner: *tie ring to ring*. In this way, we accomplish the original goal *fasten ring to ring*. Figure 3 shows the basic interactions that are needed to solve the Two Rings Problem.

Figures 1–3 show the basic content and structure of each of the three zones and their relationship with each other. In this paper, we focus on two zones of Figure 1 (i.e., Goal Zone & Objects and Features Zone) and look to the obscure features in the Interactions Zone as future research. We will begin to systematize the types of features possible in the two zones under consideration, the cognitive reasons that the obscure features are being overlooked, and techniques to counteract the cognitive reasons in order to uncover the obscure features.

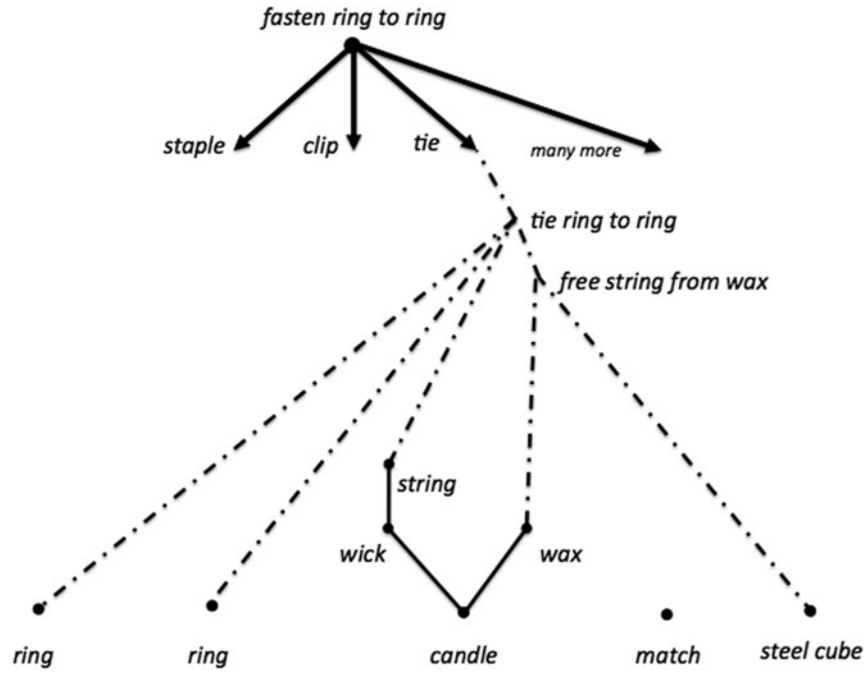

Figure 3. Interactions for solving the Two Rings Problem.

The OFH concentrates on features as the significant unit for enhancing innovation, in contrast to two other approaches to innovation in psychology that are based on representation changes (Knoblich et al., 1999; Ohlsson, 1992) and associations (Mednick, 1962). In engineering, the OFH contrasts with TRIZ (Altshuller, 1996), which, for much of its history, focused on contradictions (Rantanen & Domb, 2008). The OFH, as we will see, complements the C–K theory (Hatchuel & Weil, 2003) in that the OFH carries out a lower-level analysis of features where the C–K theory engages in a higher-level analysis.

4. An expansive understanding of a feature

In this paper, we define a feature as an effect of an interaction. As we will see, this expansive definition has several advantages for innovation. If we define a *feature* narrowly, then we are excluding from the outset, and thus overlooking, a whole range of things that might be the basis for innovative designs. If innovation is built upon the obscure, then a definition of feature needs to be expansive or we are eliminating a priori features that could become the basis of innovative solutions.

The history of a feature's definition in the psychological and engineering literatures reveals two limitations. First, the definitions are narrow. Second, the definitions do not reveal where new features of an object come from as time passes. As we will see below, the origin of new features is crucial for knowing where to look for obscure features – which are often new. Schyns, Goldstone, and Thibaut (1998) present a typical definition in their review of the psychological literature: "any elementary property of a distal stimulus that is an element of cognition, an atom of psychological processing." This definition relies on an understanding of property, which is left undefined. Furthermore, it assumes that a feature corresponds to some smallest unit of cognition. But depending on the task at hand, humans switch what is elemental in their thinking. For a carpenter, a piece of wood might be the unit of conception. For a physicist, however, we might conceive of wood at a level of atoms, sub-atomic particles, or even sub-atomic strings. Depending on the task, humans easily adjust what is the unit of cognition for that task. Finally, the definition does not tell us how new features of an object come into existence.

Salomons, van Houten, and Kals (1993) present a review of the engineering literature's definitions of feature, all of which are some variation on the following: "information sets that refer to aspects of form or other attributes of a part." The unspecified notions of "form" and "attribute" in this definition leave it at a vague level and potentially exclude many things that could become the basis of innovative designs. Furthermore, it does not give us an indication of the origin of new features.

So where do new features come from? New features come from interacting an object with combinations of other objects and conditions that it has never interacted with before. For example, superconductivity in ceramics emerged from interacting a specific ceramic material with electricity at a near-absolute-zero temperature. As another example, interacting microwaves with hard candy led to a new feature of microwaves: namely, that they can be used to cook food.

In brief, a feature of an object is an effect of an interaction. Our definition is inspired by the philosopher Nietzsche (1901/1968). As Nietzsche states: "The features of a thing are effects on other 'things': if one removes other 'things,' then a thing has no features..." (Nietzsche, 1901/1968). From this vantage point, no feature is intrinsic to the object but results from an interaction. For example, mass and length are strong candidates for being intrinsic to the object. Special relativity theory informs us, however, that as the speed of an object increases, its length contracts and its mass increases (Einstein, 1920/2004).

Length and mass are really the result of interactions: in this case, an interaction between an object travelling a certain speed and a measuring device in a frame of reference. From more recent science news, there is another reason that mass may not be intrinsic. A particle's mass appears to be the result of an interaction between the particle and Higgs bosons.

The advantages to our definition of a feature are at least fourfold. First, it is expansive in that it includes anything that produces an effect. Second, it tells us how to generate new features, which is a great source of obscure features. Third, as described more fully below, the definition permits a precise problem-solving grammar in which any effect can be expressed as a phrase of the form *verb noun-phrase prepositional-phrases* (e.g., "reduced vibrations below 1800 Hz"). The verb expresses the change that happened during the effect (i.e., something was reduced). The noun-phrase names that which was changed (i.e., vibrations) and the prepositional phrases describe important constraints and relations (i.e., the vibrations were initially over 1800 Hz). Fourth, having established a sufficiently expansive understanding of *feature*, we can begin to develop a category system for the types of features that an object can possess (see Section 6.1).

5. Other approaches to innovative design

The OFH approach to innovation enhancement emerged from the field of cognitive psychology and is the first psychology approach that leads to a systematic derivation of innovation-enhancing techniques. In contrast, two other psychological approaches to innovative problem solving stopped short of becoming systematic. The *representation change view* (Knoblich et al., 1999; Ohlsson, 1992) states that all problems needing innovation require a change in the problem's representation. However, these authors never specified the possible types of representation change, the cognitive inhibitions to noticing these needed representation changes, and techniques to assists problem solvers in noticing these needed representation changes. Similarly, the *distant association view* (Mednick, 1962) states that problems needing innovation require the use of an association that is semantically distant from the initial concepts of the problem. Again, researchers following this view have not specified the possible types of associations, the cognitive inhibitions to noticing distant associations, and techniques for assisting problem solvers in noticing these distant associations. In contrast, the OFH approach specifies the types of features possible, the cognitive inhibitions to noticing the obscure features, and techniques to assist in the noticing of obscure features.

In the engineering field, TRIZ (Altshuller, 1996) is a mature, systematic approach to innovation that can deal with the complexities of real-world problems. Multiple tools have been developed under the TRIZ umbrella, including technical system evolution, substance-field analysis, and ARIZ – Algorithm of Inventive Problem Solving (Rantanen & Domb, 2008). Given the vast richness of TRIZ, presently we will focus our comparison on early TRIZ, which was based on contradictions. A full comparison between the many facets of TRIZ would be too extensive for this paper. Furthermore, as the OFH approach has only been in existence since 2011, it seems premature to engage in a full comparison between the mature approach of TRIZ and the young yet promising OFH approach.

Early TRIZ was based on the belief that all unsolved problems involved contradictions (Altshuller, 1996). A contradiction is the attempt to have two features take on seemingly impossible values at the same time. For example, suppose one wants a pill bottle to be secure from children yet also be easy to open for adults. Being both secure and easy to open seems to name a contradiction about pill bottles that needs to be overcome in order to solve the problem. Altshuller (1996) articulated 40 principles that could help overcome various contradictions and placed them in a table. You could look up the most promising principles for your problem in the table by finding your contradictory requirements along the sides of the table.

