References to past designs

Book Section

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REFERENCES TO PAST DESIGNS

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Abstract. Designing by adaptation is almost invariably a dominant feature of designing, and references to past designs are ubiquitous in design discourse. Object references serve as indices into designers' stocks of design concepts, in which memories for concrete embodiments and exemplars are tightly bound to solution principles. Thinking and talking by reference to past designs serves as a way to reduce the overwhelming complexity of complex design tasks by enabling designers to use parsimonious mental representations to which details can be added as needed. However object references can be ambiguous, and import more of the past design than is intended or may be desirable.

1. Introduction: Designing by adaptation

Designers hardly ever start from scratch, but design by modifying existing products. Complex products such as aircraft or jet engines evolve from generation to generation, often over decades, through the transfer and revision of design elements. This transfer of design elements takes place at different levels of abstraction ranging from general solution principles to details of component manufacture.

There are sound economic reasons for reusing components and subsystems in designs, as well as approaches and solution principles. Reusing parts and tooling makes a new design cheaper. Components that have been tested and certified do not have to be recertified. The closer the new design is to an old design, the easier it is to predict, and reduce the risks of, particular failure modes over the lifecycle of the design. Within the design process, uncertainties and risks vary from high risks associated with innovative parts to low risks associated with parts with similar functional specifications reused from other products. It is easier to plan a design process when innovation is limited to some part of the product, and with other parts adapted to new needs. Design processes themselves also have parts which are adaptations of previous processes especially for similar product parts and subsystems. Again planning is easier when innovative and potentially more risky processes are limited to part of a product or to a particular process activity.

However, the use of existing solutions goes far deeper than product and process characteristics to the way in which designers reason about a new design. Reasoning by similarity and analogy is a central part of human cognition (see for instance Holyoak and Thagard 1995), and designing by analogy enables designers to cope with the otherwise overwhelming complexity of design tasks. Memories and external records of previous designs are primary sources for the elements of new designs. References to them provide concise indices to design knowledge; these indices are easy to communicate in discussions. But as representations of previous designs comprise tight linkages between function, behaviour and structure they also constrain designers in conceptualizing and developing design alternatives.

2. References to past designs are ubiquitous in engineering design

References to existing objects are ubiquitous in design processes and can be used in many different roles. Designers refer to entire objects, parts of them or even groups of objects at once. This section reports on different functions we have identified from several empirical studies but illustrated with examples from one of these, namely diesel engine design for off-road vehicles.

2.1. EMPIRICAL STUDIES

Since 1999 the first author and members of the Engineering Design Centre at Cambridge University have carried out several detailed studies in engineering design companies to understand communication between design teams, planning design processes in industry and the effects of changing parts in existing products (Eckert, Clarkson and Zanker 2004; Eckert and Clarkson 2003). Overall nearly 100 engineers and engineering managers in seven large UK aerospace and automotive companies were interviewed. The interviews were recorded, transcribed and later analyzed by the authors and other researchers for different research questions. Many informal interviews and discussions were held with designers and managers in these companies. In three of the companies several meetings were observed which concentrated on changes to existing products. Although these meetings could not be recorded for reasons of confidentiality, general characteristics of change processes were noted.

This research has included extensive interaction with Perkins Engines, who produce diesel engines for off-road vehicles such as tractors or diggers, and for generator sets. Several members of the first author's team have conducted extended case studies in Perkins with observations to analyze how existing products are changed (Jarratt 2004) and how processes are planned (Flanagan et al. 2005).

