Paying Attention to the Right Thing: Issues of Focus in Case-Based Creative Design

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Abstract

Case-based reasoning can be used to explain many creative design processes, since much creativity stems from using old solutions in novel ways. To understand the role cases play, we conducted an exploratory study of a seven-week student creative design project. This paper discusses the observations we made and the issues that arise in understanding and modeling creative design processes. We found particularly interesting the role of imagery in reminding and in evaluating design options. This included visualization, mental simulation, gesturing, and even sound effects. An important class of issues we repeatedly encounter in our modeling efforts concerns the focus of the designer. (For example, which problem constraints should be reformulated? Which evaluative issues should be raised?) Cases help to address these focus issues.

Introduction

Designers across different domains perform many of the same creative activities, whether they are involved in designing artifacts or processes. These activities can be described by contrasting them to routine design activities. In general, routine design repeats old designs in obvious ways, adapting them by well-known and often-applied adaptation strategies. Routine design assumes a completely specified problem is given and little effort is applied to elaborating or designing a feasible specification.

The kind of design we call creative, on the other hand, includes a process of "designing the design specification" (Tong, 1988), going from an incomplete, contradictory, and underconstrained description of what needs to be designed to one with more detail, more concrete specifications, and more clearly defined constraints. Creative design also often includes a process of generating and considering several alternatives, weighing their advantages and disadvantages, and sometimes incorporating pieces of one into another. It involves using well-known design pieces in unusual ways or modifying well-known designs in unusual ways. Creative designers frequently engage in cross-domain transfer of abstract design ideas. They also often recognize alternative uses or functions for common design pieces (e.g., using a styrofoam cup as a boat).

Figure 1 gives a rough sketch of the main processes we hypothesize to be involved in creative design and how they interact with one another. The designer continually updates the design specification as well as a pool of design ideas under consideration. Each alternative generated is evaluated to identify its advantages and disadvantages and to check that it satisfies the constraints in the current design specification. A key part of evaluation is "trying out" the alternative (e.g., through experimentation or mental simulation). This generates a more detailed description of the alternative, including the consequences of its operation and how environmental factors affect it.

Evaluation drives both the updating of the design specification and the modification and merging of design alternatives. It raises questions of legality or desirableness of features[1] of a design alternative and it detects contradictions and ambiguities in the specification. The resolution of these questions, contradictions, and ambiguities serves to refine, augment, and reformulate the design specification. On the generative side, evaluation identifies advantages and disadvantages of alternatives which often suggest interesting adaptations or ways of merging alternatives. Also, sometimes the description of a problem noticed during evaluation can be easily transformed to a description of how its solution would look.

The three processes interact opportunistically. The generative phase, guided by critiques from the evaluation phase, watches for opportunities to merge or adapt design ideas to create new alternatives. The design specification is incrementally updated as ideas are tested and flaws or desirable features become apparent.

The continual elaboration and reformulation of the problem (i.e., the design specification) derives ab-

[1] The features of a design alternative are not only its structural characteristics and physical properties, but also relations between combinations of features.