Later, it was realized that not all problems rest upon contradictions (Rantanen & Domb, 2008). For example, suppose a candle company wants to design a new candle for next year's line of products. The goal of designing a novel variation on current candles does not contain a contradiction. There are no contradictory requirements preventing new candles designs from existing. People have simply overlooked a feature that they could vary to craft a new design. The OFH approach, as shown in Section 6.1, has a technique that helps designers notice the overlooked (i.e., obscure) features of a candle so they can become the basis of new designs. Furthermore, even if a problem has a contradiction, because its solution is non-obvious, it must be built upon at least one feature that is being overlooked (i.e., obscure). Techniques to effectively search the possible space of features and overcome cognitive inhibitions to noticing the obscure ones, most likely, can help with any type of problem requiring innovation. For example, the OFH approach has particular techniques explored in this paper that help uncover the obscure features of the goal (i.e., *design a pill bottle that is both secure from children and easy to use for adults*). Specifically, we present techniques to overcome three goal-oriented cognitive obstacles: *narrow verb association*, *assumption blindness*, and *analogy blindness*. Other OFH techniques work bottom-up and help uncover obscure features of current pill bottle designs that might be leveraged into new, more effective designs. Specifically, we present techniques to overcome two bottom-up cognitive obstacles: *design fixation* and *functional fixedness*.

The C–K theory presents a design theory which models the interplay between two interdependent spaces, each with its own structure and logic (Hatchuel & Weil, 2003). As shown in Figure 4, K-Space stands for "knowledge space" and contains propositions about the topic of interest, each of which possesses a truth value. C-Space stands for "concept space" and contains propositions that are undecidable relative to the propositions of K-Space. Undecidable means that the propositions of K-Space are insufficient to prove either that a proposition is true or false (Figure 4).

All concepts in C-Space assume the form: "There exists an object $\boldsymbol{x}$ for which a group of features F_1, F_2, …, F_n are true in K" (Hatchuel & Weil, 2009). The goal of the design process is to formulate a concept that, if true, could satisfy the designer's goal and then transform this undecidable proposition of C-Space into a true proposition in K-Space. If an element of C-Space becomes a member of K-Space, this means that an object possessing certain features, F_1, F_2, …, F_n, is shown either to exist or proven unable to exist. During the design process, both K-Space and C-Space expand and when concepts move from C-Space into K-Space, then C-Space shrinks.

The C–K theory is general enough to model the information flow of any design activity whether that problem is ultimately solved using TRIZ, the OFH approach, or any other approach. For example, the pill bottle problem that contains a contradiction could be modeled in the C–K theory by initially positing a concept in C-Space such as the following: "There exists an object **x** that is secure from children and easy to open for adults." K-Space would initially contain all relevant truth-valued propositions about pill bottle designs, child safety measures, and so on. As the design process progressed, new truth-valued propositions could be added to K-Space or deduced from other propositions in K-Space. Furthermore, new concepts in C-Space could be

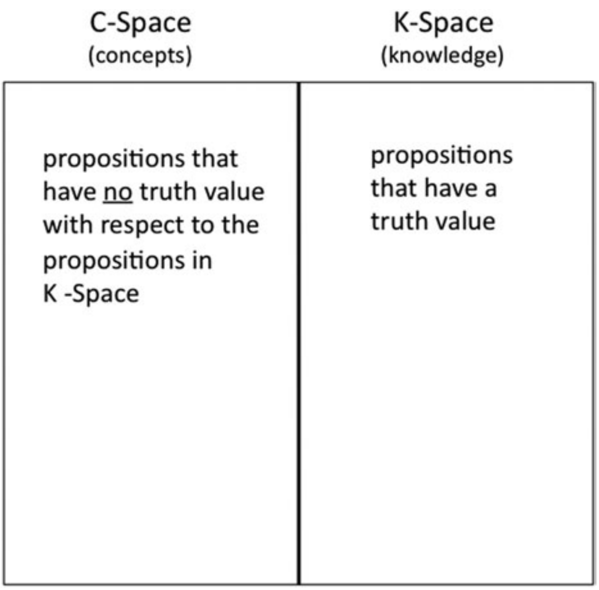

Figure 4. The two interdependent spaces of C–K theory.

deduced from other concepts in C-Space or posited anew into C-Space. The goal of the design activity would be to try to make the originally posited concept true – that there does exist a child-secure and adult-friendly pill bottle – by moving it from C-Space to K-Space.

To model the Two Rings Problem in the C–K theory, posit an initial concept in C-Space: "There exists an object **x** that securely fasten two steel rings together in a figure-eight configuration." K-Space would contain knowledge (i.e., true propositions) about the objects available to solve the problem. When the originally posited concept in C-Space is shown to be true, then it can be moved from C-Space to K-Space and the problem is solved.

The C–K theory models the general logic of the design process as well as distinguishes that which is known (elements in K-Space) from that which is proposed (elements in C-Space) and must be shown to be true (moved into K-Space). The C–K theory lists the features that the desired object needs to possess (in C-Space) and lists the features possessed by the known objects (in K-Space). The OFH approach goes further and adds the crucial distinction between common and obscure features. Figure 5 shows the division of both C-Space and K-Space into two regions: a region for the propositions mentioning only common features and a region for the propositions mentioning one or more obscure features. According to the OFH, innovation in the design process cannot occur until at least one entry is made in either the *obscure region* of C-Space or the *obscure region* of K-Space.

Consequently, the C–K theory and the OFH approach are compatible and in fact complementary. The OFH approach adds a further distinction that amends the C–K theory diagrams in the manner shown in Figure 5.

In the next sections, we present the process of uncovering obscure features first for physical objects/materials and then for goals.

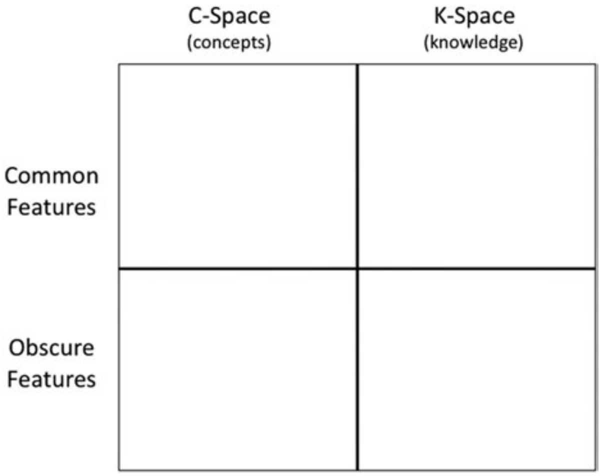

Figure 5. Amending the C–K theory with obscure features.

6. Obscure features in objects/materials

For obscure features for objects and materials, we present two classic cognitive obstacles, *design fixation* (Jansson & Smith, 1991; Purcell & Gero, 1996; Smith, 1995) and *functional fixedness* (Duncker, 1945), and techniques to successfully counteract them.

6.1 Overcoming design fixation

Design fixation is posited to occur when a designer is trying to create a novel design but fixates on the features of known designs they have witnessed (Jansson & Smith, 1991; Smith, 1995; Smith, Ward, & Schumacher, 1993). Relatedly, Ward, Patterson, and Sifonis (2004) manipulated task instructions to try to obtain more creative responses. In a drawing task to create alien creatures, some subjects were instructed to think of specific Earth animals as models while other subjects were instructed to focus on more abstract considerations such as environmental conditions and survival needs. Subjects focusing on abstract considerations produced creatures judged to be more novel. Instead of moving focus to more abstract features, we attempt to shift the subjects' focus from the commonly noticed features to the infrequently noticed features.

To address the range of possible features, we initially developed a taxonomy of types of features possessable by physical objects and materials. Starting with our definition of a feature, an effect of an interaction, we analyzed possible features into types. At the time of the analyses conducted for this paper, our Feature Type Taxonomy (FTT: McCaffrey, 2011) consisted of 32 feature types (see the Appendix). Our latest version of the taxonomy, however, borrowed feature types used in the TRIZ matrix (Altshuller, 1996) and now consists of 50 feature types. We continue to refine the FTT based on our experience with new design problems. Because the FTT attempts to provide a panoramic view of the feature space of a physical object/material, we propose that designers look at the objects/materials of their problem through the lens of the FTT so as to bring their attention to the features that are normally overlooked for those objects/materials. In this way, they can possibly relieve their fixation from the features that known designs are based on and increase the novelty of their designs.

