Chapter 8

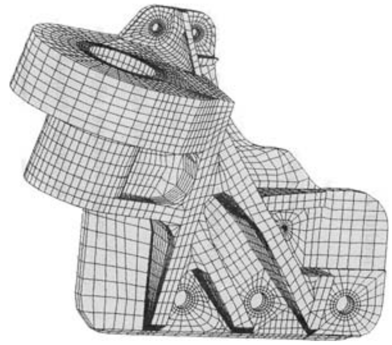
Thinking and representing in design

Martin Stacey
De Montfort University

Kristina Lauche
University of Aberdeen

What are the mental processes of design thinking? How do different designers vary in their ability and skills? How do the powers and limitations of human thinking interact with the nature of design problems to shape the processes of designing? Some people claim design should proceed very analytically and rationally. Others emphasise the intuitive aspects of designing. This depends largely on the design task undertaken and the product that is designed. But it is also a question of how designers think and what they are thinking about. Experts can be more effective because they have different strategies from novices. Understanding how designing works as a human activity can be useful in understanding the causal connections in design processes, and for changing design processes in ways that exploit and enhance designers' abilities and take account of human limitations.

There is a large and increasing body of research on how designers think. This chapter does not attempt to survey it. Instead we concentrate on the relationship between design thinking and how designers interact with the representations that they generate in creating and reasoning about designs, such as sketches, diagrams and CAD models. While this is only one facet of the psychological factors that influence design processes, it is directly affected by changes to design processes, and influences the success of those changes.

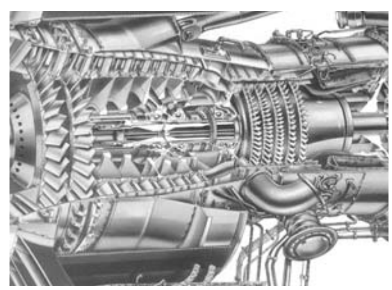


8.1 Generating a mesh for a finite element stress analysis. Experienced engineers estimate the value the analysis should produce and set the meshing points correctly. Less experienced engineers set the points almost at random and often don't recognise when the analysis result is out by an order of magnitude.

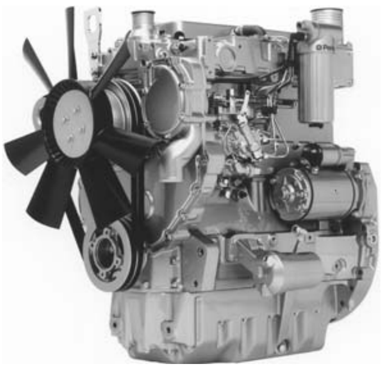
A psychological perspective

In this chapter we discuss design from our perspective as cognitive and organisational psychologists. Design activities have been analysed and studied in great detail, both in laboratory experiments and in field observations. The experimental approach means that a phenomenon can be studied in detail and any confounding factors can be eliminated, thereby allowing causal conclusions. The difficulty is that it often remains an open question whether the results can be generalised to designing in the 'real world' of a company. Also, a lot of research has focused on a small number of phenomena which can be studied comparatively easily, such as observations of sketching, but are not necessarily important to all types of design. Therefore, some researchers have argued that it is equally important to carry out field studies in the workplace. The danger with this approach is that all the results ever do is provide a description without any theoretically founded explanation or intervention.

We have included both types of research in the evidence we report. Psychological researchers have often shied away from studying complex



8.2 Reducing the rumble in a jet engine combustor. These low-frequency noises arise from subtle details in the shape of the combustor and the details of the combustion process. A few rumble experts know what changes to make, while other jet engine designers see this as a black art. Reproduced with the kind permission of Rolls-Royce plc

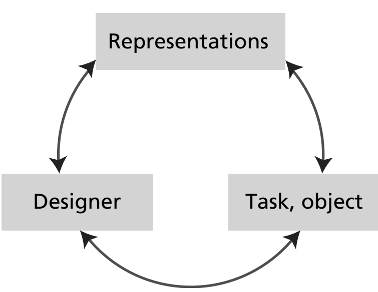


8.3 Reasoning about change propagation. Some engineers think through the sequences of connections between components, struggling to incorporate multiple propagation paths, while others reason by analogy to problem they have encountered with similar designs in the past.
© Perkins Engines Company Limited

activities in natural contexts, because they are too open-ended, and the volume of data overwhelms methods that give insight into finer-grained thinking processes in small-scale experiments. This can make research results difficult to relate to complex industrial situations, but observations are a valuable source of insights.

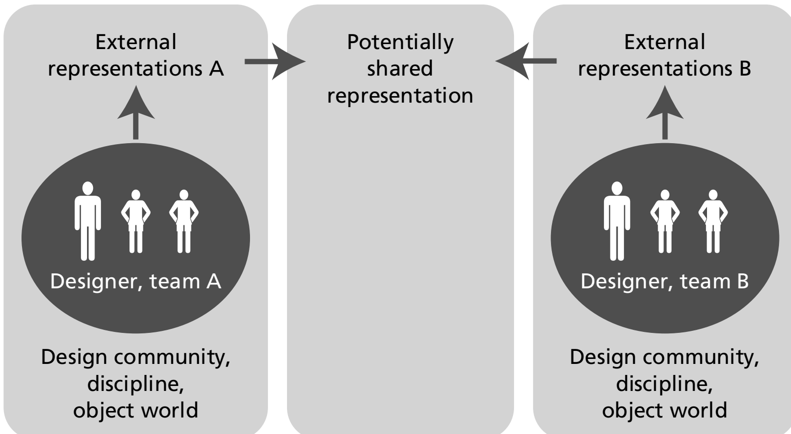
Researchers view design from a variety of theoretical perspectives. Information processing psychologists aim to understand how the mind works in terms of the mechanisms of mental processing, and how relatively simple mental operations combine to create complex behaviour. This includes seeking to understand the structure and content of mental representations – our internal descriptions of things outside ourselves (real, or possible, or impossible). In information processing psychology, other people are sources of sensory inputs. In social interactions, the content of our mental representations of the environment, goals and actions is different from what it is in solitary problem solving, but the mechanisms are the same.

Activity theory aims to understand human action in its cultural and historical context. The use of external representations for communication is a general psychological process: the symbols of language and the artefacts we create mediate between the individuals' minds and the task they are trying to achieve (Vygotsky, 1962) (Figure 8.4). Through these representations we can all access and contribute to our shared culture: language, received wisdom, historical artefacts and classical designs all form part of our common understanding of the task and influence design (Leont'ev, 1978). Design thinking means internalising what we see and externalising to others what we think. Only if mental representations are externalised can they become accessible to others. These external representations may in turn foster a shared mental model of the design object (Figure 8.5).



8.4 Representations mediate between the designer's intentions and the object they design

Sociological design researchers, such as Minneman (1991), Bucciarelli (1994), Glock (1998) and Henderson (1999), come from a research tradition that views the development of shared understanding as fundamentally problematic. They focus on how meaning gets communicated, in terms of the content of the talking, sketching, gesturing, exchange of documents and so on that comprise communication. The difficulties inherent in achieving a shared understanding of design problems and design solutions shape the interactions and working practices of designers, and understanding how and how far it does happen is a profound challenge for sociology, psychology and philosophy.



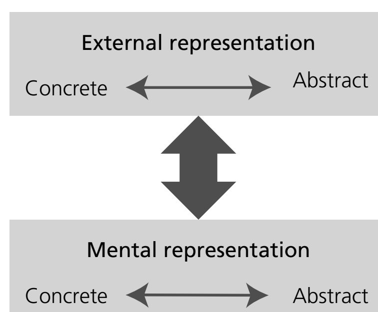
8.5 Building shared representations

Overview

The next section discusses how designers use graphic representations and models during their work and how this affects individual thinking and interactions with others. The following sections provide a more detailed explanation of the underlying mental processes, including: discussion of how designers form and use mental models of their designs; a description of some types of mental action that are characteristic of designing and a characterisation of expertise and skilled behaviour in design; discussion of some of the special characteristics of creative thinking; and some issues to think about in considering representations in new processes and methods, where the properties of representations can be usefully analysed using Green's (1989) cognitive dimensions framework.

The role of mental and physical representations in design

Understanding human thinking involves understanding how we create mental representations though the interaction of what we perceive and what we know, and how we use mental representations, both in tandem with direct perception of external things and independently (Figure 8.6). How designers work depends crucially on the interaction between their mental abilities and the representations in which they conceive, describe and communicate design ideas. New methods, procedures and computer tools require designers to represent design information differently and think about old problems in new ways. Effective choices of representations enable designers to use new methods and tools rather than struggle to work around their limitations.



8.6 External representations vs mental representations

Designing involves both abstract and concrete thinking.