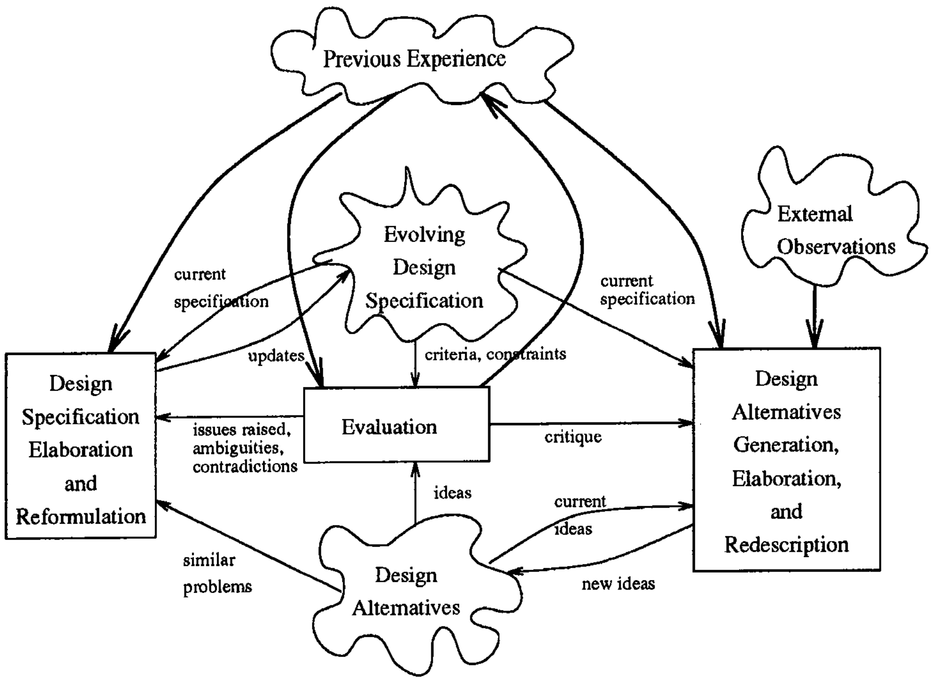

Figure 1: Rough sketch of creative design processes.

stract connections between the current problem and similar problems in other domains, facilitating cross-contextual transfer of design ideas. Continual re-description of what the solution (i.e., the evolving design) looks like primes the designer for opportunistic recognition of alternative functions of objects.

These processes rely heavily on previous design experiences and knowledge of designed artifacts. An expert designer knows of many design experiences, accumulated from personally designing artifacts, being given case studies of designs in school, and observing artifacts designed by others. Our observations and analyses lead us to propose that reminding of these experiences is crucial to generating design alternatives. When a design experience is recalled, it suggests a potential solution that can be critiqued with respect to the new problem, adapted to meet the needs of the new situation, or merged with other proposed solutions.

We believe that case-based reasoning (Kolodner, 1993) can play a large role in modeling these processes. Research in case-based reasoning has provided extensive knowledge of how to reuse solutions to old problems in new situations, how to build and search case libraries (for exploration of design alternatives), and how to merge and adapt cases. Many of the activities of creative designers can be modeled by extending routine problem solving processes that exist in current case-based systems.

Design cases provide a rich collection of details that are used in several ways in addition to generating ideas, including

- reformulating and elaborating the problem specification or proposed solutions,
- predicting the outcome of making certain design decisions,
- enabling visualization and simulation of proposed designs, and
- communicating abstract ideas in concrete terms.

What cases seem to do is to help the reasoner determine how to productively continue reasoning. The question we ask is how? How does the designer know which details to pay attention to? Which aspects of an old design can suggest problem reformulations or can fill in missing details of the specification? During problem reformulation, which constraints should be relaxed or strengthened? How are evaluative questions and criteria incrementally raised to critique the proposed design options?

We call this problem "focus." These issues are relevant in understanding what knowledge must be captured in case libraries, the form this knowledge should be in, and what types of indices are needed to allow retrieval of relevant cases. At the same time, cases help address many of these focus-related issues, particularly raising evaluation criteria and suggesting interesting, useful problem reformulations.

Example Design Episode

We concentrate primarily on an example design episode from an exploratory study we conducted of a student mechanical engineering (ME) design project.

The design task was to build a device to quickly and safely transport as many eggs as possible from one location to another. The device could be constructed from any material, but had to satisfy a set of size, weight and cost restrictions. The initial description of the problem was vague, ambiguous, and incomplete, requiring a great deal of elaboration and reformulation. One of us participated in the seven-week project as a member of a four-person team, rather than as an outside observer. Active participation in the project allowed us to become immersed in the issues the students were dealing with and to observe a great deal of the design process, including "official" as well as informal team meetings (e.g., while choosing materials at a store or while attending class).

The following is a short excerpt from a discussion early in the project concerning how to launch the eggs from the center of a child's wading pool. This excerpt was chosen because it involves a reformulation of the original problem statement. It illustrates the types of design experiences and artifacts the students typically recalled and the variety of ways they used these remindings. It also gives us some insight into the basis upon which design experiences are remembered.

1 S2: Think about how heavy eggs are....

2 S4: Yeah, we need something that's going to propel this thing. I mean it's only going this far but if you think about it, it's gotta lift up 12 inches and land over there. I've got a feeling it's really gotta propel you know [motor noise] and then just go [splat noise] with a thud.

3 S1: I've got this picture in my mind of this really dramatic missile. If it's in the water, it... it could sink and it would be like a missile coming out of a submarine. [He demonstrates, pretending his pen is a missile, makes fizzing noise] ... coming out of the water, ... splashing water out.

4 S3: That reminds me cause you see those missiles come out one at... What if we did something where we sent eggs over one at a time?

5 S3: So we could have something over there to catch them like a big pillow or something I don't know, but that way you wouldn't have to launch the whole set of them. You just launch one at a time.