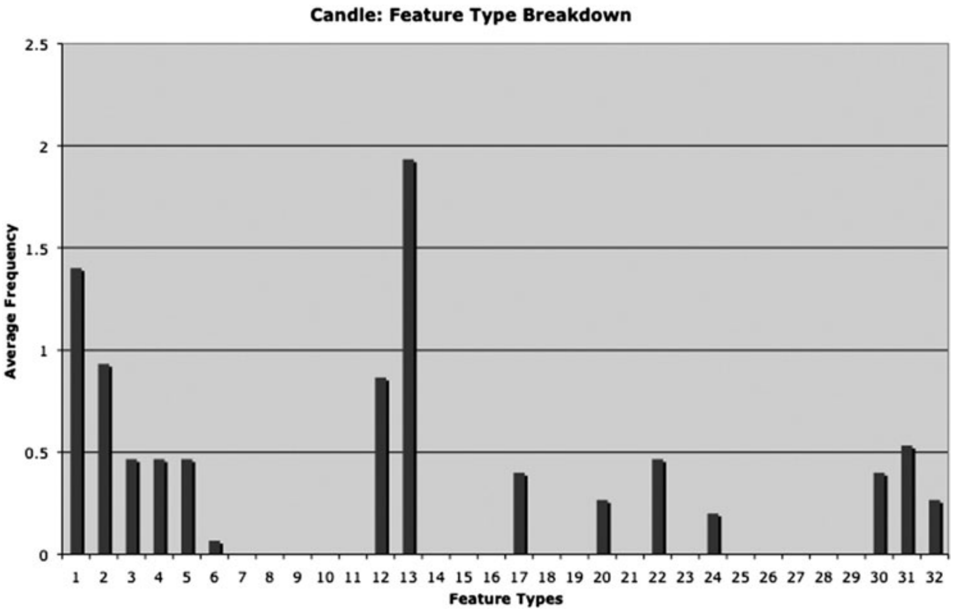

Figure 6. Which feature types of a candle are commonly noticed?

To test our hypothesis that feature types of objects are overlooked, we had 15 undergraduate psychology majors write down as many features as they could in 4 min for each of 14 common objects (e.g., candle, basketball, and broom). We categorized their responses in the 32 categories of the FTT. All the feature types are listed in the Appendix, but for the examples discussed in the text, we will only mention the relevant feature types. To save space, the *x*-axis of Figure 6 only shows the 32 feature types presented by number. The numbering scheme can be fully decoded by looking up the numbers in the table in the Appendix. The *y*-axis of the graph represents the average number of times these subjects listed a feature of a particular type.

Figure 6 shows the bar graph for a candle. For all 14 common objects analyzed, these subjects overlooked on average 20.7 of the 32 categories (64.7%). In other words, on average 20.7 of the 32 categories had either one or no responses. To test our hypothesis that new designs of an object can be built based on the overlooked feature types for that object, we present the results of a case study in which the first author challenged himself to create a series of novel candle designs and then tested their novelty by having two candle companies examine the designs. Because candles have been in existence for approximately 5000 years, certainly, in that time period, nearly every type of candle has already been invented. It is unlikely that novice candle designers could come up with a design that candle experts have not already seen or thought about. However, as all 32 feature types of the FTT apply to every object and subjects overlooked many feature types of a candle (as shown in Figure 6), this suggests that many new candle designs are possible that build upon the overlooked feature types.

In the course of two 1-h sessions, the first author created 10 candle designs that he personally thought were new. Each design was based on one or more obscure feature types from Figure 6. He then obtained an audience with two different candle companies in Massachusetts, which both confirmed that 9 of the 10 designs were actually new to the candle industry. One of the candle companies, *Pilgrim Candle*, is licensing one of the designs from us: the *self-snuffing candle*. We present below how the FTT was used to generate the *self-snuffing candle*. The other candle designs were crafted using the FTT in a similar manner.

In our survey, not a single subject mentioned anything about the motion (type #28) of a candle (e.g., "candles are motionless when they burn"). This oversight suggests that putting a candle into motion of its own dynamics might be a promising avenue for new designs. Candles do exist, however, that leverage the rising hot air that comes from a burning candle to trigger motion in small fans above them. Furthermore, candles exist in which the candle sits on a spring and moves to maintain its same basic height because it becomes lighter and shorter as it burns. These are the only two moving candles we found, which suggests that candles moving of their own dynamics is an underexplored category.

As motion is an obscure feature of candles, the first author looked for objects that are commonly associated with motion. This would allow him to find two domains to combine together: candles, where motion is uncommon, with another object, where motion is common. Specifically, he focused on vertical motion and listed those objects already closely associated with vertical motion: elevator, escalator, justice scales, rocket, kite, and so on. He next attempted to adapt the motion-producing mechanism used by these objects for use with a candle. Presently, we will only illustrate the blending of a candle with a justice scale. A candle is placed on one side of a scale-like structure and is counterbalanced by a weight on the other side. As the candle burns, it loses weight and slowly rises. A snuffer is placed above the candle so it would slowly move into the snuffer and extinguish itself. We named this candle the *self-snuffing candle*.

Our evidence suggests that nearly two-thirds of the possible feature types (64.7%) of common objects are overlooked, especially for the population of undergraduate psychology majors. Our case study provides an "existence proof" that it is possible to turn the overlooked feature types into designs deemed novel and desirable by industry experts. We suggest that examining any object through the lens of the FTT could unearth obscure features that could lead to new designs. Examining an object through the lens of the FTT shifts the attention from the commonly noticed features to the obscure feature types, and thus could possibly help designers overcome *design fixation*. Future work will move beyond our case study to test this hypothesis in an experiment.

6.2 Computer assistance for the FTT

We have a patent filed for software which receives a list of an object's known features from either an electronic source or a group of people, categorizes the features based on an FTT, and produces a bar graph as output (McCaffrey, 2013a). This software helps designers quickly identify obscure features of an object so they can leverage them into innovative designs.

6.3 Overcoming functional fixedness

Functional fixedness is the tendency to fixate on the common use of an object or its parts (Duncker, 1945). A consequence of *functional fixedness* is that people tend to overlook the features of the object that could lead to other uses. McCaffrey (2012) presented the first technique to successfully overcome functional fixedness. In the Two Rings Problem, for example, people generally notice the candle's wick but tend not to notice that the wick is a string. The word *wick* implies the use of burning to emit light, which often inhibits people from analyzing the wick further. The basic idea of a counteracting technique for *functional*

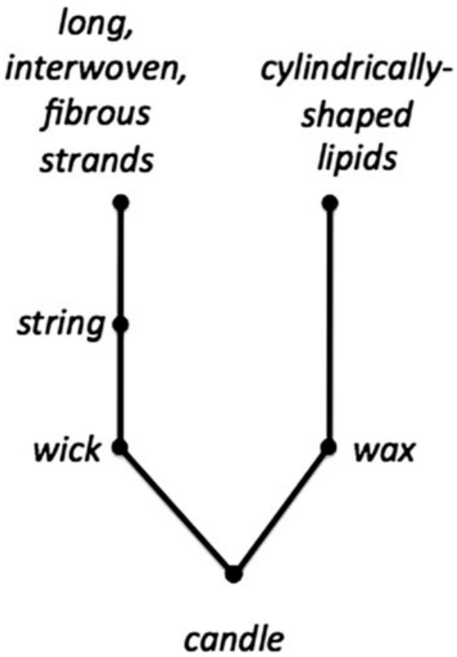

Figure 7. Generic parts diagram for a candle.

fixedness is to build a tree of parts for an object using the following method. For each part description, ask yourself two questions. Can the part be further decomposed into subparts? If so, place the sub-parts in the next level of the tree. Does your description imply a use? If so, then create a more generic description that does not imply a use. Figure 7 shows a parts diagram for a candle after following this technique.

Because *wick* is closely associated with a use, we created a more generic description based on its material composition. Because *string* is also closely associated with a use (i.e., tying things together), we created an even more generic description that includes the shape (i.e., *long*) and material make-up (i.e., *fibrous strands*) of a string. In the context of a candle, *wax* is closely associated with how it contributes to the use of the candle. So, to be cautious, we created a generic description of candle wax. The leaves of this parts tree contain descriptions that do not imply a use. Because the parts get smaller as one moves up the diagram, the relative sizes of the parts are implicit in the diagram. This generic parts technique (GPT) is designed to overcome functional fixedness, which generally hinders people from noticing four types of features (i.e., material, shape, size, and parts) (McCaffrey, 2012).

Prior to the GPT, Knoblich et al. (1999) suggested breaking an object into its parts (i.e., chunk decomposition) but this technique does not fully overcome *functional fixedness*. In the Two Rings Problem, for example, people need to notice that a wick is a string, but chunk decomposition leaves subjects at the level of wick and wax, which is generally insufficient to move people beyond the common function of a wick.

Fourteen subjects (i.e., undergraduate psychology majors) in a psychology experiment were taught to execute the GPT technique and then given eight benchmark innovation problems to solve (McCaffrey, 2012). Benchmark problems consisted of the standard insight problems used in psychology experiments, including the Two Rings Problem.

Subjects using the GPT solved 67% more benchmark innovation problems than a control group (also 14 subjects) who were given no technique to help them solve the problems (49% solution rate for the control group and 83% for the GPT group). Based on a *t*-test, this difference was highly significant, $t(26) = 4.23$, $p < .001$, and had an incredibly large standardized effect size, a Cohen's *d* of 1.6 (scale for Cohen's *d*: 0.25 is a small effect, 0.5 is medium, and 0.8 is large). These results strongly suggest that the GPT can help counteract *functional fixedness*.