Effective combinations of representations can facilitate thinking fluently about design problems in a wider variety of alternative conceptual terms. (The design of tools and methods also demands careful consideration of task demands, to minimise effort and, where appropriate, to stimulate creative thinking). Designing involves both abstract and concrete thinking. Depending on the tasks and individual preferences, designers think about underlying physical principles, functional features or the concrete form of their design object, often in rapid alternation.

Variety of use of representations

Engineers use different types of representation depending on the task. Besides geometry they have to consider functional requirements and structural constraints, as well as information about the characteristics of components, materials, performance, construction processes and so on.

Eckert *et al.* (2004) observed and interviewed 20 helicopter design engineers about the representations that they used. Sketches were often used to generate or communicate ideas in early design phases. Many engineering tasks were not concerned with the creation of geometry directly but with function or performance. Engineers involved in these types of tasks typically did not use pictorial sketches. Avionics engineers sketched blobs and lines to outline the components and connectivity of systems. Software packages played a larger role in numerical modelling of stress or heat, and designers used the colour coding of the resulting diagrams tacitly to reason about shape. Rapid prototyping and testing complemented the computational analysis. More abstract representations, such as performance diagrams or matrices, were used to analyse the functionality or the relationship between parts or describe the connectivity.

Understanding the organisation of complex systems involves abstracting away from the form and detailed operation of individual components to focus on skeletal representations of what they do and how they are connected. A variety of notations have been developed for showing functional and causal relationships between abstract representations of design elements, as graphs (such as Petri nets and Bond graphs) and as tables.

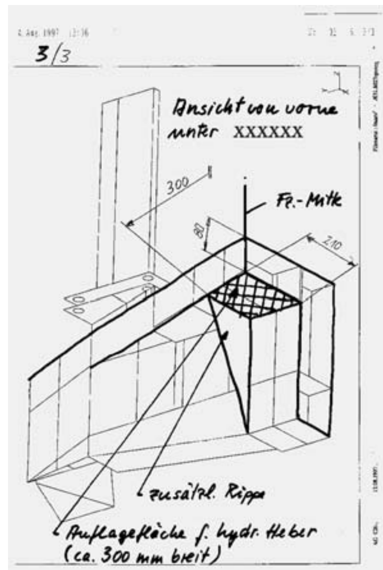
Sketches are often used to generate or communicate ideas in early design phases.

Design research has focused on sketches of geometric form as a medium for generating ideas and communicating them. The following discussion will therefore use sketching to illustrate more general features of design cognition. Similar issues also apply to the representation of design processes, which are discussed in Chapter 2 on design process planning.

Representations support individual design problem solving

External media function as a way to unburden working memory for complex operations so that the designers can see their design ideas and thus have less need for accurate memories of their earlier thoughts. As we describe in the next section, the external representations function as cues for recalling and reconstructing elements of mental representations. Being able to transform mental representations into physical shape by sketching is for many designers a way of 'thinking with their hands'. For many designers, especially in early conceptual design or creative problem solving, design thinking is inseparable from physical action to create external representations; so, for them, sketching is generating ideas not describing ideas. Sketching, therefore, has an immediacy that other media do not have. Sachse and Hacker (1997) found that, when instructed to use sketching while designing on a CAD system, engineering students produce better solutions in the same time as the control group who only used the CAD system.

Schön (1983) influentially described designing as a dialogue between the designer and the sketch, in which the evolving sketch suggests interpretations of the design beyond what the designer intended to draw. Perception of sketches alternates between *seeing as* and *seeing that* (Schön and Wiggins, 1992; Goldschmidt, 1991); Goldschmidt (1991) observed designing progressing as an alternation between pictorial and non-pictorial reasoning. A common thread in research on sketching in design is that designers reinterpret ambiguous sketch elements to suggest new possibilities (see Purcell and Gero (1998) for a review). Engineers use sketches as representations of their mental concepts but sometimes also attribute a different meaning to the lines and see them as something else (Pache *et al*., 2001). This reinterpretation of ambiguous sketches can serve as a means for stimulating creative, non-intended ideas, often triggered by dissatisfaction with the current design (McFadzean *et al*, 1999). New concepts or requirements can enable designers to re-examine sketch features from a new perspective (Suwa *et al*, 1999).



8.7 An example of an engineering sketch. Engineers like to sketch when they are solving problems. These sketches are often generated in meetings or brought to meetings as illustrations. Different interpretations can lead to different views of the problem. Engineers need to reach a shared understanding or risk costly changes later (reproduced with permission – Lauche *et al*., 1999).

Joint designing and development of shared understanding

Engineering design is a collaborative activity: not only do designers engaged in different tasks need to exchange information and coordinate their activities, but, also, a lot of important decisions are made in meetings or informal discussions (Bucciarelli, 1994; Badke-Schaub *et al*., 2001), and designs are sometimes created jointly. Design teams use a variety of shared artefacts. Rather than writing lengthy verbal descriptions, some designers generate

8.8 A much-praised computer tool for mass customisation. The Web interface allows customers to pick the material from a range of tarpaulins and make their own cutting patterns for their choice of bag. Image www.freitag.ch

largely non-annotated graphical representations (Weber *et al.*, 1999). During video-conferencing with limited bandwidth they give preference to seeing drawings rather than their colleagues' faces (Weber *et al.*, 1999). Minneman (1991) describes designers negotiating through proposal and counter-proposal for mutual understanding as much as agreement, and has argued that ambiguity in sketches has a beneficial effect in suggesting new ideas in design meetings. However, it is provisionality in design representations rather than ambiguity that matters: how strongly someone is committed to a proposal, the degree of precision intended, whether details are meant seriously or represent qualitative categories. The challenge lies in signalling provisionality while avoiding misinterpretation. Designers can signal provisionality in sketches relatively easily by degree of apparent roughness, but sketches are easy to misunderstand, especially when the creator cannot be consulted (Stacey and Eckert, 2003).

Designers often fail to recognise that the resulting problems are communication problems (Eckert, 2001). Finished-looking graphic representations are often interpreted as more fixed than is intended or appropriate. For instance, designers are more ready to modify and change a joint representation when it is drawn by hand on a flipchart or electronic white board, rather than a spreadsheet or professional presentation (Kunz *et al.*, 2001). In meetings, designers use speech, sketches and gestures in combination to disambiguate each other, and signal how far decisions are open or negotiable, through subtleties of phrasing and tone of voice (Minneman, 1991; Neilson and Lee, 1994; Brereton *et al.*, 1996; Glock, 1998). These signals are missed by those who communicate across distances.

Communicating across object worlds

Communication between members of design teams can involve subtle problems when different specialists have mental representations of designs and design problems that comprise differing concepts, objects, features, properties and relationships – what Bucciarelli (1994) terms their *object worlds*. Members of design teams with different fields of interest and responsibility share and exchange sketches, diagrams, specifications, CAD models and so on, but interpret them differently.

Reading representations is a learned skill, and the mappings between the elements of sketches or diagrams and descriptions and what they stand for depend on the conventions of a community as well as any geometric resemblance (Henderson, 1999). Similarly, terms for concepts can mean different things to different people (for instance Bucciarelli (1994, ch. 6) discusses the different meanings placed on the term 'module voltage' by the members of a team designing a photovoltaic generator).

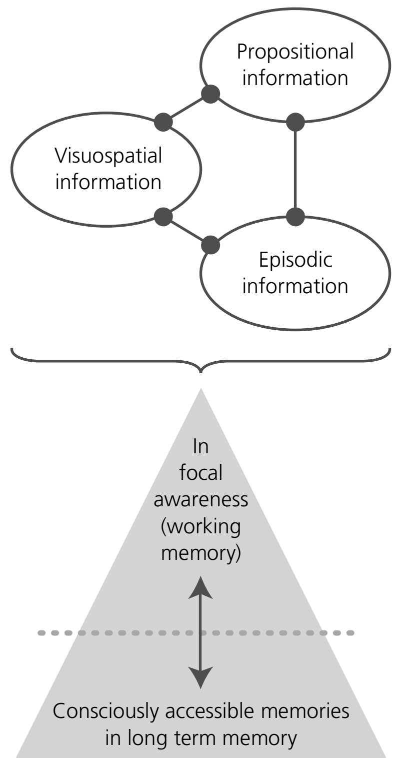
Design researchers term the objects such as sketches and CAD models that are shared by different participants in a design process, and which convey information between them, *boundary objects* (Star, 1989; Bucciarelli, 1994). That is, objects that enable communication between object worlds, so that the inhabitants of the different object worlds have compatible understandings of the state of the design.

Mental representations

Although thinking usually involves direct interaction with one's environment, it happens in one's head: sensory perceptions create mental descriptions of what is out there – mental representations – which depend on one's memories. These mental representations trigger the direction of attention, the recall of memories, conscious reasoning and goal setting, the imaginative synthesis of mental representations of possible situations, and physical actions. In this section we outline how designers' mental representations of designs and design problems work, and how this governs the ways they use external representations such as sketches to cope with the size and complexity of design tasks.