6 S2: Put that down: launching individually.

[S3 records idea on post-it.]

[Unrecorded conversation while flipping tape:

7 S4: We can put them each in a tennis ball.

8 S4 mentioned ping-pong ball shooters.

8 S1 didn't know what S4 was talking about.]

8 S4: Well, they're actually little springs some of them.

8 S1: Are they?

8 S4: Yeah, you know how when we were kids we could take those things that would shoot ping-pong balls and pull them back...

8 S2: I remember those! I loved those!

8 S4: ... and shoot them? Yeah. You were a deprived child.

8 S1: Were they guns?

8 S4: Yeah.

9 S4: That's actually, hmmm. That would be about the size of an egg. If we were to send it over one at a time.

10 S2: Yeah, a lot heavier, though, the eggs.

11 Later (after this meeting), S3 visualized how the idea would work and imagined that the eggs would all end up landing at the same target spot and smash each other. So S3 thought of rotating the launch mechanism so that it throws the eggs in all directions. S3 noted one interesting consequence of this was that the eggs could be thrown all at once, each in a different direction.

12 The rotating launch reminded S3 of a recently suggested idea: "flinging motion where the device is spun around and around and then let go." This had been recorded externally on a post-it.

13 This was then adapted (generalized) from having a group of eggs at the end of the string to a single egg.

14 [Two days later, this idea was discussed further while the students were going through each idea proposed so far (recorded on post-its).]

15 S3: What I was thinking was that you could just have a pole and you could have all these strings just like a May Day dance, you know where you have all the eggs hanging from strings and you spin that and the eggs all fly out and then you just let go and then they all fly.

16 S4: Now I like... that's actually pretty interesting there, cause you could .. tie them all to something like a softball...No.

17 S4: Maybe something like... I'm trying to think of something that... What about something that's squishy?

18 S4: It's gotta have... What if it has some kind of fluid, like an orange? If you put an egg inside a hollowed out orange, half hollowed out orange, each of those little things would squash, you know inside of an orange. (I just ate an orange for lunch... I bring real-life experiences to this.)

19 S1: Well, that's the concept of a shock absorber. And the way it works is... If you just have a sealed shock. If you have... What a sealed shock would be would just be a balloon. If we had the eggs sitting on top of this big balloon and it went down, whenever the balloon squashed, there'd be pressure inside the balloon and it would jump back up again, so it would bounce.

But if you have a shock absorber that has a little seal out, whenever it... it's like a balloon w/ a little tiny hole, so whenever it hits the ground, it squashes and the air shoots out so it doesn't recoil. And an orange, whenever it's squashed, the juices would go squirting out and it wouldn't rebound.

During this design episode, the students recalled many cases, most of which are devices, some in action. Two different aspects of cases seemed to get the most attention: how a device works and what are its results (i.e., what it accomplishes, how it might fail, its pros and cons). Often, what was remembered seemed to get embellished through a sort of mental simulation, sometimes causal (e.g., the operation of ping-pong ball shooter 8) and sometimes imagistic (e.g., the submarine launch 3, 4).

These remindings are used in many different ways.

1. They *generate* design ideas that can be re-used directly, adapted to the current situation, or merged with other design pieces. For example, tennis balls (7) and softballs (16) are recalled to be reused for the new purpose of protecting eggs.
2. They *predict* the outcome of proposed solutions. For example, the leaky shock absorber (19) is used to predict that an orange would not be a resilient egg protector. This is useful in *evaluating* proposed solutions.
3. They *communicate* ideas. For example, the May Day dance (15) is used to quickly communicate the structure of a design alternative.
4. They help simulate or visualize the behavior of a proposed design alternative. This is useful in *elaborating* both proposed solutions and vague, incomplete specifications. For example, S1's mental picture of a submarine submerging and launching a missile (3) is used to help simulate the desired behavior of the device being designed. Simulation and visualization are also key ways of collecting data to be used to *evaluate* a proposed solution. For example, the problem with the initial proposal to launch eggs individually, like a submarine does, was detected by mentally simulating the launch and realizing that all eggs end up at the same spot and could break each other (11).
5. Remindings can also lead to a complete *reformulation* of the problem. For example, remembering that submarines launch missiles one at a time (4) led to converting the problem from launching a group of eggs in a single launch to launching each egg individually in multiple launches.

Focus Issues

A number of focus-related issues come up as we examine the design episode above. We describe each here and discuss what seems to provide the necessary focus. In many instances, previous design cases themselves help direct the designer's attention.

Which cases are recalled?