Functional fixedness is a common problem emanating from a close association of an object/part with its common use. People tend to overlook the raw object itself and look at the object through the lens of the effects that it tends to produce during its common use. The GPT is the first technique to successfully strip away this layer of common effects in a systematic manner in order to help people consider more of the raw object itself.

6.4 Computer assistance for the GPT

Subjects using the GPT did not solve all the problems in the previous experiment and their 83% solution rate still leaves room for improvement. An examination of their solution sheets reveals that none of the subjects created a full generic parts diagram (McCaffrey, 2011). Furthermore, a postexperiment questionnaire reveals that all subjects performed the GPT mostly "in their heads" (McCaffrey, 2011). To counter this sloppiness in using the GPT, the GPT was implemented in software and then a small pilot study was conducted in which two subjects used the software while working on the same eight benchmark problems from the psychology experiment just described (McCaffrey & Spector, 2011). The software was designed to help users construct parts diagrams by continually asking questions such as "Can the wick be decomposed further into parts?," "What is the material make-up of a wick?," and "Does your description imply a use?" For all eight benchmark problems, the program guided its users to the key feature for solving the problem and all problems were solved by both subjects. Future work will formally test what the pilot work suggests: that GPT software can improve performance beyond executing the GPT by hand.

6.5 Summary of obscure features of objects/materials

We presented two cognitive obstacles to noticing obscure features of physical objects and materials, *design fixation* and *functional fixedness*, and their countering techniques. The countering technique to *design fixation* switches a designer's focus to the overlooked features of the object/material under consideration. The countering technique to *functional fixedness* unearths obscure features of four types: parts, shape, material, and size. When attempting to uncover obscure features of physical objects and materials, which technique should be used first? At this point in our research, we have no recommendation on the order that the techniques should be tried. Both techniques could uncover a feature that becomes the key to an innovative solution and the order of use is a topic of future research.

7. Obscure features of goals

Often, the trouble in design comes from an inaccurate or unrefined statement of the goal. Hirtz et al. (2002) posits that an engineering goal or operation can be expressed as a verb. Hirtz et al. (2002) develop a hierarchy of approximately 200 verbs that covers most of the changes that can take place for physical objects and materials. This hierarchy starts from eight basic verbs (*branch*, *channel*, *connect*, *control*, *convert*, *provision*, *signal*, *and* *support*) and then branches into more specific versions of these highly general verbs. For example, a more specific version of *branch* is *separate*. In this article, we focus on two ways that obscure features of verbs could be unearthed to assist design innovation. We introduce two new cognitive obstacles, *narrow verb associations* and *assumption blindness*, and their counteracting techniques.

7.1 Overcoming narrow verb associations

The structure of the verb hierarchy developed by Hirtz et al. (2002) is also found in the online dictionary and thesaurus WordNet (Miller, 1995) developed at Princeton University. WordNet divides synonyms of verbs into those that are more general (hypernyms) from those that are more specific (hyponyms). Figure 8 shows a small portion of WordNet's hierarchy for the verb *fasten*.

Note that each of the hyponyms of *fasten* suggests a specific way to fasten things and also implies what objects or materials are used. For example, the verb *tie* suggests a way to fasten things together using string, rope, and so on. Importantly, there are 61 hyponyms of *fasten* in WordNet with each suggesting a way to accomplish the fastening. Perhaps, WordNet's list of verb hyponyms could be used by designers to consider the many ways to enact a general verb. Specifically, we hypothesize that WordNet contains more verb hyponyms than people can generate on their own. To test this hypothesis, we had 15 subjects (i.e., undergraduate psychology majors) list all the synonyms they could for six verbs. The number of hyponyms in WordNet for each of the six verbs is given in parentheses in the following list: *fasten* (61), *remove* (172), *guide* (50), *transport* (46), *mix* (24), and *separate* (115). Subjects listed 8.1 synonyms on average with a margin of error of 2.8. Furthermore, 3.9 synonyms on their lists were hyponyms. Based on these results, it appears that the WordNet verb structure could expand the human ability to list the synonyms of verbs, in general, and the hyponyms of verbs, in particular. We call the tendency for humans to list only a few synonyms of verbs *narrow verb associations*.

7.2 Computer assistance for narrow verb associations

Navigating the WordNet verb structure, especially when represented as a hierarchical tree as shown in Figure 8, would perhaps allow designers to easily peruse the many ways that their goal could concretely be accomplished. As the WordNet verb structure is more extensive than the 200 verbs in the hierarchy proposed by Hirtz et al. (2002), we would create a verb hierarchy that preserved the hierarchical relationships proposed by Hirtz et al. (2002) but also included all the verbs used in WordNet. In this way, the verb

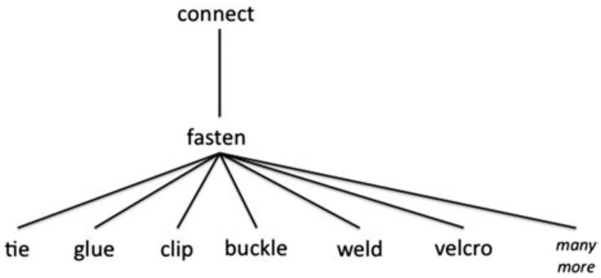

Figure 8. Sample of verb hierarchy in WordNet.

relationships most relevant for engineering goals are maintained while many new verbs are included to fill in any gaps that may exist in Hirtz et al. (2002).

7.3 Overcoming assumption blindness

Another challenge related to the goal verb is the many assumptions hidden behind the verb chosen to express the goal. Often, humans are oblivious to many of the assumptions made by the verb so we call this *assumption blindness*. For a concrete example, an engineering firm approached us with the following unsolved problem: *adhere a coating to Teflon*. Because of the features of Teflon, this problem is equivalent to *adhere a coating to a no-stick surface*. Everything the company tried had failed and most often damaged the Teflon.

To measure the assumptions that people are blind to for the verb adhere, we recruited 15 subjects (i.e., undergraduate psychology majors) to list all the assumptions they could for this verb. More specifically, we asked them to consider what features of the final solution they were assuming when they used the verb *adhere*. We categorized the assumptions they listed based on the categories of the FTT. As shown in Figure 9, this population of subjects are generally unaware of 15 of the 32 categories (47%) of the feature types assumed by the verb *adhere*. That is, 15 of the 32 categories contained either no response or only a single response.

We used the information of the overlooked assumptions to solve the Teflon problem. Specifically, our solution to the Teflon problem required being aware of three assumptions. Engineers at the company were aware of two of the assumptions, but were unaware of the crucial third assumption. First, the engineers were aware that the verb *adhere* implied the use of a chemical process (i.e., feature type: type of energy). Second, engineers were aware that two surfaces (i.e., feature type: number) were being adhered together, but had not explored the possibility of more than two surfaces being involved. Third, crucially, they were unaware of the assumption that direct contact between the coating and the Teflon

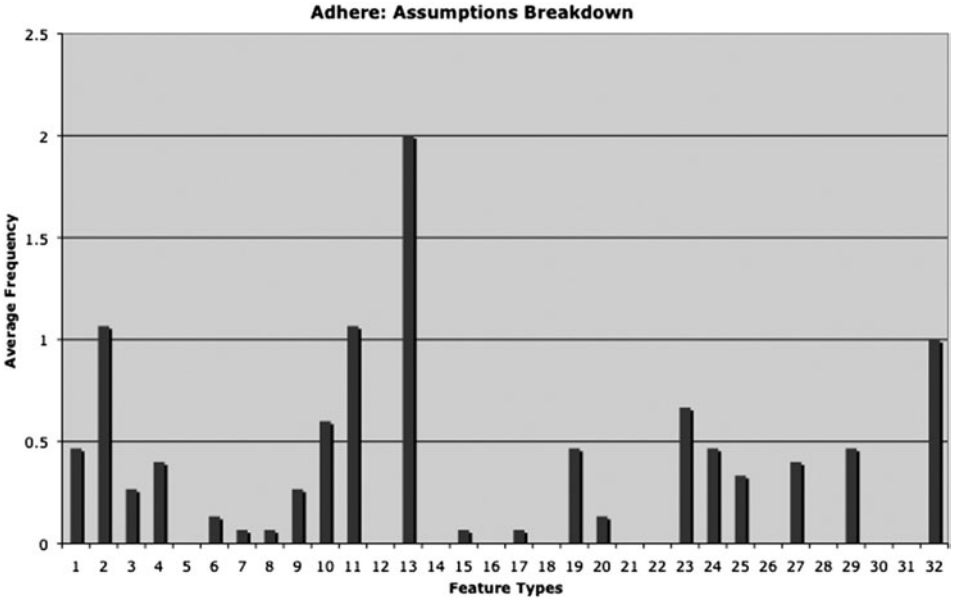

Figure 9. Features assumed by the verb *adhere*.

must cause the adherence (i.e., feature type: causal relations). Direct contact between the coating and the Teflon is necessary for a solution, but that contact may not cause the adherence. Simultaneously negating all three assumptions led to a solution deemed plausible by the presenting engineering firm. The solution consisted of a sandwich of three surfaces (i.e., coating, Teflon, and magnet) in which the coating indirectly stuck to the Teflon due to its attraction to the magnetic surface beneath the Teflon. The coating, of course, must possess the proper chemical makeup to attract the magnetic surface.