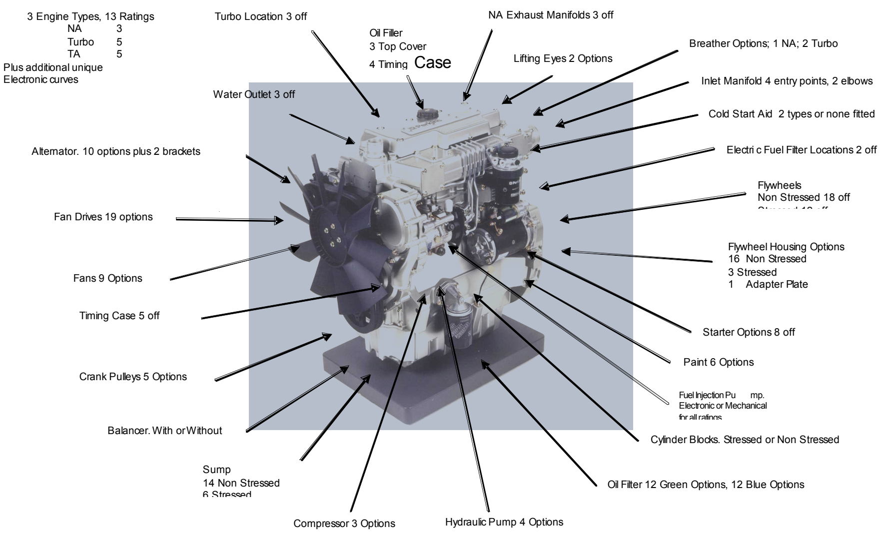

Figure 1: Versions of a diesel engine

Diesel engines were patented in 1898 and are very mature products; they have been refined over many generations of engines but their fundamental solution principles have changed little. Unlike car engines, off-road diesel engines are built to run at 100% of capacity most of the time when they operate, requiring great reliability. Under increasing legislative pressure diesel engines have been developed to produce much cleaner emissions. The off road market requires a range of products to cover the spectrum of power requirements from a few kilowatts to hundreds of kilowatts. Each engine has a large number of different versions to meet the needs of particular customer vehicles, as illustrated in *Figure 1*. The development of a new generation of engines is driven by legislation from several sources, particularly US Environmental Protection Agency and EU directives on emissions. However, new versions are constantly initiated to meet customers' specific requirements, which mainly involve changes to the geometry of engines. Creating customized versions is a key part of the business.

2.2. ROLES OF OBJECT REFERENCES

In all the case studies we have conducted, objects references have been a recurring part of many design discussions as well as interviews. References to previous designs play an important role in all the following activities.

- **Design change**. Existing products are changed to meet new customer needs or to eradicate errors in the product (see Eckert, Clarkson and Zanker 2004). In discussing what should be changed, designers talk with reference to the existing product or its versions, to express solution principles, design details and design behaviour. When a component is changed this often has knock-on effects on other components. The extent of change in terms of which components are affected is often estimated by analogy to other design processes, in which similar changes have been made.

  Object references play a vital part in identifying a suitable starting design for a change. For example when a customer approaches Perkins with requirements for a new engine version, Perkins sales engineers examine whether an existing engine already meets those requirements. This can be a formulaic process, but often depends on remembering specific engines sold in the past. If a new version is required, a change request is raised. A decision is made about which engine is closest to the new engine. This existing engine is taken as a starting point. Particular features are drawn from other engines. A typical description of a new engine can sound like this: "The new engine is pretty similar in dimensions and configuration to the tractor engine we did for customer X, if we do with the fly wheel what we did on the 4 cylinder one for customer Y, ….”. As there are far more potential configurations than there are names from them, in fact over 30 000 different ones, a past engine is a convenient shortcut for a combination of options, which could otherwise not be expressed succinctly. The engines don’t have names, and they typically get referred to by the customer’s name.

In design change, past objects are used as starting points; as sources of systems and components that can be reused; as sources of solution principles that have been successfully employed; as reference points for any relevant features and as shorthand for experiences in design, manufacturing, service and use.

- **Design process planning**. At the beginning of a design process, tasks need to be identified, gateways defined and resources allocated. While much of this is covered by standard procedures, design managers need to make judgements about which problems it will be necessary to solve, which parts, processes or solution principles can be reused, and how the skills of the people involved match these tasks (Eckert and Clarkson 2003). The similarity assessments involved in process planning are similar to those in change assessment; however planning is a far more open-ended process. Companies can estimate how much effort is involved designing a particular component. For example Perkins keeps certain components fairly constant, because their redesign would cause significant design effort, while others are much easier to redesign. Projects need to be planned as soon as a concept is accepted, but before the company really knows what innovation will be required for the new product. They usually do this by trying to assess how different the new project will be in terms of product and process from a number of familiar projects. Typically the project manager requests plans from individual team leaders who have worked on a similar part in the past. The team leader assesses the effort involved in designing the part by reasoning about how long similar parts took in the past, whether these can be modified thus speeding up the process, or whether a redesign would take the same length of time as the original part, given the experience of the available team members. Then it is necessary to decide which parts to design anew. Both time estimates and expertise estimates are done with reference to past designs. The project manager then collates the plans, accounts for the conservativeness of personal estimates, and adds a contingency factor to the entire plan. As planning is so dependent on personal experience, individual managers plan in very different ways. In contrast to discussions about changes, people seldom mention the sources of plan elements when they are communicating plans to their colleagues. In interviews managers explained how they plan and make estimates in terms of assessing similarities to previous processes. However, they were much vaguer about the processes of making these references than they were about elements of the designs themselves.