Types of information

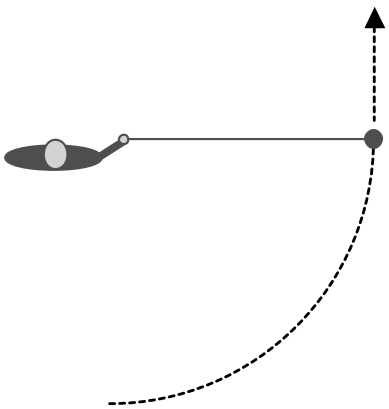
Humans have consciously accessible memories for three distinct types of information (Figure 8.9): visuospatial information, in which shape and extent, and sometimes movement, is inherent; propositional information that can be described in statements, and episodic information that is inherently experiential and time dependent. Designers' mental representations of designs combine visuo-spatial and propositional information (Goldschmidt, 1991). Episodic memory can play a role in envisioning how a design is used (Schön, 1988).



8.9 Types of information

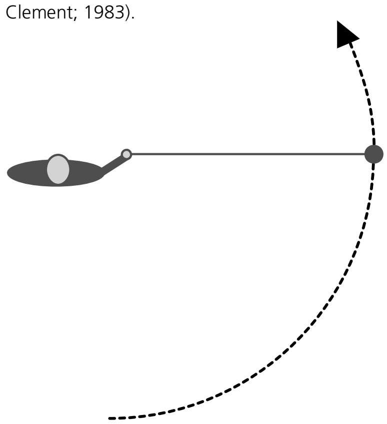
Mental models

Mental models are representations of the form and properties of physical objects (or other kinds of systems with causally connected components), with which people envision their behaviour, to understand what the objects or systems do or predict what they will do (Johnson-Laird, 1983). The users of interactive computer systems and other consumer products form mental models of how they work, which often differ markedly from their designers' mental models of how they work (Norman, 1988).



Imagine whirling a weight on the end of a rope in a horizontal circle around your head. How does it move when you suddenly let go?

People who have paid attention in physics, and internalised Newtonian mechanics, will imagine and describe the path of the flying weight as a straight line in the horizontal plane, perpendicular to the line of the rope at the moment of release; while the object drops with increasing speed in the vertical plane (due to gravity). People who have not learnt mechanics often imagine that the weight will move in a curved path, and give similarly wrong answers to other problems to do with force, motion and gravity (McCloskey, 1983). Their naïve intuitive physical beliefs correspond remarkably closely to theories of motion held by scholars in the centuries before Newton (McCloskey, 1983; Clement; 1983).



8.10 Naïve physics

People think about how physical systems behave through a combination of reasoning with consciously articulated propositional beliefs, and imagining changes in visuospatial forms and relationships. The relationships between the structure of physical systems and how they act and change are partly learned tacitly through experience of the world and encoded in visuospatial or kinaesthetic form. Tacit beliefs about how objects move can be wrong and misleading, and can often persist through quite a lot of education (Figure 8.10; McCloskey, 1983).

Relationships between form and behaviour are also partly learned consciously, from verbal descriptions of physical principles. DiSessa (1983, 1993) describes people reasoning about how physical systems behave by recalling and applying what he terms p-prims (for phenomenological primitives): elemental causal or explanatory relationships that appear to fit particular situations. As people learn more about physics, they learn new p-prims and alter the priority with which they recall them and apply them. Mental models of all but the simplest systems are invariably incomplete and unstable (Norman, 1983), and people may have multiple mental models of an object or system, which are not necessarily compatible. The users of interactive devices may use both models of the structure and causal processes within a device, and models of how it behaves in response to inputs – what Young (1983) called a task-action mapping model (Norman, 1988). Engineers reason about the characteristics of a variety of different abstractions of designs, for which they have different mental models, and construct models of these abstractions in explicit external form to perform different kinds of analyses (Hoover *et al.*, 1991).

Working memory

Reasoning about the behaviour of complex physical systems is limited by the capacity of working memory – what we currently hold in conscious attention. Humans can switch the focus of conscious attention extremely quickly, but it is impossible to hold all the components of a complex design and their relationships in mind at once. Miller (1956) famously estimated the capacity of working memory at seven plus or minus two chunks of information. The richness of the mental representations in conscious awareness depends on the size of the chunks – the combinations of elements of information that people have grouped into units that they retrieve from memory as a whole. As well as the size of chunks, the richness and strength of the associations between different chunks influence one's ability to retrieve related information reliably. For instance, Akin (1978) found that architects' memories for architectural drawings depend on schematic encoding of drawing chunks. The ease and accuracy with which items of information can be remembered depend on the number and meaningfulness of the associations that are formed to other items in memory; studies of expert–novice differences in various fields show that experts do not just know more, but their knowledge is structured so that situations trigger recall of both appropriate general principles and appropriate specific information (Bédard and Chi, 1992).

Memory recall is reconstruction

Research on what people recall from memory, and how, indicates that this is best viewed as an active process of constructing coherent mental representations from comparatively sparse and incoherent components, rather than as faithful and passive retrieval (Bartlett, 1932; Koriat *et al.*, 2000). Recognising an object or situation as a member of a category (such as being in a restaurant) activates a learned schema for constructing a mental representation of a situation of that type, creating expectations that it will include components with particular characteristics, roles and behaviour (Schank and Abelson, 1977; Schank, 1982).

When these expectations are violated the situation is perceived as being different or surprising. Studies of memory for drawings of faces (Wulf, 1922) and for stories (Bartlett, 1932) have shown that unusual features that are perceived as significant are highlighted and exaggerated, while other unusual features are smoothed towards what is standard for the category (Koriat *et al.*, 2000). Perceptual recognition of an object or scene as a member of a category (which involves the use of the category representation to construct a representation of the individual) can distort what people perceive, highlighting salient unusual features and minimising others, as well as enabling them to perceive the object or scene as a configuration of particular components (Goldstone, 1998).

Although designers' memories include details of both exact form and context, research on mental imagery, perceptual learning (Goldstone, 1998), and expertise in electronics (Egan and Schwartz, 1979), as well as radiology (Myles-Worsley *et al.*, 1988), and chess (Gobet and Simon, 1998), indicates that visuospatial representations are highly structured, incorporating categorisations of both structural features and emergent visual features. It is difficult to assess how much of the mental representation of an individual design, or a sketch, is unique to it, and how much is reconstructed from representations

The ease and accuracy with which items of information can be remembered depends on the number and meaningfulness of the associations that are formed to other items in memory.

of more general categories. The structure and redundancy in visuospatial representations enable details to be reconstructed from sparse mental descriptions.

Research on memory has shown that the mental representations that guide thinking cannot be divided neatly into the content of conscious awareness controlling behaviour and memories passively awaiting recall. How readily memories for objects, concepts or events are recalled, or serve to influence other cognitive processing, depends on how recently and forcefully someone has perceived or been reminded of them. This effect works not only for the items themselves, but also for other related items (Baddeley, 1996). The priming of memories for recall by the activation of related memories depends on the organisation of memory; thus, it depends on both associations and generalisation across cases to create categories and abstract types (Anderson, 1983).

8.11 Objects often serve as mental references. Famous buildings, such as Lloyds of London, are shared mental reference points amongst a community of professionals.

Categories and exemplars as reference points

Design researchers have found that designers in a variety of fields make use of memories of both individual designs and design elements, and generalisations into categories. Schön (1988) describes functional types and references as forms of architectural design knowledge. Drawing on the cognitive theory of dynamic memory proposed by Schank and Abelson (1977; Schank, 1982), Oxman (1990) argues that precedents are used in design as prototypes, through a process of typification in which individual designs, problems *etc.* are used to create and refine more abstract generalisations, and are indexed in memory by these generalisations. Eckert and Stacey (2003b) argue (from observations of fashion and knitwear designers' working practices and how they describe designs to their colleagues) that remembered designs often serve as exemplars and indices for subtly differentiated categories. Eckert's later observations of engineers indicate that commonly known objects play an even larger role in engineering, where there are fewer potential reference designs than in textiles and they are shared by the members of multidisciplinary design teams.

Multiple mental representations

Designers can think about the same problems using very different mental models and reasoning strategies, according to how well they create concrete visuospatial representations of the structure of the design, and abstract propositional representations of its functions. Engineers who are highly skilled in applying analysis techniques reason about the consequences of making changes to a design by constructing lattices of causal connections, which are imagined in relatively abstract propositional terms. This approach yields a deep understanding of why changes have particular consequences, but reasoning mistakes can lead to completely wrong conclusions. Detailed and concrete visuospatial representations of structure and behaviour support retrieving related designs from memory and reasoning about similarities and differences. Other engineers reason about the same sorts of change by making predictions from how similar designs behaved in the past. While some very experienced engineers can make good predictions by similarity reference, the effects of small changes can easily be overlooked. By providing these predictions, they can enable their analytical colleagues to construct correct causal models for computing more precise results.