Of all the design experiences each student designer has had, why are these particular ones recalled? In other words, on what basis are the cases recalled? For example, what made S1 recall a shock absorber (19) and use it to analyze the effectiveness of an orange as a structure to protect an egg?

A hallmark of a creative designer is variety. Given the same problem to solve several times, the creative designer might come up with several qualitatively different solutions. We hypothesize that this happens because on each occasion, the designer is reminded of different cases, knowledge, or principles for solving the problem. Each time, the designer has different cues available to use for retrieval, despite the fact that the problem itself is the same. That is, the probe to memory that recalls previous designs or design knowledge includes not only the problem specification but also aspects of the context the designer is in or has been in recently.

In the given design episode, there are a variety of types of features that form the basis for reminding. Many remindings were based on a description of the *problem*, i.e., the function or behavior desired. The submarine launching a missile (3) was recalled as an example of a device that launches from water.

The ping-pong ball shooter (8) may have been recalled by looking for a device with the desired behavior of multiple launches of individual objects. In addition to the desired behavior, prominent *visual cues* may have played a role: the rounded shape and white color of the objects to be launched could have contributed to the memory probe if S4 visualized the desired behavior.

Structural cues describing the proposed solution, or structural constraints the solution should have, often remind students of an existing device that shares those features. For example, the structure of the proposed design that flings all eggs at once on strings reminded S3 of the maypole used for May Day dances (15).

Also, *background cues* can have an effect. S4 used not only structural cues (squishy, containing fluid) to recall an orange (18), but also cues from recent or current experiences (what S4 ate for lunch). Background interests provide additional cues. S1 is planning on becoming an automotive engineer and is often reminded of designs from the automobile domain, such as the shock absorber (19).

Understanding the basis for recalling design experiences is crucial to organizing a library of design cases and choosing indices to allow access to the cases. This is discussed further in the last section.

Which features of cases are examined?

Once a relevant design case is recalled, which aspects are examined? Some lead to problem reformulations or fill in missing details of the problem specification. Some are undesirable features that suggest new constraints that should be added to the problem specification to prohibit them. Some help elaborate a proposed solution. But how is the designer's attention drawn to those aspects that can do these things?

For example, there are numerous facts associated with submarines. What drew S3's attention to the fact that they launch missiles one at a time (4), as opposed to facts about how missiles are aimed at their target or about the cramped, claustrophobic interior? Focusing on this aspect led to a complete reformulation of the problem from launching a group of eggs to launching eggs individually.

When S1 used a mental picture of a submarine launching missiles (3) to elaborate the desired behavior of the mechanism being designed, why did S1 focus on sinking and then launching, but not on other aspects of the submarines operation, such as spying on or targeting other ships using a periscope?

When S4 brought up a ping-pong shooter, first the spring mechanism responsible for shooting was considered (8). Then the weight and size of the ping-pong balls shot was considered and compared to eggs (9,10).

The reasoning goal plays a significant role in focusing attention. When S1 recalled the submarine missile launch, the team was elaborating the problem specification by describing what the mechanism should do. It was also considering the problem of launching a heavy object out of water.

In pursuing the problem elaboration goal, S1 was interested in filling in details of the behavior of the mechanism to be designed and was focused on what aspects of the submarine's launching behavior transfer over to the egg-carrying device. So S1 was drawn to coarse-grained, high-level behaviors of the submarine and missile performed when launching from water (submerging, shooting, coming out of the water). On the other hand, S3 was viewing the submarine missile launch case from the perspective of trying to borrow its solution to the launching problem. So S3's attention was drawn to the solution detail that multiple, relatively small missiles are launched one at a time. (Attention to the small nature of the missiles may have been additionally emphasized by the hand gestures S3 made in acting out the launch.)

The ping-pong ball shooter was also considered from two different viewpoints. The team considers how the gun works as part of the goal of borrowing its solution and focuses on the spring mechanism: how the spring is loaded and released. Then S4 seemed to be considering whether the gun can be reused directly. The goal of evaluating the applicability of this existing design to the current one focused S4 and S2 on the size and weight of the ping-pong balls shot, compared to eggs.

Which evaluative issues are raised?

The evaluation process checks each design option that is generated against the current design specification. It forms a critique, identifying how well the option satisfies the constraints or how badly it fails. It also notices questionable features whose desirableness or legality are unknown. In addition, a designer has goals and guidelines that are not in the initial design specification itself but whose violation or achievement can be noticed. For example, a meal planner might like meals to be easy to prepare, but may not include this in every design specification. Goel and Pirolli (1989) identify several classes of constraints that are of this nature, including domain-specific technical constraints (such as structural soundness), legislative constraints (such as building codes), common sense, pragmatic constraints (for example, "short construction time" or personal safety), and self-imposed, personal preferences (such as "not spicy").