- **Cost estimation**. To select between design alternatives and to make no-go decisions, designers need to estimate the part, manufacturing and service costs. As there are no effective costing tools for early design, these estimates are often made by cost engineering experts based on high level similarities, without any assessment of how detailed properties will affect cost. Throughout the design process compliance with costing targets is assessed continuously on a component level. When designers make changes, they often reason about whether a similar change in the past caused cost problems.
- **Communication of specific design ideas or solutions**. Designers often describe particular detailed solutions with reference to designs in which the solution has been employed. These reference designs can be quite independent of the starting points for design changes. They are selected for very specific purposes. For example the Perkins engineers might use a competitors' engine to express particular design ideas. Object references in communication can be opportunistic and personal. Less so in Perkins, but in the aerospace companies we worked with, many engineers were aircraft enthusiasts and would express design features with reference to historic aircraft that had used a particular solution principle. Solutions seem to be indexed by references to single examples – "we did the …. as we did for the Italians" – making the conversations almost impenetrable for outsiders (see Eckert and Stacey 2000; Eckert, Stacey and Earl 2003). The references can contain a rich message expressed concisely. Objects that combine features provide a convenient way to express or refer to these groups

of features. However the scope of these references can be ambiguous. The comparison points through which a design is communicated do not have to be the same as those used in the generation of the design, because they might have been created later or the similarities might have been recognised later. A reference to a completed product is not only a concise way of expressing ideas, it also adds a degree of credibility to a suggested solution, because it derives from something that already works.

- **Generation of solution ideas**. When designers look for new ideas for entire designs or particular aspects of a design, they review their own past designs and the designs of their competitors. For the mature products whose development processes we study, idea generation happens at several points in the process. At the very beginning a new product is devised by a very small team of people. Perkins has a chief conceptual designer, who has been working in the company for several decades. He is familiar with all the past products, and comments that when thinking about aspects of a new engine he mentally surveys the designs and configurations of past engines to draw ideas from them. He also assesses the impact of changes that need to be made to create the new engines; this is a systematic procedure guided by remembering where problems have occurred in the past. He also explained that his main way of reasoning about product trade-offs is by thinking about how well engines that incorporated a similar trade-off decision have worked in the past.

  Idea generation also occurs at a more local and detailed level later in the design process especially when resolving problems. Almost paradoxically a lot of innovation happens late in design processes or even during changes once a product has gone into production. This happens partly to avoid changes to frozen parts. Designers often comment that when they are looking for solutions to specific problems they need to know about past designs and where the company has already solved this problem. In Perkins, which has produced hundreds of engines, this is a serious issue. These comments were often made in Perkins apropos of experts retiring. For example a cost engineer, whom we spoke to shortly before he left the company after over 40 years with Perkins, commented that he had a personal filing cabinet full of past cost-saving solutions, which he would remember and get out in particular situations.

Increasingly companies look to other industry sectors to see how they have solved similar problems. For example aerospace designers look at car designs and conceptualize the solutions they find in terms of the cars in which they have occurred. Up to now we have not encountered systematic procedures for looking at other industries, but have heard many causal references to solutions in other industry sectors.

- **Corroboration of design ideas**. When designers work out several solution alternatives for a particular part or system, they often look at competitor designs, on the assumption that if their competitors have employed a particular standard solution concept for this particular problem, they must have tested it. This use of references to other designs is similar to the communication of provisional ideas by reference, but occurs at a different point in the process, after ideas have been partially developed; and with a greater degree of reflection. When object references in communication are thought of on the spur of the moment, references for corroboration are carefully thought through. For example Perkins, when considering a new configuration for some struts, considered either using one large one or several small ones. When they realized that one of their competitors had employed a multi-strut version they opted for it as well.
- **Evaluation of solutions.** Once design solutions have been generated, specific object references again play an important role in corroborating the new design. Now it is possible to assess the similarity of the new but yet untested design and an existing reference design with known long term performance characteristics. In a right-first-time design culture this is increasingly important, as designers are only allowed to use physical testing to verify a design, rather than to try out a design or learn about its performance. Perkins is developing a "confidence measure" (Flanagan et al 2005) which assesses how sure they are that a new design component will work. This is computed from a combination of particular evaluations and similarity to existing components. If a component is very similar, they have greater confidence and need less testing to be sure. This

does not replace the testing necessary to assure safety, but can guide the design effort in an organization.