In sum, a goal verb hides many assumptions about the features that the final solution will possess. The FTT provides a way to help notice many of these assumptions. Our undergraduate subjects listed all the assumptions they could for the verb *adhere* (e.g., chemical energy is involved), but still overlooked many. Our professional engineers were blocked from a solution to their Teflon problem because they overlooked one crucial assumption that the FTT could have helped them uncover. In general, the more assumptions we are aware of, the more likely we will be able to solve the problem at hand.

7.4 Computer assistance for assumption blindness

Because almost all engineering goals can be expressed by one of approximately 200 verbs (Hirtz et al., 2002), we plan to create an extensive database of assumptions for each of those verbs. For each of the 200 verbs, contributors to the database would proceed through the categories of the FTT and name the assumptions the verb has for each category. For example, the verb *adhere* assumes that the solution uses chemical energy (from FTT category #23: types of energy/force). Designers could use the database to examine what is hidden behind their chosen goal verb. Furthermore, users of the database would be able to add new assumptions to the verbs in the database as well as position new verbs into the hierarchy. For example, the verb *adhere* our Teflon example is not listed in Hirtz et al. (2002) but could be added as a more specific version of the verb *connect*. The newly added verb *adhere* would inherit some of the assumptions of *connect* as well as take on specific assumptions of its own that are not relevant to *connect*.

7.5 Overcoming analogy blindness

During problem solving, it is generally very difficult for humans to notice an idea from another domain that could be adapted to solve the current problem. In classic psychology experiments, Gick and Holyoak (1980, 1983) had subjects read a brief military story just before working on a problem involving surgery. Unbeknownst to the subjects, the military story contained the key structural idea for solving the surgery problem. Solution rates were at 30% for the surgery problem after mere exposure to the military story, but rose to 80% if the subjects were given an explicit hint to use the military story to solve the problem. Without direct guidance that an analogical solution was lurking in a particular story, subjects did not tend to notice the relevant relations at the proper level of abstraction without becoming distracted by the more superficial relations.

To counter the difficulties of successful analogical transfer (i.e., analogy blindness), some researchers have focused on ways to reduce the struggle of retrieving analogies from memory and ways to better represent analogical information in order to make analogies easier to recognize. If a potential analogy is initially encoded based on its deeper relationships, then this can improve memory recall while working on a structurally similar problem (Clement, 1994; Clement, Mawby, & Giles, 1994; Falkenhainer, Forbus, & Gentner, 1986, 1989; Gentner & Rattermann, 1991; Gentner, Rattermann, & Forbus, 1993). Encoding based on deeper relations may be achieved by using a general linguistic description. For example, instead of saying that a pair of scissors cuts, more generally, one might say that it separates or divides.

Linsey and colleagues replicated these findings from the psychology literature on engineering design problems (Linsey, 2007; Linsey, Laux, Clauss, Wood, & Markman, 2007; Linsey, Markman, & Wood, 2008a, 2012; Linsey, Wood, & Markman, 2008b). One of the major findings of this line of research is that a more general linguistic description at the time of encoding resulted in both better retrieval and better application at a later time (Linsey, 2007; Linsey et al., 2008a, 2008b). Success rates of retrieval and application were as high as 40% better when the initial linguistic description at encoding was at a more general level (Linsey, 2007, 2008a, 2008b).

To facilitate the creation of a general linguistic representation, Linsey and colleagues developed the WordTree Design-by-Analogy Method (Linsey et al., 2008a; Linsey et al., 2008b; Linsey et al., 2012), which was partially automated in 2011 (Oriakhi, Linsey, & Peng, 2011). We will first present the WordTree method before presenting our more fully automated *Analogy Finder* (AF) method (McCaffrey, 2013b) in the next section.

The flowchart of the WordTree method is shown in Figure 10. Because we claim that our AF method is more fully automated, for comparison purposes we indicate which steps of the WordTree method are performed by machine and which steps must be performed by human. Figure 10 is an adaptation of a figure that appeared in Oriakhi et al. (2011).

The overall thrust of the WordTree Design-by-Analogy Method is to re-represent the problem of interest using various linguistic representations in order to trigger an association to a distant method that might help solve the current problem. The human starts by expressing functions and customer needs crucial to the problem (step #1). A machine looks up synonyms for the terms selected by the human problem solvers (step #2). The use of WordNet (Miller, 1995) allows the creation of a hierarchy of hypernyms and hyponyms, as illustrated in Figure 11 (adapted from Oriakhi et al., 2011).

For step #3, humans initially created the WordTree (Linsey et al., 2008a; Linsey et al., 2008b) but later this step became automated (Oriakhi et al., 2011). The remainder of the steps of the flowchart are conducted by humans. By examining the entries of the WordTree, humans make associations in order to try to identify potential analogies and

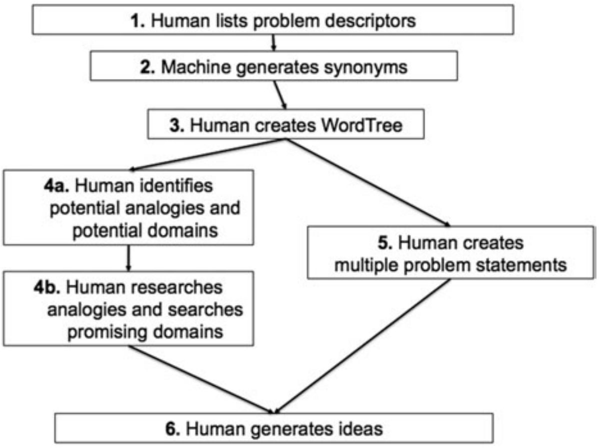

Figure 10. WordTree design-by-analogy method.

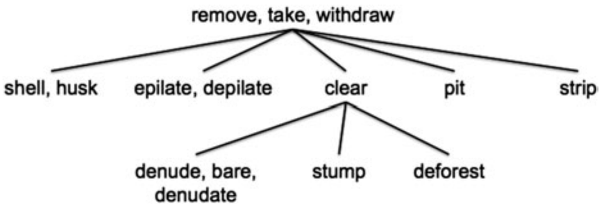

Figure 11. Part of the WordTree for the verb "shell."

potential patent domains that might be promising sources for analogous solutions (step #4a). In step #4b, humans then actually research the potential analogies they thought of and search through the promising patent domains. Alternatively, humans may also work on step #5, which involves re-wording the problem statement based on the words uncovered by the WordTree.

Because generating WordTrees by hand is labor-intensive, the existence of an automated process to perform this task triggered subjects to significantly increase the likelihood that they would want to use the WordTree Design-by-Analogy Method (Oriakhi et al., 2011). Furthermore, the partially automated WordTree Design-by-Analogy Method increased subjects' assessment of the value of this method for a typical design engineering problem (Oriakhi et al., 2011). In effect, reassigning step #3 of Figure 10 to machines increases the assessment of perceived usability and value of the overall method.

If some automation is good in the analogy finding process, then more automation is most likely better. The next section presents a new representation scheme that leads to AF, which permits substantially more automation than the WordTree Design-by-Analogy Method.

7.6 *Fuller computer assistance for analogy blindness*

Hirtz et al. (2002) articulated a hierarchy of approximately 200 verbs that can describe almost any engineering goal or operation. An action verb (e.g., *divide* or *transport*) expresses the desired change of an engineer's goal or the actual change of an engineering operation. If no change is desired, then there are verbs to express this desired outcome also (e.g., *maintain* or *keep*). An action verb is to be distinguished from verbs such as *be* and *have*, which most often are used to express static relationships: *The chair is furniture* (a meronymic relation) and *The chair has legs* (a part-whole or partonomic relation).

We consider the action verb to name just part of the function (i.e., the change), whereas previous literature suggests that verbs more fully express the function (Stone and Wood, 2000; Fu, Cagan, Kotovsky, & Wood, 2011). "Verbs tend to describe functionality because they correspond to what something *does* or should *do*. Nouns tend to describe components, applications, or elements of a design, and thus are chosen here to represent surface attributes of the patents" (Fu et al., 2011). We refine this dichotomy by suggesting that nouns can also be crucial to expressing another aspect of the function: that which needs to be changed in the manner described by the action verb. Thus, we expand the verb-based description of the function to a verb–noun-based description.