Not all of the evaluation criteria and problem constraints are explicit at the start of the design. They gradually surface as ideas are proposed and criticized. A key focus-related issue is: of all the evaluative issues that could be raised, why do certain ones come to mind? In the ME design project, some issues were always raised. For instance, the issue of egg safety was a primary consideration, based on the initial problem statement. Others are derived from primary goals of the designers. For example, the team was to design an egg-carrying device for at least two eggs, but one student (S2) strongly advocated that the device have a high egg-carrying capacity. This meant that S2 often brought up issues concerning how well the proposed designs accommodated the weight and space required for several eggs (1, 10).

Other evaluative issues had to be discovered as ideas were proposed. One way this sometimes occurred is that features of a proposed alternative seemed to draw attention to particular issues that might not have been considered otherwise. Some of the features are more distinctive or odd and these seem to index directly into the set of implicit criteria held by the designer. For example, during the ME design project, the students were testing how well various types of spongy material cushioned eggs when dropped from two stories. A person walked by who had done a design project which also involved protecting an egg from breaking on impact. He said he wrapped the egg in a sponge soaked in motor oil and then stuffed it in a Pringles can (a narrow cardboard cylinder in which potato chips are stacked). One of the aspects that was new about this case, compared to the ideas the students had been considering is the idea of soaking the sponge in motor oil. Focusing on the motor oil aspect reminded the students of their personal preference that the device be clean. The motor oil aspect seemed to be directly associated with the cleanliness criterion.

A second way evaluative issues are discovered is through case-based projection. Previous design cases can be used to project or derive the outcome of the current one. In the design episode, S1 recognized the similarity of the orange as a cushioning "device" to a shock absorber with a leak (19) and could predict the problem of not being able to bounce back upon impact. (S1 could also explain why, based on the causal model associated with the knowledge of shock absorbers.) This helped raise the issue of resiliency (the cushioning device must be able to bounce back) upon which to criticize the orange idea (18). Navinchandra (1991) refers to this as *criteria emergence* and he models the use of cases to raise new criteria in CYCLOPS, a landscape design program.

Which problem constraints are reformulated?

During problem reformulation, how is the designer's attention drawn to particular constraints to relax or strengthen?

Turner (1991,1993) provides an initial attempt to model the problem reformulation process, which he implemented in a program called MINSTREL. Turner proposes a case-based model of creative reasoning in which a given problem is transformed into a slightly different problem and then used as a probe to a case library. A recalled solution to the new problem is then adapted back to the original problem (using solution adaptations that are associated with the problem transformations). A set of "creativity heuristics" is used to transform the problem. Examples include generalizing a constraint (and perhaps suspending it altogether), and adapting a constraint to require a related, but slightly different outcome (e.g., injuring instead of killing).

However, MINSTREL does not address important focus questions, such as what guides the problem reformulation? Which features or constraints should be adapted? We believe that incorporating feedback from the evaluation of proposed alternatives can provide focus. Evaluation can home in on what is ambiguous or vague in the problem specification and try to take advantage of new views that result from relaxing or pushing the limits of the constraints. Also, when the need to compromise arises, conflicting constraints come into focus and the designer considers how they can be changed.

In the example episode, trying to understand how a recalled design solves a pending problem (launching a heavy projectile from the water) draws attention to a constraint that can be relaxed. S3 realized that the submarine doesn't launch one heavy object, but several relatively small missiles one at a time. This revealed a constraint in the current problem (launch all eggs at once) that could be relaxed (launch each egg one at a time).

Note that the problem of focus in reformulation is not just how does a designer know which constraint of several given constraints can productively be changed. It is also one of *revealing* the constraint in the first place. The students did not think of their problem in terms of moving a *group* of eggs in a *single* launch. They assumed the eggs would be launched all at once as a group, but this assumption was not explicit. Contrasting problems solved by previous designs with the current problem is an important way to make explicit the underlying assumptions so that the designer can decide whether the assumed constraints are essential or can be lifted.

Which problem constraints are of primary importance?

Of several solutions under consideration, one might be more appropriate than the others or several might each contribute to a solution. Evaluative procedures must be able to evaluate each individual alternative by itself as well as in light of the others. Several focus questions arise: How is relative importance among the criteria decided? How are preferences among alternatives made?