In summary designers employ object references throughout the design process; however references are most frequent and important at the beginning and the end. Designers use object references to come up with ideas, assess changes and plan processes at the beginning. Later they use different object references to corroborate design ideas and evaluate solutions.

2.3. SUPPORT FOR DESIGNING WITH OBJECT REFERENCES

Tools and methods for supporting designers in using past designs and solution principles have focused on idea generation and design synthesis particularly in the early stages of design. The importance of designing by adaptation is well-recognised by design theorists, notably Gero (1990), as well as practitioners (see Eckert, Stacey and Clarkson 2000). And case-based reasoning techniques (see Kolodner 1993) have been widely used in research on design synthesis (see Voss, Bartsch-Spörl and Oxman 1996). Case-based reasoning systems select a reference design and modify it to meet new requirements. This parallels the role of object references in change. Generative and grammatical techniques comprise sets of generative rules that are extracted from a canon of reference designs.

Other researchers have recognized the more opportunistic nature of object references in design generation and the potential value of supporting the retrieval of previous designs. For example Büscher et al (2001) have developed a computer tool that catalogues reference designs for the communication of ideas in landscape design; Goldschmidt (1995, 1998) discusses the role of visual databases in using precedents and references in architectural design.

Curiously, although there is a large body of literature on design process planning, little attention has been paid to the adaptation of existing plans to new designs, although this is a well-known approach in manufacturing process planning. The tools that come closest to supporting design process planning by object reference are attempts to develop process modelling building blocks (Bichlmaier 2000; Wynn, Eckert and Clarkson, 2005).

3. Design thinking requires complexity management

Human beings are severely limited in the complexity of the things they can keep in mind at one time (see Cowan 2001), and typical engineering products that designing engineers create are far too complicated to comprehend fully. Designers employ a variety of strategies for coping with this complexity and wealth of information.

3.1. THINKING WITH HIERARCHIES OF COMPONENTS

As Simon (1996) pointed out, designed complex systems are organized as 'nearly decomposable' hierarchical structures with components whose interactions are much simpler than their internal workings, so that it is feasible to understand each element in terms of its behaviour and the interactions of its subcomponents. In some design processes, notably in software, choosing appropriate components to achieve clear and simple decompositions is an important part of designing; reorganizing component hierarchies is an important part of object-oriented software development (see Fowler 1999).

3.2. THINKING WITH ABSTRACTIONS

An alternative, and complementary, approach to reducing the complexity of the thinking designers need to do is to consider different *aspects* of a design separately. For instance Hoover, Rinderle and Finger (1991) observed designers employing different abstractions and corresponding graphic representations to perform analyses of different aspects of their designs. However simplifying by abstracting away from concrete embodiments of design ideas is difficult. Many teachers of engineering design have advocated methods involving thinking abstractly about the functions that products and their subsystems should perform, such as Suh's (2001) axiomatic design method, Andreasen's (1991) theory of domains, and the functional analysis that is part of Pahl and Beitz' (1995) method. These methods are widely taught, but in practice most engineers struggle to think about designs in the abstract with no physical embodiment in mind. Nam Suh has commented (personal communication) that some engineers taking industrial training courses on axiomatic design have great difficulty thinking in functional terms. Other methods for designing in abstract functional terms make the mental operations they require easier by constraining the abstractions they require. TRIZ (see Savransky 2000) is a method for identifying appropriate solution principles for engineering problems based on the analysis of numerous patented designs; it works by abstracting out the essential functional transformations required by a problem and mapping these to a set of standard solution principles. It is usually used in conceptual design, but can also be applied in the development of design ideas in later stages of the process. It provides a systematic method for finding and using analogies to past designs (stored in a relatively abstract form). C&CM is a method for analyzing and modifying existing designs, based on assigning functions to working surface pairs of specific designs, thus providing functions with a specific location on an object (see Albers, Ohmer and Eckert 2004). C&CM requires abstraction to a functional view but keeps the functional thinking connected to physical embodiments and localized to interactions between individual components.

Mechanical engineers typically think visually about designs, often with mental images of designs that may be more specific than is strictly necessary for the current task. We have found that when designers are prompted to list the functions that their product must carry out, they often list the functions that particular components need to carry out, once they go beneath the top level functions (see Jarratt 2004 for an example of a group session to elicit product functionality). In many other situations, designers talk about functions by immediately mentioning the components that carry them out.