Visuospatial thinking is very important in most types of engineering designing, and many designers are good at it. Most engineering design creation involves relating visuospatially imagined structure to functions and constraints that are reasoned about in propositional terms. Moreover, many mechanical engineers think in terms of visually imagined concrete instances of mechanisms or machines when there is no actual need to do this for the problems they are solving. Some find it very hard to think in the abstract functional terms envisaged by top-down design methodologies (Andreasen, 1980) and by computer tools for designing in terms of networks of functions. For example, Nam Suh of the Massachusetts Institute of Technology has said that many engineers take naturally to his axiomatic design method (Suh, 1990, 2001), while others find it very difficult and unnatural. One reason for this is that mental representations of designs in terms of abstract statements of functions, and transformations and transmissions of matter, energy and information, form sparse networks of items of information with relatively arbitrary connections between them, with little redundancy. So they do not form large and strongly connected chunks as readily as spatial information from visual perception of sketches, diagrams and the artefacts themselves, which contain a lot of redundant and mutually reinforcing connections between elements.

8.12 Designers find it difficult to think about functions abstractly. They often make reference to known shapes to describe functions, finding it difficult to break away from such visual descriptions.

Another reason why many engineers find it difficult to reason abstractly without reference to particular physical embodiments is that functions and behaviour are hard to imagine except as the actions of concrete spatial things, and functions are usually associated in memory with examples of machines that embody those functions. Recalling a concept – a category of designs or design elements – cues the recall of features typically present in a design embodying the category, either as elements of a composite archetype, or because the representation of some aspect of the concept cues the recall of exemplars of the concept. Thus, thinking about designs in functional terms often imports structural and behavioural information into the designers' mental representations of the design situation. Conversely, a visuospatial representation of the form of an object is tied to its identity as a type of thing with functions and behaviours, and cues recall of its functions and behaviours. Ignoring these associations can prove impossible, even when one is actively trying (Jansson and Smith, 1991; Purcell and Gero, 1996).

Individual differences

The differences between individuals are larger than most people imagine. Reasoning abilities and styles differ according to how well people form different kinds of mental representations (Figure 8.13). At one extreme, some people have very little subjective mental imagery, and that is fleeting and fragmentary; while at the other end some people have images they subjectively experience as stable, detailed pictures of scenes and situations, and recall or generate them easily – sometimes too easily. However, there is no strong relationship between subjective mental imagery and the ability to solve a lot of visuospatial problems (Neisser, 1970). Some people who have rich static images find imagining movement difficult, as the rich detail and spontaneous retrieval of other images gets in the way of making changes to them. Strong associations to large coherent visual memories are likely to be an advantage in finding visuospatial analogies, and may be a handicap in reasoning about movement and causal processes.

8.13 Flight simulator. Some people find it difficult to generate mental images, while others find it difficult to picture movement.
© Airbus

The relationship between subjective mental imagery and the 'real' objects they refer to is also subtle and not fully understood. Psychological theorists still argue about whether mental imagery is essentially pictorial, most famously Kosslyn (1980, 1994), or essentially comprises symbolic descriptions, most famously Pylyshyn (2002, 2003). There is evidence that even when a rich mental image is subjectively experienced as complete, details within it do not exist until attention focuses on a part of the image (Kosslyn, 1980, 1994). But visuospatial representations that are subjectively experienced as images may not just be missing details, they may also be missing entire categories of information; and relationships or resemblances that are not an explicit part of the structure of the scene imagined may be invisible when they would be perceptually obvious in a picture.

Seeing objects, photographs, sketches, schematic diagrams and, so on triggers the creation of mental representations of designs through perceptual recognition. People can actively control the focus of attention to obtain the elements of an external representation that they need, so having an external memory enables them to use much more complex information than they can hold in a coherent mental representation otherwise. As we have seen, people can perceive features and relationships that were not previously part of their mental representations of the designs, though this usually requires active search. But the external representation functions as a set of cues for constructing mental representations. For this, accurate depiction is only required when fine details differ from category-normal in significant ways, and the appearance of roughness cues the inclusion of uncertainty or provisionality in the mental representation.

Mental actions

Designing comprises various sorts of mental and physical action, using and creating mental and external representations. In this section we view designing as mental action, at the level of individual moves through the spaces of possible designs, to examine how external representations contribute directly and indirectly to the actions that create new designs. We also look at design thinking as skill – learned capacities for constructing representations of design problems, making particular kinds of moves in design spaces, evaluating design proposals, and for structuring the design process.

The designer's understanding of the problem co-evolves with the solution.

Basic elements of design cognition

Analyses of design processes at different levels of detail converge to a view of designing, originally formulated by Asimow (1962), as comprising a cyclic process, of formulating the problem, making a change to the proposed design, evaluating the new state of the design, reformulating the problem, making another change to the design, and so on. The designer's understanding of the problem co-evolves with the solution (Dorst and Cross, 2001). What gives design thinking its characteristic form is that the design cycle is fractal down to the level of mental actions, with cyclic design processes for subproblems nested within a single stage of a larger task. Complex engineering design processes employ specialists to perform particular evaluations in the outer loops, while the smallest cycles of evaluating and changing happen entirely mentally in a few seconds. Like other problem-solving activities, designing involves means–ends analysis and a hierarchical structure of goals and subgoals (Simon, 1996). At each level the subtasks include decision making, retrieving information, recording information, and planning, as well as generating design ideas. Design activities include well-defined subproblems, many requiring deductive reasoning and procedure following, rather than propose-and-evaluate idea construction. Successful creative thinking requires both fluency in idea generation – divergent thinking – and in linear problem solving – convergent thinking; these abilities are not highly correlated. Of course, designing also involves the many activities involved in managing processes and human relationships, which are beyond the scope of this chapter.

A lot of what we know how to do is tightly bound to particular situations.

Situated cognition

A lot of what we know how to do (what psychologists term procedural knowledge) is tightly bound to particular situations; and much of human thought is inseparable from perception of one's environment and action in direct response to it, guided by conscious and latent goals (Suchman, 1987; Clancey, 1997). A lot of problem solving, including design, proceeds by applying characteristic sequences of mental actions to situations of particular types, triggered by goals and elements of perceptions and mental representations that belong to particular categories – though the exact form of the actions depends on the subtle details of the mental representations of the situations. A lot of these actions have the character of heuristics: reasoning or decision-making steps that are potentially useful but not guaranteed to be right (Duncker, 1935; Newell and Simon, 1972; see Akin (1986) for a detailed theory of architectural design as problem solving). Conscious decisionmaking about what to do next (as opposed to larger-scale goal setting) is relatively rare. Conscious real-world goal-directed behaviour typically has the character 'remember or decide what ought to be done next, or think of something to do, and do it if the estimated benefits exceed the estimated costs' (Anderson, 1990). Consciously chosen actions (which are goals to be achieved by finer-grained actions) are only planned or decided about at the level of detail that is needed. Finer details are dealt with as they arise by unplanned situated actions. Plans and goals do not rigidly dictate behaviour but form part of the mental context for situated actions, functioning as resources to guide behaviour (Suchman, 1987; Clancey, 1997). Designers are guided by plans but act opportunistically to correct mistakes, respond to unexpected events and fulfil latent goals (Visser, 1990, 1994).

Facets / Trajectories	An artefact	A process	A relation
State of			
Making sense of			
Framing futures of			

8.14 Designers need to reason about all nine aspects of the Minneman (1991) matrix

Creating an understanding

Actively creating an understanding of the problem is a vitally important part of problem solving, especially in design. This involves both perception and reasoning. Designers face problems that are inherently ill-defined, that are underspecified and in which important constraints are implicit (Simon, 1973, 1996). Designers often reformulate the design problem, to add structure and to recast it in terms more useful for guiding its solution: categorising it, thus activating additional constraints, and implicitly selecting solution strategies and eliminating alternatives.

Finding the right view of a problem is often the key to solving it (Duncker, 1935). Such reformulations can be guided by established principles and guidelines, individual preferences, the recognition of a similarity to another problem, or be more-or-less arbitrary. But patterns of thinking actions are largely determined by the requirements of the task, and hence by the form of the product. Well-defined problems can predominate in the design of tightly specified products. Hoover *et al.* (1991) point out that designers generate different abstractions of their designs for particular practical purposes, such as modelling their performance, and develop their designs further by refining these abstractions by adding more concrete detail; refinements made from different abstractions may not be compatible.