More fully, once the desired change is named as an action verb, the next thing to determine is that which needs changing, which can be articulated as a noun phrase (e.g., *reduce vibrations*, *adhere a coating, strengthen wood chisel*, and *control solidification*). The noun phrase can be one word (i.e., *vibrations*) or multiple words (e.g., *a coating* and

```
effect ::= verb nounPhrase
nounPhrase ::= [determiner] adjective* noun [noun]
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Figure 12. Grammar for finding analogous solutions.

wood chisel). The noun phrase can name something concrete such as *coating* as well as something more abstract such as the process of *solidification*.

To express our grammar more formally, we use the Extended Backus-Naur Form (EBNF) (Aho, Sethi, & Ullman, 1986), which is a compact notation mostly used to define the syntax of computer programming languages (Figure 12). In EBNF, the "::=" symbol means "is defined as." Straight brackets indicate that the item inside the brackets is optional. An item superscripted with a "*" means that there can be zero or more occurrences of that item.

Here is an interpretation of the lines of this grammar. First, an effect consists of a verb to express the desired change and a noun phrase to express what needs changing. As shown in Figure 12, prepositional phrases are omitted from the expression of an effect when using the software AF (McCaffrey, 2013b). Second, a noun phrase may contain a determiner (i.e., *the*, *an*, or *a*) and a list of adjectives to modify either a single noun (e.g., *cell*) or a pair of nouns (e.g., *cancer cell*).

In this section, we detail the algorithm that leverages the grammar of Figure 12 in order to find analogous ideas from any collection of text (e.g., a company's legacy documents or a collection of journal articles). In this paper, we focus on searching a patent database.

Importantly, the algorithm interweaves human and machine contributions at various points in the process. At any step of the algorithm, the partner (human or machine) that is most skilled at that step will perform it. In this way, we leverage the strengths of each partner to maximize the effectiveness of the overall algorithm. The following steps are illustrated in the flowchart in Figure 13.

Step 1: The human enters the goal using the syntax from Figure 12 (e.g., *reduce vibrations*).

Step 2: The machine uses an electronic thesaurus to determine the synonyms of the entered verb and the main noun of the noun phrase. This step helps take into account the diverse ways to express the desired effect. Different inventors might describe what their invention does in different ways. If a technical dictionary is used to supplement a general electronic thesaurus, then this step also takes into account the technical ways that a particular field describes a desired effect.

Step 3: The machine adds stems to the initial verb (e.g., *reduce*), the initial noun (e.g., *vibrations*), and their synonyms. For example, for the verb *reduce*, the machine might also add the following: *reduces*, *reduced*, and *reducing*. For the noun *vibrations*, the machine would ensure that both the singular and plural forms are included.

Step 4: The human edits (i.e., adds to or deletes from) the synonym lists returned in step #2 until the lists contain only words close to the human's original intent. If the phrase *reduce vibrations* were entered, for example, then for the verb *reduce*, the machine might return *change* and *de-emphasize* among the many candidate synonyms. The human might delete them after determining that the verb *change* is too general to be helpful and the verb *de-emphasize* does not reflect the sense of *reduce* that the human originally intended.

Step 5: The machine takes the human-approved synonym lists and generates all verb–noun combinations. For example, if the set of verb-synonyms has nine members and the set of noun-synonyms as six members, then the set of verb–noun combinations would contain 54 members. For *reduce vibrations*, the final synonym set of verbs might contain

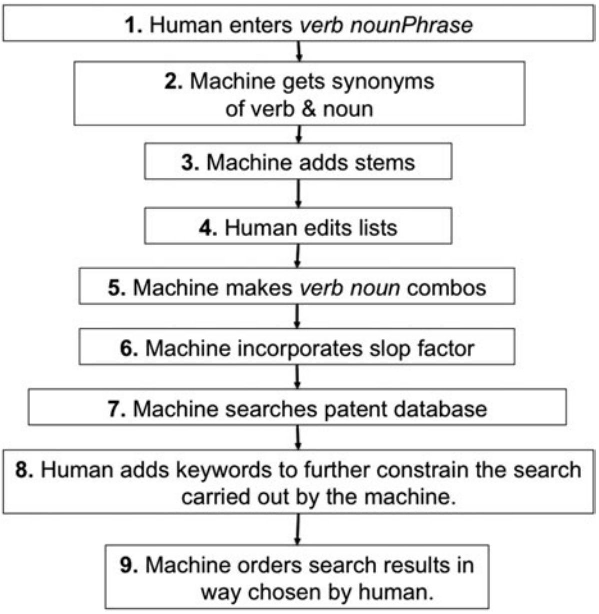

Figure 13. Flowchart of analogy finder algorithm.

verbs such as *diminish* and *lessen*. The final synonym set of nouns might contain nouns such as *undulations* and *perturbations*. These members would produce combinations such as *diminish undulations* and *lessen perturbations*.

Step 6: The machine conducts the patent database search using a "slop factor," which is a small positive integer that represents the maximum number of words that can separate the verb and noun while still being considered a match. Given *reduce vibrations* and a slop factor of three, the following text segments would be considered a match: *reduce extreme vibrations* and *reduce some of the vibrations*. Although it is an open question as to the ideal slop factor for finding analogous solutions, based on our current experience we start with a default slop factor of three but it can be adjusted by the user.

Step 7: The machine uses the set of verb–noun phrases from step #5 together with the slop factor from step #6 to search the patent database for the patents that contain any of these many phrases. The machine returns all the patents that match. The first hypothesis is that if a patent contains one of these phrases, then there is a significant probability that the patent is relevant to the desired effect expressed by the initial search string. The second hypothesis is that if a patent does not contain any of these phrases, then there is a low probability that the patent is relevant to the desired effect. Future research will test these hypotheses.

Step 8: The human enters any other keywords to further constrain the search. For example, the human might enter a plus sign followed by a word such as " + chemical" to indicate that the word "chemical" should occur in the patent in order to be considered a match. A word following a minus sign such as "−chemical" indicates that a patent will be considered a match only if the word "chemical" does not occur in the patent. Furthermore, a human could enter multiple words such as " + chemical −magnetic." This phrase means that in order to be a match the word "chemical" should occur and the word "magnetic" should not occur. The machine takes into account these simple constraints to further limit the number of search results.

Step 9: The human selects how the search results should be ordered. The search results could be ordered based on things such as the alphabetical order of the search strings, the domain classification system of the patent database, date of filing, or any combination of these or other criteria.

Iterating steps 1–9, the human user continues to examine patents while adjusting various wordings, constraints, and orderings until one or more promising ideas are uncovered that might be adaptable as a solution to the problem.

In comparison with the WordTree Design-by-Analogy Method, notice that while the WordTree Method has automated two of its six steps the AF method has automated six of its nine steps. Furthermore, the WordTree method focuses on the synonyms of single words while AF focuses on synonymous two word phrases (i.e., verb–noun combinations). We argue that a two word phrase (e.g., *reduce vibrations*) more fully expresses the desired effect than just a single word alone (e.g., *reduce* or *vibrations*).

A non-provisional patent has been filed in the United States for the AF algorithm on 21 November 2013 (McCaffrey, 2013b). A prototype version of AF exists and was made possible by funding from three National Science Foundation (NSF) grants: #1127609, #1261052, and #1345439. Importantly, now that a prototype of AF exists, we are poised to rigorously test it – especially in head-to-head comparisons with the WordTree Design-by-Analogy Method.

7.7 *Case study for AF*

In lieu of experimental results, in this paper we will present a case study, which suggests the effectiveness of AF for helping designers find obscure analogous solutions that they would normally overlook. Because the companies we have worked demand propriety regarding the problems we assisted them with, for this paper we will re-solve the Teflon problem that was originally solved using the *assumption blindness* technique (see Section 7.3). Admittedly, using AF to re-solve an already-solved problem is a bit contrived because knowing the solution will lead us to make decisions that will make sure we find the known solution. However, showing how a problem can be solved through multiple techniques is instructive in comparing how the two techniques may lead designers along different pathways to the key obscure feature(s). In sum, given the proprietary nature of our success stories, presently for this paper, we have little choice but to show another pathway to the solution of the Teflon problem.

The YouTube video, http://www.youtube.com/watch?v=XQfOF6zVKYQ, walks viewers through how AF could help find a solution for adhering a coating to Teflon. The following text articulates the basic steps shown in the video.

First, we typed in a verb–noun phrase that expressed the desired functionality: *adhere coating*. AF immediately generated a list of synonyms for *adhere* and a separate synonym list for *coating*. Using WordNet (Miller, 1995), AF returned 25 possible synonyms for *adhere* and 9 synonyms for *coating*. We examined each list and kept the words that seemed to express the proper nuances of our original meaning. After finishing the editing process, three verbs remained (i.e., *adhere*, *attach*, and *fasten*) as well as three nouns (i.e., *coating*, *covering*, and *layer*).