However, engineers switch between different levels of abstraction, and there are differences between different kinds of engineers that depend on the tasks they carry out. Anecdotal evidence from 20 interviews with helicopter designers (Eckert, Clarkson and Zanker 2004) revealed an interesting difference in how designers thought through their design problems. All the designers were asked about their mental representations, and a clear pattern emerged. The apprentice-trained engineers, who were team leaders for key mechanical components, claimed that they visualized design problems in terms of concrete three dimensional solutions, based on past designs that they knew. By contrast several of the design analysts, who were university-trained, explained that they reasoned about design problems in terms of correlation relationships between key parameters and properties of the components and systems they analyse. Similar distinctions seemed to emerge among the Perkins engineers but they were not systematically questioned on the point.

3.3. THINKING WITH DESIGN CHUNKS

Designers cope with the limited capacity of working memory when reasoning about more complex designs and situations than they can keep in their entirety in focal attention, by being able to reconstruct and retrieve elements of complex mental representations as they switch their attention (see Cowan 2001 for a discussion of the capacity of working memory).

Designers working on their own or in meetings commonly use sketches and other graphic representations of design information, that can serve as cues for the rapid recollection or reconstruction of information when it is needed (see Purcell and Gero 1998, for a review of research on sketching in design). And sketches often have an important role in the collaborative development of designs in meetings (see for instance Minneman 1991). The explicit information content of the representations created in the course of designing is only the tip of the iceberg: it provides cues triggering the recall of designers' knowledge about the types of design elements signalled by the representations, and this knowledge guides interpretation of the representations. Similarly interpreting CAD models and schematic diagrams is a learned skill involving the activation of knowledge in memory.

In our studies of how engineering designers work, we have found that designers activate chunks of design knowledge by verbal references to individual past designs and to narrowly and concretely defined classes of designs. We have also observed that this is an essential part of knitwear designers' design thinking and discourse (Eckert and Stacey 2000).

The chunks of design that designers recall are often highly structured; while only parts or aspects of a design may be held in working memory at one time, they activate memories for other parts (see Anderson 1983). Memories for designs include concrete details of how functions are embodied in solution principles and how solution principles are implemented with specific types of components, and how these are configured. Memories of structural elements are linked to memories of behaviours and problems such as vibration, as well as functions. Depending on how well they remember them, designers can imagine designs employing elements of past designs, that have more structure and detail implied by the relationship to the past design than the designers can keep in working memory. This additional information can be recalled as required and compared to the needs of the present situation. Thus designing by adaptation enables designers to reason about complex designs more easily. Rather than deduce consequences they recall the implications of previous design decisions.

How much of the remembering of past designs is recall and how much creation is not obvious; as evidence from mental imagery research indicates that details of visuospatial representations are only generated when attention is directed to them (Kosslyn 1980), and extensive psychological evidence indicates that memory recall is heavily dependent on memory for categories and causal relationships (see Schank and Abelson 1977). Oxman (1990) and Kulinski and Gero (2001) argue that constructive memory processes play an important role in design thinking.

4. Adapted designs can bring more than is intended

The consequence of references to existing designs is that when designs are created by modifying remembered or referred-to designs, or adopting elements of them, more is imported into the new design than just a solution principle for the subproblem that the designer is focusing on. The imported design element is imagined as a concrete embodiment, modified to fit the new context – to be coherent with the rest of the design. It also carries with it assumptions about its physical properties, materials, manufacturing process and context of use. Some of these assumptions may be necessary for the design to work; others may be invalid in the context of the new design.

When designers want to think abstractly about solution principles, the abstractions trigger memories for examples. Designers find it difficult to break away from the design elements and solutions to problems they remember, to imagine something different, even when they *know* they are inappropriate – this is known as *fixation* (see Jansson and Smith 1991; Purcell and Gero 1996). Designers may not question particular aspects of a design that have always been done in a particular way. These assumptions (part of the designers' *mental set*) can apply to features of existing designs that are inherited. Designers can also fixate on a particular feature of a new design from the beginning and never modify it. Memories for designs may not include the rationales for design decisions – or the designers may never have known them – but they may fear to change design elements in case they will no longer work correctly; unimportant features may simply be carried over.