Darke (1979) argued that the designs of the architects she studied were shaped by the aspects of the design problems that were explicit and salient in the architects' minds when they generated the essential features of their conceptual designs; and that the most prominent aspect of the problem situation for an architect is typically the physical characteristics of the site a building is being designed for.

8.15 Child's beaker. In a study on fixation, Jansson and Smith (1991) showed design students a mug with a mouthpiece and told them to create a non-spill mug without a mouthpiece: despite this instruction, the majority of designs incorporated a mouthpiece.

Manipulating past designs

Designers' pattern synthesis actions that create or modify new designs, combine, manipulate and transform the objects, features and properties they have available in memory, often derived from past designs (Lawson, 1997). The most strongly available design elements are those in conscious awareness or available in the designer's visual field. This depends on what the notational conventions of sketches and other external representations make salient (Zhang, 1997). Knowledge of previous designs biases designing towards similar designs even when designers know they are actively trying to create something different – a phenomenon known to psychologists as fixation (Figure 8.15; Jansson and Smith, 1991; Purcell and Gero, 1996).

8.16 Passenger jet. Engineers are often able to assess the feasibility of designs and recognise what analyses are required. Skilled specialists can, for example, predict aerodynamic properties and the transmission of forces and stresses.
© Airbus

Designers assess the quality of changes to designs (envisioned mentally or using external representations) perceptually, as well as by explicit reasoning. In some design fields, perceptual evaluations are very tightly coupled with design synthesis actions, and play a crucial role in the development of conceptual designs. Humans are extraordinarily good at perceiving the important features of their environment, including categories, symbols and meanings, as well as subtle similarities and differences. This ability is precisely tuned to the demands of the current task. Experienced designers know about and can recognise more perceptual features (Egan and Schwartz, 1979), and this is a highly trained skill in many design professions. Thus, designers create designs conforming to their perceptually recognised visuospatial constraints and requirements (within the limitations of the power of their pattern synthesis actions); and recognise the degree to which they conform to visuospatial constraints and requirements. In aesthetic design, perceptual visuospatial knowledge of the context and of what is required is an essential part of formulating the problem (Eckert and Stacey, 2001).

Designers rely on perceptual evaluations either when the problem is simple enough to see or too complex to analyse. For example, knitwear technicians can spot whether two curves of different shape have the same lengths. At the other extreme are complex emergent phenomena in jet engine design, such as combustor rumble, where only a few experts have a detailed tacit understanding of the relationship between combustor shape and rumble, and everybody perceives it as a black art. The experts have learned complex associations between features of combustors and levels of rumble. The interplay of perceptual and explicit reasoning can be seen when engineers build up analysis meshes. Experienced engineers know the order of magnitude of a result and conduct computer analysis to fine tune the value. They perceive the features of the object that are significant for the analysis and the relationships between them, and recognise correct meshing points or use situation-specific knowledge to reason about them, and get analyses close to the real value. Novices might put the points in the wrong places, and not even recognise when their solutions are out by several orders of magnitude.

Design as skill

Experienced designers usually know more than novices. Not only do they know more facts, rules, principles, guidelines and examples, but their knowledge is more highly organised so that it is more accessible and applicable when needed. But expertise, especially in design, is primarily skilled action, for perceiving, formulating and solving problems (see Bédard and Chi (1992) and Bolger (1995) for introductions; see Chi *et al.* (1988) and Ericsson and Smith (1991) for seminal research on expertise).

While most studies of expertise distinguish between experts, intermediates and novices, Raufaste *et al.* (1998) make a further distinction between experts and super-experts, leading authorities who spend a lot of time reflecting on very difficult cases; they point out that much of the research on expertise has contrasted super-experts with novices and neglected ordinary experts, who are competent but mostly deal quickly with routine cases.

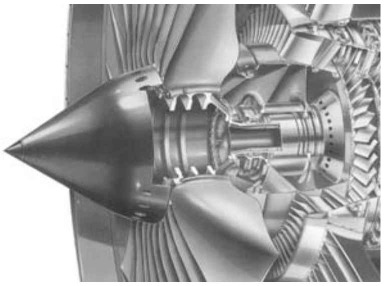
8.17 Aircraft cockpit. Mechanical engineers and avionics engineers often know little about each other's tasks. Even experts are effectively novices in the other field.
© Airbus

Experienced engineers working outside the scope of their expertise may have more general strategic knowledge to call on but will suffer the same difficulties as novices in recognising significant features and formulating problems, and will need to reason backwards from their goals to how to achieve them (Figure 8.17).

Expert problem solving in any field requires a rich and powerful set of associations between different situations and appropriate actions. Experts (performing routine tasks) work forward from the present situation: they know how to recognise the pertinent features of the problem situation, they know what to do, and do it, without needing to formulate a plan. For experts in many fields, their task-specific problem-solving procedures include recalling and adapting solutions to previous problems; for designers, these are elements of previous designs.

Experts are subject to fixation on previous designs in a different way from novices. Because they possess memories of a greater stock of relevant designs, they will be better able to find an appropriate model, and escape a particular recent exemplar, but will find it harder to escape closer matches to the present situation and stronger situation–action associations. People with expert knowledge have both richer and stronger associations between elements of their factual knowledge, and more specialised mental procedures. Thus they can focus recall from memory and mental actions more narrowly. This can be an advantage, but mental actions can embody tacit constraints inherited from previous similar problem situations that are no longer relevant, leading to incorrect or unsuccessful problem solving (Wiley, 1998).

Novices, who lack task-specific situation–action associations, explore and learn from their mistakes. They reason backwards from what they want to how they can get it, applying general problem-solving strategies to the facts that they know. Task-specific procedures are created as the starting points



8.18 Jet engine. Ahmed and Wallace (2004) found that the novices were aware of their information needs in only one-third of their queries.
Reproduced with the kind permission of Rolls-Royce plc

8.19 Sports car. Only a few areas of engineering designers employ active strategies for creating mental representations. For example, a car stylist employs a process very similar to a fashion designer.

and outcomes of such reflective problem-solving processes are associated in memory, to create situation–action pairs. Now no reasoning is needed to go from recognising the situation to performing the action. Situation–action associations that are repeatedly successful are strengthened and generalised; when they fail, situations are differentiated so that more tightly specialised situation–action associations are formed (Anderson, 1983). People learn to avoid actions that are related to the appearance of failure, interpersonal conflict or other negative rewards. In non-routine situations, experts do means–ends reasoning just like novices, but their conscious, reflective problem-solving strategies are also a learned skill. By learning from the success and failure of their reasoning they develop more elaborate and powerful specialised strategies for the problems they meet in their field.

Expert designers put considerable effort into articulating their problems (typically more than novices). By collecting all the available constraints on the design, they minimise the range of designs they need to think about. As designers gain experience, they develop skills in recognising, formulating, prioritising requirements and constraints, and employing them in their design thinking. Skilled actions learned by expert engineers include identifying the different issues they need to consider and what information they need to solve a task (Ahmed *et al.*, 2003). Of course, skills that contribute to high performance include process management and cooperation with others (Sonnentag, 1998).

In many fields, the skills developed by experts include reading the notations and graphic conventions used in their field. Increasing skill in reading graphic conventions reduces the time and effort involved in generating appropriate mental representations from external design representations, as a greater variety of symbol combinations become perceptually recognisable. As Henderson (1999) notes, this is an important aspect of professional group membership and possession of a shared object world. In some industries designers employ active strategies for creating the mental representations they will require later for creating designs. This is more prevalent in fashion -driven industries, where designers learn categories that implicitly define the spaces of acceptable designs within current fashion (which the designers use to formulate design goals) and that provide components of the designer's own new designs (Eckert and Stacey, 2001, 2003a). While engineers study competitors' products and look for applicable solution principles when required, constant opportunistic gathering of sources of inspiration is seldom part of their work culture.

Mental actions: creative thinking

In this section we consider some of the skills and mental actions required when standard solutions will not work, and expertise is not enough.

A great deal of engineering design is routine design, in the sense that it involves either modifications or transformations of existing design elements that do similar jobs – design by adaptation – or the application of well-understood procedures for creating concrete embodiments of standard solution principles – design by refinement (Oxman and Oxman, 1992).

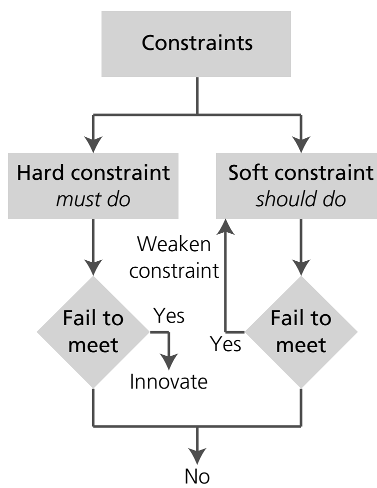
In these situations the product architecture is understood – so designers can create mental representations of what the design should be in the form of skeletally imagined components, because they know the mappings from functions to structural elements to fulfil those functions. But sometimes more innovative designing is required (Figure 8.20), when straightforward adaptations of previous designs are insufficient. Not only are more radical transformations required, but finding a suitable design or solution principle to adapt may not be easy.