Recalled cases seem to be important here. They suggest solutions, frameworks, design strategies and design philosophies, which can provide constraints with which to evaluate a solution and the preference criteria with which to prioritize the constraints. This also facilitates reformulating the specification, making trade-offs, and relaxing constraints. There may also be general and domain-specific strategies for setting priorities that we haven't discovered yet.

Priorities must be set flexibly, however. It is interesting that in the design episode, the reformulation of the original problem to one of launching eggs individually was proposed in response to the problem of launching a heavy object from water which would require a large launch force. However, the design at the end of the episode (flinging all eggs at once) lost this advantage of individual weaker launches, since it requires just as strong a launch force to launch all eggs as a group as it does to launch them individually, but in parallel. The designer must be able to opportunistically realize that a solution is good, even though it might not fit the original goals or address concerns that were primary earlier. If a positive aspect of a proposed solution makes a new constraint or goal explicit (e.g., "be entertaining" or "look neat") or solves some other pending problem, then the designer must be able to weaken the relative importance of the conflicting goals or constraints.

Summary: Lessons Learned and Open Issues

Our seven-week exploratory study broadened our understanding of the role cases can play in design. Not only are previous designs useful in generating design alternatives and in predicting the outcomes of proposed designs. They also aid evaluation, visualization, and simulation. These are key to performing the kinds of complex elaborations and reformulations of both solutions and problem specifications that are characteristic of creative design. In particular, previous design cases help address many focus issues that permeate these activities.

Understanding the role previous design cases play, the aspects that designers pay attention to, and on what basis cases are recalled helps determine a) the content of design cases and b) how to index them.

Case Content

From our observations of creative designers, we are starting to identify the types of information cases should contain. These include symbolic descriptions of a device's common functions and behaviors, its structural composition, causal descriptions of how it works, and the results of its operations, how it fails, and its pros and cons. Many of these can be encoded straightforwardly in the familiar framework of typical case descriptions, which in general capture a problem, its solution, and the outcome of the solution (Kolodner, 1993). However, there are key representational issues to be solved. One is how to encode the imagistic information that seems to be a prominent part of what is recalled and reasoned about with respect to a device. Another issue is how to capture both abstract, general knowledge about devices and more specific experiences with particular devices. The design cases must be represented on several levels of abstraction, perhaps having abstract device representations associated with several more concrete cases that represent specific experiences with the device.

Indexing

The effective use of design cases depends crucially on being reminded of the appropriate cases at the right time. By investigating the types of features that remindings are based on, we are beginning to understand how to index these design cases. Useful indices include not only the function of the associated device, its behavior, and its structure, but also prominent visual, auditory and other sensory features.

In addition, non-obvious, cross-contextual remindings (which often lead to unorthodox design alternatives) are sometimes based on abstract similarities. Other remindings are based on derived or computed features rather than available ones. An important open problem is determining which kinds of derived features tend to be most useful for design, whether there is a set of derived features that is common to design across domains, and when those features get derived.

Recent studies of creative problem solving protocols (Kolodner and Penberthy, 1990) suggest that anticipatory indexing is not sufficient to fully explain retrieval. Features that were not salient at the time a case was experienced might be important for retrieval in the current situation. Drawing new, abstract connections might be a result of re-indexing cases in terms of what is now relevant or important. We hypothesize that by continually updating the design specification, designers derive abstract connections between the current problem and similar problems (possibly in other domains). These abstractions can be used to see previous cases differently.

While working on a design problem, designers often perform sensitized recognition of current design options and objects in their environment as they reexamine and re-index ideas recently brought up or experienced. For example, in the ME design project, the students were considering using a spring launching device and went to a home improvement store to choose materials. While comparing the strengths of several springs by compressing them, they noticed that the springs bent. One student mentioned that if they were to use springs, they would have to encase the springs in collapsible tubes to prevent bending. Later, they saw a display of toilet paper holders in the store's bathroom section. They immediately recognized them as collapsible tubes which could be used to support the springs.

What is interesting is that the toilet paper holders were not immediately retrieved by the abstract index "collapsible tube." The holders had to be re-indexed under this description when they were recognized. A key to sensitized recognition is refining the description of the solution. The process of critiquing proposed ideas often yields descriptions of what an improved solution would look like: what properties it would have, what function it would provide, and what criteria it satisfies. This primes the designer to opportunistically recognize solutions in observations of the external world and in recently considered design options.

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