The ability to make use of object references is closely linked to expertise (see Lawson 2004). However with increasing expertise designers make more use of more abstract schemata in conceptualizing new designs (Ball, Ormerod and Morley 2004); Lawson (2004) presents an example of architects using shorthand phrases to mention shared schemata. Experts have seen more designs and have more experience with design processes; they have a greater and more subtle understanding of visual and behavioural patterns, and therefore can spot resemblances to other designs – and ways they are relevant – that a novice might not see. Experts also know which parts of a product can be modified easily and which not, and therefore prioritise design decisions accordingly. However the development of decision strategies based on past unsuccessful or difficult experiences with ideas or solutions may sometimes limit their creative scope compared to novices. Potential solutions may be filtered out for invalid reasons (see Eckert, Stacey and Wiley 1999). The development of detailed memories for a sufficiently wide range of previous designs, as well as categories of solution principles, is an important part of education in architecture, and a fundamental part of the transition from a design novice to a design expert. For example novice jet engine designers learn about the theoretical and engineering development of turbojets in order to reason and converse about these engines and their parts.

5. Object references are chancy and potentially ambiguous

Objects references used to communicate design ideas to others can be ambiguous, because it may not be clear whether designers wish to reuse the entire reference object or only one part or aspect of it. As we have pointed out elsewhere (Eckert, Stacey and Earl 2003) this can not only be a source of hidden mismatches between different designers' understanding or views of the design, but also the genesis of creative ideas as object references suggest new solutions.

Reasoning by object reference can be a powerful way of selecting and working with large and coherent solution chunks, but can also be a chancy and unsystematic process. How particular previous designs are retrieved from memory may depend on what aspects of the design problem trigger recall, or are in mind when the designer searches for a related design; problem framing is an essential part of design thinking (Schön 1988; see Cross 2004). Research on the construction of analogies indicates that analogous situations are retrieved according to how similar they are to the aspects of the current situation that people focus on, and that this depends on how they have constructed a mental representation of the analogous situation (Dunbar 2001). If designers think about adapting one previous design, the features of that design may over-constrain how they think about particular parts of the new design, when a component or solution principle from a different design might be more appropriate. For example project managers complain bitterly that designers forget that they have already generated a component, employed in another product, that would meet the exact requirements for the current design problem. Designers and their companies sometimes put considerable effort into redeveloping something that already exists in another product. While this can be a sign of bad information management, it can also be a design shortcoming with designers failing to identify what designs and design elements might be relevant.

6. Designing by adaptation is the creation of conceptual coherence

We have observed engineering designers employing analogies to past designs for a variety of purposes. Not only is adaptation an essential aspect of designing, but comparisons and adaptations of previous designs are important for communicating ideas and planning processes. References to past designs are ubiquitous in design discourse. The common thread is the search for as close a match as possible to a current problem that specifies both some of the elements of a solution, and the constraints the solution has to meet. Dunbar's (1997) observations of molecular biologists and immunologists at work reveal a similar pattern: scientific reasoning in conversations and meetings makes frequent use of analogies, almost always to very similar situations. Dunbar found that analogies served three major goals: formulating theories, designing experiments, and giving explanations to other scientists; analogies are frequently used when unexpected findings occur. Dunbar discovered that the scientists he observed have little memory of the reasoning processes that have gone into a particular scientific finding, and in particular the analogies they employed; the analogies appeared to serve as scaffolding, discarded as soon as they achieve their purpose. Dunbar concluded from this that it is necessary to treat retrospective reports of reasoning processes with caution.

What the different uses of object references in designing also have in common is that they employ universal psychological mechanisms for developing mental representations of situations by aligning different elements to achieve conceptual coherence (Thagard 1989; Thagard and

Verbeurgt 1998; Johnson-Laird, Girotto and Legrenzi 2004). The design synthesis actions involved in the development of new designs employ the building blocks provided by the designer's memories and current perceptions; these include mental representations of past designs as well as representations of categories and solution principles, plus representations of requirements and constraints. The elements, requirements and constraints in focal awareness exert the strongest influence, but elements activated in memory by related recent experience are *primed* for easier recall (see Anderson 1983). These elements are modified and combined into a mutually consistent structure in the rapid construction of mental models of modified designs through a process of constraint satisfaction (see Johnson-Laird 1983; Johnson-Laird, Girotto and Legrenzi 2004).

This process depends on the identification of significant similarities between the current situation and some past design or more abstract schema. This depends both on the resemblances between elements and on the structural relationships between elements; the development of a coherent mapping is crucial (see Gentner 1983; Gentner and Markman 1997). In experiments on similarity judgements, similarities between individual features are more powerful when similar items are recalled from memory; but broader structural similarities are more powerful when visually available items are compared (Gentner, Ratterman and Forbus 1993). But people readily recall structural analogies from memory when searching for particular structural relationships, and when their memories for the to-be-recalled analogies include these relationships (Dunbar 2001).

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