8.20 Helicopter. Often innovative design problems turn up within larger routine design problems, in enabling the use of existing components and approaches, and stopping changes propagating through a design, as Eckert *et al*. (2004) discovered in a study of the customisation of helicopters. Photo © AgustaWestland

Designing with constraints

Designing is guided by the constraints on the product. Hard constraints, to which the product must conform, act differently from guidelines, targets, and soft constraints, to which the product should conform (Figure 8.21). All these features of the problem formulation serve to activate learned problem solving procedures, including the recall of prefabricated solution chunks. Thus, they channel designers into repeating and adapting designs they have produced before.

When designers are unable to create designs conforming to all the soft constraints, they weaken or discard the less important constraints, to make their designs produced by their standard methods meet the task demands as well as possible. But when hard constraints are in conflict, they can prevent standard solutions from working. This situation forces designers to try to innovate, by exploring and using reflective problem-solving strategies, and progressively refining their understanding of the problem. From repeated failures and partial successes they refine their strategies for reformulating problems and generating novel ideas. The role of difficult combinations of hard constraints as a spur to creativity has been observed by many outstandingly creative people, for instance Gordon Murray, the racing car designer, who constantly needed to work around and exploit complex technical regulations (Cross and Clayburn Cross, 1996).

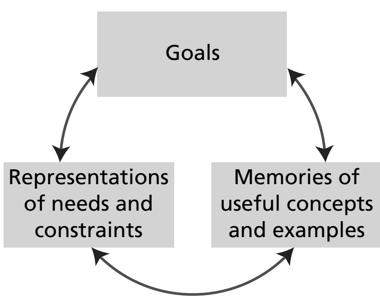


8.21 Different types of constraint

Analogical reasoning as a mechanism of creativity

We view the key creative step as the recognition of an analogy between the requirements of the current situation and some other machine or process or form. This can be a specific exemplar or an abstractly imagined category. The structure mapping theory views analogical reasoning as identifying a correspondence between the structures of the relationships between the components of two different composite entities (Gentner, 1983). The more different the characteristics of the components themselves, the more abstract and radical the analogy.

The difference between innovative and routine design is one of how far the formulation of the design problem needs to be abstracted away from the salient features of the design elements that perform similar tasks in similar designs, to guide the generation of solutions that do not share those features. This usually requires reframing the problem, by describing needs and constraints in different terms, as functions, or as different kinds of functions, so that different salient features of the problem guide the retrieval of different analogies from memory. In cognitive terms this is a difference of degree, as similarity between entities with similar components is recognised through the same mechanisms as analogy between entities with dissimilar components (Gentner and Markman, 1997). Nevertheless, finding abstract analogies is hard, because, first, the problem situation has associations in memory to more concretely analogous designs, on which designers fixate; second, there are no prior associations in memory between the problem situation and any abstract analogies to it; and third, reframing the problem is often difficult.



8.22 Elements of design cognition that are required to generate creative ideas

Constraints enhance creativity

The challenge in applying methods and processes for innovative design is to turn the narrowness and tight focus of most people's analogy recognition and design synthesis actions to advantage. This is achieved through enabling designers to formulate their design problems in ways that facilitate the generation of appropriate ideas (Figure 8.22).

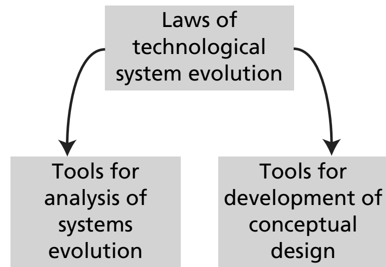
Designers often elaborate the first promising idea they think of, investing time and effort in it and becoming emotionally committed to it, when instead they should look further for more and better initial ideas. A major purpose of some design methodologies is encouraging designers to look for a range of possible alternative designs in conceptual outline before committing to any one (either by conscious selection, or by investing too much effort in elaborating it). Some established methods for generating innovative design ideas, such as TRIZ (Figure 8.23), work by encouraging designers to formulate problems that have tight and novel constraints, or that make particular solution principles the most salient sources of analogical mappings. Brainstorming functions, in a loose and unsystematic way, to get designers to consider the relationships between the problem and the arbitrary constraints and potential analogical mappings suggested by the ideas put forward in the brainstorming session.

In many fields of endeavour, creative breakthroughs often come from finding a different problem to solve. In engineering this can be done by adding constraints to underconstrained problems, or by removing constraints from overconstrained problems. Engineers are taught to reformulate problems by stripping away assumptions about how a machine should work to obtain a more abstract, functional view of what their designs should achieve. As we have explained, excluding assumptions about physical embodiments from functional formulations of problems is not necessarily easy.

The phenomenon of fixation in design stems from the design synthesis actions being tacitly overconstrained by the association of functional requirements with particular physical embodiments. Simon (1996) explained the well-known phenomenon that insight in problem solving frequently occurs after a break (incubation) as due to the forgetting of unhelpful associations with the problem in memory. Designers in many fields routinely add constraints to underconstrained problems to define them clearly enough to solve, by choosing standard solutions, or, where there are none, by making major decisions about the form of the design arbitrarily or according to personal preference.

Finke (1990) got people to imagine combinations of arbitrary shapes (which he terms preinventive forms) and then use them to solve problems requiring creative thinking, thus giving them a much tighter set of constraints; he found that his subjects did better in the constrained condition than when allowed to think freely. Using chance forms to meet design goals is often a fruitful idea-generation strategy in artistic design fields.

In innovative designing, external representations are needed for the structure of the product architecture. Graphic representations of functions and behaviour can make designers' mental representations of functional aspects of design problems more salient and coherent, facilitating the search for radical analogies and novel embodiments of principles. Finke's (1990) results suggest that arbitrarily selected preinventive forms might also facilitate this (Benami and Jin, 2002). Finke *et al.* (1992) conceive of



8.23 TRIZ is a systematic technique for generating innovation (Altshuller, 1994). It requires designers to formulate their problems in an abstract way using a matrix of 39 parameters, where each cell points to patented solutions. Altshuller also developed a set of 40 principles, such as replacing mechanical systems by optical, acoustic or thermal ones, or eliminating failure-prone processes altogether.

In many fields of endeavour, creative breakthroughs often come from finding a different problem to solve.

preinventive structures – novel visual patterns, object forms, mental blends, mental models, verbal combinations – as being initially formed without full anticipation of their resulting interpretation. Benami and Jin (2002), presenting a model of creative conceptual design in engineering, argue that the stimulating properties of preinventive entities in external representation are meaningfulness, relevance to the matter at hand, divergence (the capacity for finding multiple uses for the same entity), incongruity (conflict or contrast between elements) and emergence (the extent to which unexpected features appear).

Improving representations in design processes

In this section we discuss ways to improve design processes by improving the representations designers use. Negotiating a common understanding of shared representations is a first step to improving design processes. We will not attempt to survey the large body of academic research on developing better CAD systems or computer sketching systems (see Do (2002) for one indication of what is possible). Rather, we will discuss ways to think about the issues involved in choosing and using effective representations.

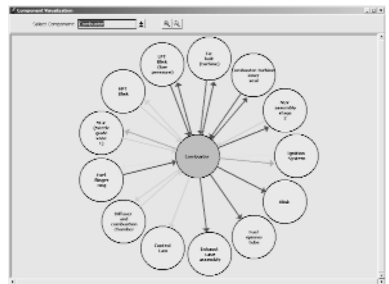
There are two challenges in improving engineering design processes at the level of designers' thinking:
- enabling designers to find the information they need;
- finding ways to display information graphically.

There are two challenges in improving engineering design processes at the level of designers' thinking. The first is enabling designers to find the information they need. Searching for information takes up a lot of their time; for designers, knowledge and procedures for analysing their information needs, and strategies for searching for information, are an important part of expertise (Kuffner and Ullman, 1991; Ahmed *et al*., 2003; Ahmed and Wallace, 2004). The second is the concern of this chapter: finding ways to display information graphically that facilitate reasoning with it and manipulating it.

Visualisation

Most importantly, this involves ways of making significant features and relationships directly visible in the display, eliminating the need to reason about what they are. Analyses in terms of mental representations and operations are not needed for this. What is required are techniques for translating both geometric and abstract structures into graphic forms that make certain features and relationships salient. Tufte (1983, 1990, 1997) provides valuable guidance on how to do this in a wide variety of situations, though focusing primarily on data displays and maps. In changing procedures to use different representations, or to migrate manual activities onto computers, it is essential to understand the functions served by the representations used in the current process, and how they are used, to ensure that the new procedures support the same kinds of thinking.