Hitting the search button at this point triggered AF to create verb–noun phrases from the chosen verbs and nouns. In this case, three verbs and three nouns generated nine verb–noun phrases (e.g., *attach covering* and *fasten coating*). AF searched for the occurrence of any of these nine search phrases anywhere within a patent's text (e.g., the title, abstract, body, and claims). AF searched all patents available in the digital version of the U.S.

Patent database – approximately 7 million patents. Using the default "slop factor" of three intermediate words, AF found 14,935 patents that contained any of these nine phrases. Adjusting the "slop factor" down to zero (i.e., meaning that the verb and noun need to be adjacent to be considered a match) returned 548 patents.

At this point, we entered other keywords to partition the 548 patents into sub-groups based on the type of energy used in the solution. Hirtz et al. (2002) provides a list of 12 basic energy types to consider: human, acoustic, biological, chemical, electrical, electromagnetic, hydraulic, magnetic, mechanical, pneumatic, radioactive, and thermal. Using keywords related to each energy type, we categorized the 548 patents by the dominant energy type used in each patent.

There were many patents that contained the word "chemical" (i.e., 221 of the 548 patents), which is suggestive (but not definitive) of chemical energy being involved. In contrast, relatively few of the patents contained the word "magnetic" (i.e., 44 of the 548 patents). Knowing that the presenting company had been stuck on this problem for some time, we decided to examine the more obscure energy types for this problem – including magnetic energy. Multiple patents showed how magnetism could be used to fasten multiple layers to each other. These patents most likely would have triggered the idea for the *Teflon sandwich solution* that we initially crafted in Section 7.3 using another method.

AF allowed us to navigate through the space of actual patents that achieve the desired effect (i.e., *adhere coating*), regardless of how the effect was expressed. The method of countering *assumption blindness* described in Section 7.3 allowed us to navigate through the space of assumptions made by how the desired effect was expressed. Both approaches could prove to be useful and, at this point, we do not have a recommendation for which method should be tried before the other.

7.8 Summary of obscure features of goals

In sum, we initially focused on the verb of an expressed effect and counteracted two ways that the chosen verb can hide obscure features: *narrow verb associations* and *assumption blindness*. When we took into account both the verb and the noun that express the effect, we were able to devise a technique to help counteract *analogy blindness*. Given that AF has just recently become a working prototype, we are now poised to move beyond anecdotal evidence and will soon conduct a controlled experiment between the WordTree Design-by-Analogy Method and AF.

8. Beyond physical objects to innovation in general

In this paper, we have focused exclusively on innovating with physical objects. However, what about other domains such as the life sciences, marketing, and management processes?

We understand the OFH to be a universal property of innovation for any domain: that any innovation is built upon at least one obscure feature. If this is correct, then it is the kinds of features that will change from domain to domain.

For example, as a biological entity (e.g., organ and cell) is also a physical entity, all of the feature types from our current FTT will apply to it. However, many more feature types should be added to account for the features that distinguish something organic from something inert. Regarding marketing, a tangible consumer product is a physical entity (e.g., microwave popcorn) so our current FTT applies to it, but new feature types are required to cover consumer issues related to price and convenience of the product, for example. The domain of management – which works with people, organizations, and processes – will require its own FTT specific to these less tangible entities. In sum, we believe that the principles of the OFH apply to any domain. It is the entities and types of features that each domain deals with that differ. Consequently, each domain will require the construction of its own FTT to describe the relevant features of the pertinent entities.

9. Conclusion and future work

The pathway to design innovation goes through the obscure features of the problem at hand. This statement sums up the OFH for innovation (McCaffrey, 2012). After articulating three locations of possible obscure features (i.e., the available objects/materials, the goal of the problem, and the interactions among the available objects/materials), we then focused on the first two locations. Specifically, we articulated two cognitive obstacles (i.e., *design fixation* and *functional fixedness*) related to the obscure features of an object/material as well as their counter techniques. We also presented three cognitive obstacles (i.e., *narrow verb associations*, *assumption blindness*, and *analogy blindness*) related to the obscure features of a goal as well as their counter techniques. We demonstrated how software could be implemented for each of the counter techniques.

We are in the process of applying each of the counter techniques to problems of ever-increasing complexity to test how well the OFH techniques help with real-world problems. Furthermore, as the OFH approach is more fully tested on increasingly complex real-world problems, we will be in a position to fully compare its strengths and weaknesses against those of TRIZ.

Future research also involves the following tasks. Articulate other cognitive obstacles to innovation that hide obscure features of the available objects/materials and the goal. Devise countering techniques to these newly discovered cognitive obstacles. Analyze the third location (i.e., the interactions among the objects/materials) for how it shields the obscure from human awareness. By creating countering techniques to every revealed cognitive obstacle, we will continue to develop an effective approach to innovation based on unearthing obscure features and leveraging them to do useful work.

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Note

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References

Aho, A., Sethi, R., & Ullman, J. (1986). *Compilers: Principles, techniques, and tools*. Boston, MA: Addison Wesley.

Altshuller, G. (1996). *And suddenly the inventor appeared: Triz, the theory of inventive problem solving*. Worcester, MA: Technical Innovation Center, ISBN 0-96-407402-8.

Clement, C. A. (1994). Effect of structural embedding on analogical transfer: Manifest versus latent analogs. *American Journal of Psychology*, *107*(1), 1–39.

Clement, C. A., Mawby, R., & Giles, D. E. (1994). The effects of manifest relational similarity on analog retrieval. *Journal of Memory & Language*, *33*, 396–420.

Cox, G. (2005, December). Cox review of creativity in business: building on the UK's strengths. Retrieved July 9, 2013, from http://www.hmtreasury.gov.uk/independent_reviews/cox_review/coxreview_index.cfm

Duncker, K. (1945). On problem-solving. *Psychological Monographs*, Hole No. 270 *58*(5), i-113.

Einstein, A. (2004). *Relativity: The special and the general theory*. (R. W. Lawson, Trans.) New York, NY: Barnes & Noble (original work published in 1920).

Falkenhainer, B., Forbus, K. D., & Gentner, D. (1986). The structure-mapping engine. In *Proceedings of the meeting of the american association for artificial intelligence*. Philadelphia, PA: Association for the Advancement of Artificial Intelligence.

Falkenhainer, B., Forbus, K. D., & Gentner, D. (1989). Structure-mapping engine. *Artificial Intelligence*, *41*, 1–63.

Fu, K., Cagan, J., Kotovsky, K., & Wood, K. (2011). Discovering structure in design databases through functional and surface based mapping. *In: Proceedings of the ASME 2011 international design engineering technical conferences & computers and information in engineering conference* (pp. 1–11). New York, NY: American Society of Mechanical Engineers (ASME) Technical Publishing.

Gentner, D., & Rattermann, M. J. (1991). Language and the career of similarity. In S. A. Gelman & J. P. Brynes (Eds.), *Perspectives on language and thought: Interrelations in development* (pp. 225–277). London: Cambridge University Press.

Gentner, D., Rattermann, M. J., & Forbus, K. (1993). The roles of similarity in transfer: Separating retrievability from inferential soundness. *Cognitive Psychology*, *25*, 524–575.

Gero, J. S. (1990). Design prototypes: A knowledge representation schema for design. *AI Magazine*, *11*, 26–36.

Gero, J. S., & Kannengiesser, U. (2004). The situated function–behaviour–structure framework. *Design Studies*, *25*, 373–391.

Gick, M. L., & Holyoak, K. J. (1980). Analogical problem solving. *Cognitive Psychology*, *12*, 306–355.

Gick, M. L., & Holyoak, K. J. (1983). Schema induction and analogical transfer. *Cognitive Psychology*, *15*(1), 1–38.

Hatchuel, A., & Weil, B. (2003). A new approach of innovative design: An introduction to C–K theory. *In: Proceedings of the international conference on engineering design* (pp. 109–124). Somerset: The Design Society.

Hatchuel, A., & Weil, B. (2009). C–K design theory: An advanced formulation. *Research in Engineering Design*, *19*, 181–192.

Hirtz, J., Stone, R., McAdams, D., Szykman, S., & Wood, K. (2002). A functional basis for engineering design: Reconciling and evolving previous efforts. *Research in Engineering Design*, *13*, 65–82.

Jansson, D. G., & Smith, S. M. (1991). Design fixation. *Design Studies*, *12*, 3–11.

Knoblich, G., Ohlsson, S., Raney, G. E., Haider, H., & Rhenius, D. (1999). Constraint relaxation and chunk decomposition in insight problem solving. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*, 1534–1555.