In many situations designers need to consider and modify different aspects of their designs, and perform different kinds of actions – comparisons, identification of relationships, ordering into sequences, parameter changes, synthesis of new forms, discovering the consequences of changes, and so on. These may require different representations that make different features and relationships perceptually visible.



8.24 Connectivity. Graphic representations of the different dependencies between the components of a design are developed to aid change prediction (Jarratt *et al*., 2004).

Designers of complex products, whose structure, function and performance need to be considered in different ways in parallel, need to switch between different mental models supported by different external representations and information sources. So a potentially fruitful avenue for academic research into design process improvement is the provision of alternative graphic notations for design information, both for computer tools and for designers to sketch with. An example is the research into graphic representations of the dependencies between the components of a design, and between the tasks in a design process. Another example is the research into graphic notations and computer tools for tracking design rationales (Buckingham Shum *et al*., 1997; Heliades and Edmonds, 2000; Bracewell and Wallace, 2003).

Cognitive dimensions

Green (1989) argues that representations of complex information structures, such as the programming environments used by software developers (Green and Petre, 1996) and the graphical notations used in electronics (Petre and Green, 1992), can be considered as good or bad on a number of cognitive dimensions. The cognitive dimensions of information artefacts determine how easy or hard they are to use or modify in particular ways. Designing computer tools for displaying and manipulating complex information structures (like designs) involves making trade-offs (consciously or unconsciously) between different cognitive dimensions. Pencil and paper is a medium for representing information structures, like a CAD system, but with very different positions on the cognitive dimensions. Using a pencil frees designers to be inconsistent, go beyond standard notational conventions, and give symbols different meanings, but they are still bound to notational conventions (however idiosyncratic) that make some types of information salient rather than others, may fail to show significant dependencies, and may make certain kinds of comparisons and evaluations difficult. And as soon as a description needs to be both detailed and consistent, hand-drawn diagrams or drawings become a very viscous medium.

Visibility and juxtaposability. Ability to view components easily. How easy is it to see or find the various parts of the notation while it is being created or changed? If the users need to compare or combine different parts, can they see them at the same time?

Viscosity. Resistance to change. When the users need to make changes to previous work, how easy is it to make the change?

Hard mental operations. High demand on cognitive resources. What kinds of things require most mental effort with this notation? Do some things seem especially complex or difficult for the users to work out in their heads (for example, when combining several things)?

Closeness of mapping. Closeness of representation to domain. How closely related is the notation to the result that the users are describing? What parts seem to be a particularly strange way of doing or describing something?

Hidden dependencies. Important links between entities are visible. If the structure of the product means some parts are closely related to other parts, and changes to one may affect the other, are those dependencies visible?

Progressive evaluation. Work completed can be checked at any time. How easy is it for the users to stop in the middle of creating some notation, and check their work so far? Can they do this any time they like? Can the users find out how much progress they have made, or check what stage in their work they are up to? Can the users try out partially-completed versions of the product?

Provisionality. Degree of commitment to actions or marks. Is it possible for the users to sketch things out when they are playing with ideas, or when they are not sure which way to proceed? What features of the notation help them to do this? What sort of things can the users do when they do not want to be too precise about the exact result they are trying to get?

Premature commitment. Constraints on the order of doing things. When the users are working with the notation, can they go about the job in any order they like, or does the system force them to think ahead and make certain decisions first?

Secondary notation. Extra information in means other than formal syntax. Is it possible for the users to make notes to themselves, or express information that is not really recognised as part of the notation? If the notation was printed on a piece of paper that the users could annotate or scribble on, what would they write or draw? Do the users ever add extra marks (or colours or format choices) to clarify, emphasise or repeat what is there already?

Detail in context. Ability to see both complete descriptions of local information and their relation to a wider picture. Is it possible to see how elements relate to others within the same notational layer? Is it possible to move between them with sensible transitions?

Synopsis. Support for holistic views. Does the system provide an understanding of the whole structure when the user 'stands back and looks'?

Free rides. New information is generated as a result of following the notational rules. Can users read new information off, as a result of making measurements and observations of the things they put there previously?

Unevenness. Bias towards specific solutions or actions. Does the system push users' ideas in a certain direction because certain things are easier to do?

8.25 Some cognitive dimensions (selected from a fuller list in Blackwell *et al.*, 2003)

Conclusions

Various kinds of graphic representations and models are an important part of most aspects of engineering, but many engineers fail to recognise their influence on individual thinking, communication between designers, and the organisation of design processes. In some activities the entities and relationships the representations make explicit become the concepts designers think with. Many design processes could be improved if their participants understood each other's information needs and how information can be most effectively conveyed.

Changing processes, methods and tools changes designers' tasks and information needs; this changes the functions of existing representations of design information, and may create a need for new representations. The development of new methods and procedures should include a careful consideration of what designers' information needs are and what graphic representations of design ideas can best meet those needs. While this chapter has concentrated on representations of designs, most of the points it makes apply equally well to representations of processes, which are frequently important in guiding design processes but which have attracted little research.

References

Ahmed S, Wallace KM (2004) Understanding the knowledge needs of novice designers in the aerospace industry. Design Studies, 25: 155–173

Ahmed S, Wallace KM, Blessing LTM (2003) Understanding the differences between how novice and experienced designers approach design tasks. Research in Engineering Design, 14: 1–11

Akin Ö (1978) How do architects design? In: Artificial intelligence and pattern recognition in computer-aided design. North-Holland

Akin Ö (1986) Psychology of architectural design. Pion

Altshuller G (1994) And suddenly the inventor appeared. TRIZ, the theory of inventive problem solving. Technical Innovation Center, Worcester, MA, USA

Anderson JR (1983) The architecture of cognition. Harvard University Press

Anderson JR (1990) The adaptive character of thought. Lawrence Erlbaum

Andreasen MM (1980) Syntesemetoder på systemgrundlag. PhD thesis, Lunds Tekniska Högskola, Denmark

Asimow M (1962) Introduction to design. Prentice Hall

Baddeley AD (1996) Human memory. Psychology Press

Badke-Schaub P, Stempfle J, Wallmeier S (2001) Transfer of experience in critical design situations. ICED'01, Glasgow, UK

Bartlett FC (1932) Remembering. Cambridge University Press

Bédard J, Chi MTH (1992) Expertise. Current Directions in Psychological Science, 1: 135–139

Benami O, Jin Y (2002) Creative stimulation in conceptual design. ASME DETC'02, Montreal, Canada

Blackwell AF, Hewson RL, Green TRG (2003) Product design to support user abstractions. In: Handbook of cognitive task design. Lawrence Erlbaum

Bolger F (1995) Cognitive expertise research and knowledge engineering. Knowledge Engineering Review, 10: 3–19

Bracewell RH, Wallace KM (2003) A tool for capturing design rational. ICED'03, Stockholm, Sweden

Brereton MF, Cannon DM, Mabogunje A, Leifer LJ (1996) Collaboration in design teams: mediating design progress through social interaction. In: Analysing design activity. John Wiley

Bucciarelli LL (1994) Designing engineers. MIT Press

Buckingham Shum SJ, MacLean A, Bellotti VME, Hammond NV (1997) Graphical argumentation and design cognition. Human–Computer Interaction, 12: 267–300

Chi MTH, Glaser R, Farr MJ eds (1988) The nature of expertise. Lawrence Erlbaum

Clancey WJ (1997) Situated cognition. Cambridge University Press

Clement J (1983) A Conceptual Model Discussed by Galileo and Used Intuitively by Physics Students. In: Mental Models. Lawrence Erlbaum

Cross NG, Christiaans H, Dorst K eds (1996) Analysing design activity. John Wiley

Cross NG, Clayburn Cross A (1996) Winning by design: the methods of Gordon Murray racing car designer. Design Studies, 17: 91–107

Darke J (1979) The primary generator and the design process. Design Studies, 1: 36–44

DiSessa AA (1983) Phenomenology and the evolution of intuition. In: Mental models. Lawrence Erlbaum

DiSessa AA (1993) Toward an epistemology of physics. Cognition and Instruction, 10: 105–225

Do EY-L (2002) Drawing marks acts and reacts: toward a computational sketching interface for architectural design. Artificial Intelligence in Engineering Design Analysis and Manufacturing, 16: 149–171

Dorst K, Cross NG (2001) Creativity in the design process: co-evolution of problem-solution. Design Studies, 22: 425–438

Duncker K (1935) Zur Psychologie des produktiven Denkens. Springer
Eckert CM (2001) The communication bottleneck in knitwear design: analysis and computing solutions. Computer Supported Cooperative Work, 10: 29–74
Eckert CM, Stacey MK (2001) Designing in the context of fashion – designing the fashion context. Design Thinking Research Symposium, Delft, The Netherlands
Eckert CM, Stacey MK (2003a) Sources of inspiration in industrial practice: the case of knitwear design. Journal of Design Research, 3(2)
Eckert CM, Stacey MK (2003b) Adaptation of sources of inspiration in knitwear design. Creativity Research Journal, 15(4): 355–384
Eckert CM, Clarkson PJ, Zanker W (2004) Change and customisation in complex engineering domains. Research in Engineering Design, 15(1): 1–21
Egan DE, Schwartz BJ (1979) Chunking in recall of symbolic drawings. Memory and Cognition, 7: 149–158
Ericsson KA, Smith J eds (1991) Toward a general theory of expertise: prospects and limits. Cambridge University Press
Finke RA (1990) Creative imagery: discoveries and inventions in visualization. Lawrence Erlbaum
Finke RA, Ward TB, Smith SM (1992) Creative cognition: theory research and applications. MIT Press
Gentner D (1983) Structure-mapping: a theoretical framework for analogy. Cognitive Science, 7(2): 155–170
Gentner D, Markman AB (1997) Structure mapping in analogy and similarity. American Psychologist, 52(1): 45–56
Glock F (1998) Konstruieren als sozialer Prozess. Deutscher Universitätsverlag
Gobet F, Simon HA (1998) Expert chess memory: revisiting the chunking hypothesis. Memory, 6: 225–255
Goldschmidt G (1991) The dialectics of sketching. Creativity Research Journal, 4(2): 123–143
Goldstone RL (1998) Perceptual learning. Annual Review of Psychology, 49: 585–612
Green TRG (1989) Cognitive dimensions of notations. In: People and computers V. Cambridge University Press

Green TRG, Petre M (1996) Usability analysis of visual programming environments: a 'cognitive dimensions' framework. Journal of Visual Languages and Computing, 7: 131–174

Heliades GP, Edmonds EA (2000) Notation and nature of task in comprehending design rationale. Knowledge-Based Systems, 13: 215–224

Henderson K (1999) On line and on paper. MIT Press

Hoover SP, Rinderle JR, Finger S (1991) Models and abstractions in design. Design Studies, 12: 237–245

Jansson DG, Smith SM (1991) Design fixation. Design Studies, 12: 3–11

Jarratt TAW, Eckert CM, Clarkson PJ, Stacey MK (2004) Providing an overview during the design of complex products. DCC'04. Boston, MA, USA

Johnson-Laird PN (1983) Mental models. Harvard University Press

Koriat A, Goldsmith M, Pansky A (2000) Towards a psychology of memory accuracy. Annual Review of Psychology, 51: 481–537

Kosslyn SM (1980) Image and mind. Harvard University Press

Kosslyn SM (1994) Image and brain. MIT Press

Kuffner TA, Ullman DG (1991) The information requests of mechanical design engineers. Design Studies, 12: 42–50

Kunz A, Müller S, Kennel T, Lauche K, Mbiti K (2001) Supporting teamwork by new means of information technology. ICED'01, Glasgow, UK

Lauche K, Verbeck A, Weber WG (1999) Multifunktionale Teams in der Produkt- und Prozessentwicklung. In: Optimierung der Produkt- und Prozessentwicklung. Vdf Hochschulverlag

Lawson B (1997) How designers think – the design process demystified. Architectural Press

Leont'ev A (1978) Activity consciousness and personality. Prentice-Hall

McCloskey M (1983) Naïve theories of motion. In: Mental models. Lawrence Erlbaum

McFadzean J, Cross NG, Johnson JH (1999) Notation and cognition in conceptual sketching. In: Visual and spatial reasoning in design. MIT Press

Miller GA (1956) The magical number seven plus or minus two: some limits on our capacity for processing information. Psychological Review, 63: 81–97

Minneman SL (1991) The social construction of a technical reality: empirical studies of group engineering design practice. PhD thesis, Stanford University, CA, USA

Myles-Worsley M, Johnson WA, Simons MA (1988) The influence of expertise on X-ray image processing. Journal of Experimental Psychology: Learning Memory and Cognition, 14: 553–557

Neilson I, Lee J (1994) Conversations with graphics: implications for the design of natural language/graphics interfaces. Journal of Human–Computer Studies, 40: 509–541

Neisser U (1970) Visual imagery as process and as experience. In: Cognition and affect. Little Brown Co.

Newell A, Simon HA (1972) Human problem solving. Prentice Hall

Norman DA (1983) Some observations on mental models. In: Mental models. Lawrence Erlbaum

Norman DA (1988) The psychology of everyday things. Basic Books (later printings published as The design of everyday things)

Oxman RE (1990) Prior knowledge in design: a dynamic knowledge-based model of design and creativity. Design Studies, 11: 17–28

Oxman RE, Oxman RD (1992) Refinement and adaptation in design cognition. Design Studies, 13: 117–134

Pache M, Römer A, Lindemann U, Hacker W (2001) Re-interpretation of conceptual design sketches in mechanical engineering. ASME DETC'01, Pittsburgh, PA, USA

Petre M, Green TRG (1992) Requirements of graphical notations for professional users: electronics CAD systems as a case study. Le Travail Humain, 55: 47–70

Purcell AT, Gero JS (1996) Design and other types of fixation. Design Studies, 17: 363–383

Purcell AT, Gero JS (1998) Drawings and the design process. Design Studies, 19: 389–430

Pylyshyn ZW (2002) Return of the mental image: are there really pictures in the brain? Trends in Cognitive Science, 7: 113–118

Pylyshyn ZW (2003) Mental imagery: in search of a theory. Behavioural and Brain Sciences, 25: 157–237

Raufaste E, Eyrolle H, Mariné C (1998) Pertinence generation in radiological diagnosis: spreading activation and the nature of expertise. Cognitive Science, 22: 517–546

Sachse P, Hacker W (1997) Unterstützung des Denkens und Handelns bei Konstruieren durch Prototyping. Konstruktion, 49: 12–16

Schank RC (1982) Dynamic memory: a theory of reminding and learning in computers and people. Cambridge University Press

Schank RC, Abelson R (1977) Scripts, plans, goals and understanding. Lawrence Erlbaum
Schön DA (1983) The reflective practitioner: how professionals think in action. Basic Books
Schön DA (1988) Designing: rules types and worlds. Design Studies, 9:181–190
Schön DA, Wiggins G (1992) Kinds of seeing and their functions in designing. Design Studies, 13: 135–156
Simon HA (1973) The structure of ill-structured problems. Artificial Intelligence, 4: 181–202
Simon HA (1996) The sciences of the artificial. MIT Press
Sonnentag S (1998) Expertise in professional software design: a process study. Journal of Applied Psychology, 83: 702–715
Stacey MK, Eckert CM (2003) Against ambiguity. Computer Supported Cooperative Work, 12: 153–183
Star SL (1989) The structure of ill-structured solutions: heterogeneous problem-solving, boundary objects, and distributed artificial intelligence. In: Distributed artificial intelligence 2. Morgan Kaufmann
Suchman LA (1987) Plans and situated actions. Cambridge University Press
Suh NP (1990) Principles of design. Oxford University Press
Suh NP (2001) Axiomatic design: advances and applications. Oxford University Press
Suwa M, Gero JS, Purcell AT (1999) Unexpected discoveries: how designers discover hidden features in sketches. In: Visual and spatial reasoning in design. MIT Press
Tufte ER (1983) The visual display of quantitative information. Graphics Press
Tufte ER (1990) Envisioning information. Graphics Press
Tufte ER (1997) Visual explanations: images and quantities, evidence and narrative. Graphics Press
Visser W (1994) The organisation of design activities: opportunistic with hierarchical episodes. Interacting with Computers, 6: 235–274
Visser W (1990) More or less following a plan during design: opportunistic deviations in specification. Journal of Man–Machine Studies, 33: 247–278
Vygotsky LS (1962) Thought and language. MIT Press
Weber WG, Lauche K, Verbeck A (1999) Gemeinsame Vergegenständlichungen und kooperatives Handeln in multifunktionalen Teams. In: Design thinking. vdf

Wiley J (1998) Expertise as mental set: the effects of domain knowledge on creative problem solving. Memory and Cognition, 26: 716–730

Wulf F (1922) Beitrage zur Psychologie der Gestalt: VI. Über die Veränderung von Vorstellungen (Gedächtniss und Gestalt) Psychologische Forschung, 1: 333–375

Young RM (1983) Surrogates and mappings: two kinds of conceptual models for interactive devices. In: Mental models. Lawrence Erlbaum

Zhang J (1997) The nature of external representations in problem solving. Cognitive Science, 21: 179–217