Linsey, J. S. (2007). *Design-by-analogy and representation in innovative engineering concept generation* (dissertation). The University of Texas at Austin, Austin, TX.

Linsey, J., Laux, J., Clauss, E. F., Wood, K., & Markman, A. (2007). *Increasing innovation: A trilogy of experiments towards a design-by-analogy method*. Proceedings of ASME Design Theory and Methodology Conference, Las Vegas, NV.

Linsey, J., Markman, A., & Wood, K. (2008a). *WordTrees: A method for design-by-analogy*. 2008 American Society for Engineering Education Annual Conference, Pittsburg, PA.

Linsey, J., Markman, A., & Wood, K. (2012). Design by analogy: A study of the WordTree method for problem re-representation. *ASME Transactions, Journal of Mechanical Design, 134,* 041009.

Linsey, J., Wood, K., & Markman, A. (2008b). Increasing innovation: Presentation and evaluation of the WordTree design-by-analogy method. *In: Proceedings of the ASME 2008 international design engineering technical conferences & computers and information in engineering* *conferences* (pp. 21–32). New York, NY: American Society of Mechanical Engineers (ASME) Technical Publishing.

McCaffrey, T. (2011). *The obscure features hypothesis for innovation: One key to improving human innovation* (Unpublished doctoral dissertation), University of Massachusetts Amherst, Amherst.

McCaffrey, T. (2012). Innovation is built on the obscure: A key to overcoming the classic *functional fixedness* problem. *Psychological Science*, *23*, 215–218.

McCaffrey, A. (October 22, 2013a). *U.S. Patent Pending No. 14/059,578*. Non-provisional patent. Feature Type Spectrum. Washington, DC: U.S. Patent and Trademark Office.

McCaffrey, A. (November 21, 2013b). *U.S. Patent Pending 14/085,897*. Non-provisional patent to be filed. Analogy Finder. Washington, DC: U.S. Patent and Trademark Office.

McCaffrey, T., & Spector, L. (2011). How the obscure features hypothesis leads to innovation assistant software. In D. Ventura, P. Gervás, F. D. Harrell, M. L. Maher, A. Pease, & G. Wiggins (Eds.), *Proceedings of the second international conference on computational creativity* (pp. 120–122). Mexico City, Mexico: Association for Computational Creativity.

Mednick, S. (1962). The associative basis of the creative process. *Psychological Review*, *69*, 220–232.

Miller, G. A. (1995). WordNet: A lexical database for English. *Communications of the ACM*, *38*, 39–41.

Nietzsche, F. (1968). *Will to power*. (W. Kaufmann & R.J. Hollingdale, Trans.) New York, NY: Random House (original work published in 1901).

Ohlsson, S. (1992). Information processing explanations of insight and related phenomena. In M. T. Keane & K. J. Gilhooly (Eds.), *Advances in the psychology of thinking* (pp. 1–44). London: Harvester Wheatsheaf.

Oriakhi, E. V., Linsey, J. S., & Peng, X. (2011). Design-by-analogy using the WordTree method and a WordTree generating tool. *International Conference on Engineering Design, ICED11*. Technical University of Denmark. Somerset: The Design Society.

Purcell, A. T., & Gero, J. S. (1996). Design and other types of fixation. *Design Studies*, *17*, 363–383.

Rantanen, K., & Domb, E. (2008). *Simplified TRIZ: New problem solving applications for engineers and manufacturing professionals*. New York, NY: Auerbach Publications.

Rittel, H., & Webber, M. M. (1984). Planning problems are wicked problems. In N. Cross (Ed.), *Developments in design methodology* (pp. 135–144). New York, NY: John Wiley & Sons.

Salomons, O. W., van Houten, F. J. A. M., & Kals, H. J. J. (1993). Review of research in feature-based design. *Journal of Manufacturing Systems*, *12*, 113–132.

Schyns, P. G., Goldstone, R. L., & Thibaut, J. (1998). The development of features in object concepts. *Behavior and Brian Sciences*, *21*, 1–54.

Simon, H. A. (1995). Problem forming, problem finding and problem solving in design. In A. Collen & W. Gasparski (Eds.), *Design & systems* (pp. 245–257). New Brunswick, NJ: Transaction.

Smith, S. M. (1995). Getting into and out of mental ruts: A theory of fixation, incubation and insight. In R. J. Sternberg & J. E. Davidson (Eds.), *The nature of insight* (pp. 229–251). Cambridge, MA: MIT Press.

Smith, S. M., Ward, T. B., & Schumacher, J. S. (1993). Constraining effects of examples in a creative generation task. *Memory & Cognition*, *21*, 837–845.

Stone, R., & Wood, K. L. (2000). Development of a functional basis for design. *Journal of Mechanical Design*, *122*, 359–370.

Ward, T. B., Patterson, M. J., & Sifonis, C. M. (2004). The role of specificity and abstraction in creative idea generation. *Creativity Research Journal*, *16*, 1–9.

Appendix: A Feature Type Taxonomy of 32 Categories

This appendix contains the 32 categories of feature types used for the examples presented in this paper. This 32-category Feature Type Taxonomy was first presented in McCaffrey (2011).

A word on terms: the *focal entity* is the entity that is focused on as the center of attention. In contrast, the *environmental entities* are the entities surrounding or interacting with the *focal entity*. For example, the *focal entity* used to illustrate the *Feature Type Taxonomy* below is a common plastic chair. *Environmental entities* of a common plastic chair might be a desk or floor – to name just two.

Table A1. Feature type taxonomy.

Name	Description	Example (based on a plastic chair)
(1) Parts	Identifiable components of focal entity	Legs
(2) Material	Material make-up of focal entity or its parts	Seat is plastic
(3) Shape	Overall shape of focal entity/parts	Legs are cylindrical
(4) Size	Length, width, depth of focal entity/parts	Legs are about 2 feet long
(5) Color	The color of focal entity/parts	Seat is yellow
(6) State of matter	(Solid, liquid, gas, plasma) of focal entity/parts	Seat is solid
(7) Connectivity & spatial relations among parts	Physical connection and spatial relations among components of the focal entity	The legs are connected to the seat and beneath the seat (in its normal orientation)
(8) Mass	Mass of focal entity/parts	The mass of the seat
(9) Weight	Weight of focal entity/parts	A leg weighs about 1 pound
(10) Number	Number of components of a certain kind of the focal entity/parts	4 legs
(11) Designed use	The use that the focal entity was designed to fulfill	To support a human who is in the seated position
(12) Alternative uses	Other uses that the focal entity might possess	A human might stand on the chair to change a ceiling light bulb
(13) Side effects	Other effects besides the desired ones that are produced while the focal entity is in use	A side effect of sitting in a chair is the pressure of the legs on the floor, which could create indentations on the floor
(14) Superordinate	The more general classification of the focal entity based on its typical use	The superordinate of a chair is furniture
(15) Subordinate	More specific version of the focal entity based on its typical use	A subordinate of a chair is a rocking chair
(16) Synonym (based on use)	Other entities that can achieve the same use as the focal entity	Other objects (not subordinates) that can be sat on in a pinch. Example: a large flat rock
(17) Equipmental partners	Environmental entities that the focal entity is used with during its use	A chair is often used with a desk
(18) Human motor relations	How a human physically manipulates the focal entity/parts during its use	To sit in a chair requires a complex motor movements that involve bending the knees so that the seat of the person lands on the seat of the chair

(*Continued*)

Table A1 – *continued*

Name	Description	Example (based on a plastic chair)
(19) External relations	Relations of focal entity to environmental entities during the use of the focal entity	The seat of the chair relates to the seat of a person when the chair is being sat upon by the person
(20) Aesthetic	Beauty, elegance, style	The chair might have a sleek design
(21) Place	The typical physical locations that the focal entity resides in during its use	Chairs often appear in dining rooms, offices, etc.
(22) Occasion	The typical contexts that a focal entity resides in during its use	Chairs are present during a family meal or a cookout on one's deck
(23) Type of energy/force	During its use, the types of energy and forces in play both within the focal entity as well as within and among the environmental entities	Because the chair is plastic, static electricity often builds up between the chair surface and the clothes of the person using the chair
(24) External conditions	Humidity, weather conditions, strength of gravity, barometric pressure, etc.	The humidity in the house made the chair seat damp
(25) External spatial relations	The spatial relations between the focal entity and the environmental entities during its use	A chair is often situated a so that the back of the chair is about 1.5 feet from the edge of the table
(26) Symmetry	An important but often overlooked characteristic of the shape of a focal entity	Legs are symmetrical in two dimensions
(27) Time	The typical duration (milliseconds, hours) that an event lasts involving the focal entity	An occasion of sitting can commonly lasts between several minutes to several hours.
(28) Motion	The type of motion engaged in by a focal entity during its use	A chair is generally motionless when it is being sat upon.
(29) Permanence/ transience	How long the focal entity tends to last as it is used	A chair is usually lasts for many years.
(30) Causal relations	During its use, the cause-effect sequence set off among the parts of the focal entity as well as between the focal entity and its environmental entities	When a person sits on a chair, the weight stresses the connecting points between chair seat and the legs.
(31) Emotions/affect	The emotions that the object triggers in people	The chair's design may elicit a sense of nostalgia for the simplicity of the past.
(32) Miscellaneous	Elements in this category indicate that the taxonomy needs expansion or refinement	