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Objects as Carriers of Engineering Knowledge

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Objects as Carriers of Engineering Knowledge

The role of previous products in evolutionary engineering design is often neglected. In design discourse, references to objects provide terse expressions of complex information that cannot easily be expressed otherwise. Previous artifacts serve in conjunction with more general engineering knowledge to enable designers and design teams in engineering companies to work in ways that would be very difficult or impossible without them. They trigger the retrieval and active construction of personal knowledge, but also provide a scaffold for sharing knowledge and using it collectively. For companies, their products encapsulate and carry a significant part of the collective knowledge of the organization.

Keywords: object reference, engineering epistemology, design knowledge, engineering design practice, evolutionary design, analogy, knowledge level.

Introduction: Engineering knowledge in/about object references

In engineering design in industry, previous artifacts almost always play a range of important roles. An important part of what industrial engineering designers know is knowing about previous artifacts and knowing how to use them. Drawing on many years of empirical studies in engineering[1], this paper seeks to explore how already-existing physical objects are not merely the subject of knowledge but are holders of knowledge.

Physical objects serve important functions in the collective activities of designing. These are usually machines similar to the one being designed. Occasionally designers draw on other kinds of designed artifacts.[2] They are central to what design teams and companies are capable of doing, especially what they are capable of doing efficiently. How already-existing designs, along with other artifacts, contribute to the sociotechnical processes of designing is beyond the scope of this paper; theoretical tools from sociology such as actor-network theory[3] might offer a way to study this.[4] In this paper we aim to explore how already existing engineering products and designs for them function as carriers of knowledge, serving in conjunction with general engineering knowledge to enable designers and design teams to work in ways that would be difficult or impossible without them. We take the view that how knowledge is packaged, both mentally and in the objective world, makes a difference to how engineering is practised.

We consider how existing engineered products relate to the social and cognitive organization of engineering knowledge. We begin by considering how engineering knowledge is both individual and collective, and arguing that both individual-centric and collectivity-centric views of knowledge are needed, We examine the form of the knowledge that designed artifacts contribute to most centrally, *schematic design chunks*, and how specific artifacts contribute to forming and using schematic design chunks. We then look at how designed objects act as carriers of design knowledge, and how they are referred to and used in industrial design processes. Designed objects convey information to people with the skill to read them, sometimes across large gaps of time and space, functioning as objectively existing information artifacts as well as physical objects.

This paper is a reflection over our studies of the practice of design as well as several decades of cognitive and social research on how designing is done. It draws on over 20 years of empirical research on engineering processes largely conducted through interviews with practising engineers in engineering companies and observations of design meetings as well as of engineers working. These studies concentrated on engineering change, i.e., the modification of products due to problems or changing requirements[5], design process modelling and planning[6], and more recently design margins, i.e., the amount a parameter exceeds the actual requirements.[7] The paper uses diesel engines as a source of illustrations, as the second author has studied their design processes from multiple angles, looking at engineering change, process planning, communication, system architecture, testing, and supply chain management in one company over a period of 15 years. However, we never lost sight of our interest in object references; this stems from our earlier work on sources of inspiration,[8] which primed us to look for references to objects as convenient shortcuts for complex relational concepts in the subsequent engineering studies.

Engineering knowledge is both individual and collective

Engineering design is a socially organized, collective endeavour, requiring knowledge no one designer possesses and achieving results no one designer is capable of. What engineering companies and other collectivities know, and how they know it, are legitimate and serious questions for understanding engineering practice, whether or not they fit individual-centric conceptions of knowledge. Our view is that understanding how engineering knowledge is possessed and used in engineering practice requires adopting both individual-centric and collective perspectives, and that these are complementary views of the same phenomenon.

Companies and communities of practice as units of organization

The issue of what types of collectivities possess collective knowledge is beyond the scope of this paper. However we note that typical engineers working in industry are members of multiple overlapping groups. Some of these constitute communities of practice in the sense asserted by Lave and Wenger, of a cluster of people regularly interacting for common purposes and imparting knowledge through a process of acculturation including both demonstration and guidance and indirect pathways such as documentation.[9] (However what a community of practice is, and what doesn't qualify, is a slippery issue on which seminal authors disagree.[10] Relatively broad groups sharing knowledge and competences acquired through interaction and common education also propagate collective knowledge. Wenger[11] might give these groups different labels such as "constellations of practice" or "communities of imagination.") The active sharing of knowledge about past designs can be seen as part of the operation of a community of practice.

Many engineering companies employ a matrix organization, where engineers have a dual loyalty to projects and to functional groups; the generation of much new knowledge happens within project-focused activities (though some happens in R&D activities), while the functional groups are responsible for longer-term maintenance and propagation of knowledge. Organisational groupings that generate and employ knowledge collectively include design teams, which sometimes span more than one company, while occasionally divisions of very large businesses can lack detailed information about what other divisions are doing.[12]

Our concern here is the role of physical objects and individual designs in carrying engineering knowledge. The uses of existing artifacts and designs we have observed in engineering practice require organizational environments in which engineers develop a succession of similar engineered artifacts over several years. A few governmental organizations do this, such as NASA, but the vast majority of organizations that develop artifacts in this way (including the ones we have studied) are industrial enterprises. Without a collective history, individual engineers can use experiences of individual artifacts in their thinking but are less able to communicate by reference to shared local knowledge. So we refer here to the collectivities developing and maintaining engineering knowledge by developing a succession of products as engineering companies even though there are other possible loci of knowledge: subgroups within companies, user innovation communities that are not affiliated with a formal organization, projects that span multiple companies, and government agencies and other non-corporate organizations. Our analysis may be applicable to these other loci of knowledge, but it privileges engineering companies, first because they are the locus of most product development, second because functional groups within companies (and a few governmental organizations) host the communities of practice that develop and maintain local knowledge over long periods spanning multiple product generations, and third because companies (and a few governmental organizations) own the physical archives of designs and products that their engineers learn from and refer to (though sometimes engineers refer to objects they possess themselves).

Companies as agents possessing capacity for action

Engineering companies, concerned with achieving results, are concerned with the knowledge the company possesses and can apply, and much less with where in the organization it sits; in practice they treat knowledge as interpersonal. Many larger organizations engage in active knowledge management to gather, codify, manage and reuse the knowledge possessed within the company, a collective endeavour. In this paper we are centrally concerned with examining how artifacts, primarily previous designs, function as part of engineering companies' collective knowledge, and how this is connected to how engineering designers acquire, communicate and use knowledge in the form of schematic design chunks.

One way to look at engineering knowledge that is useful for understanding what is going on in engineering, is in terms of what an agent needs to possess in order to be able to perform a particular task. This, of course, includes both *knowledge that* and *knowledge how.* In philosophy, Gilbert Ryle and his successors have developed the notion of know-how as competence.[13] Cognitive scientists make use of the notion of knowledge-level models of the capabilities of intelligent agents. Allen Newell[14] argued that intelligent behavior could be described in terms of what domain knowledge and task knowledge the agent needs to possess, separately from any computational-level account of how the knowledge is represented and encoded and organized, and how the agent's reasoning processes work. Thus, different computational mechanisms may embody the same knowledge and thus achieve the same competence in solving particular problems. Declarative knowledge, that can be articulated or represented in a form that constitutes a set of assertions, is to some extent replaceable with procedural task knowledge that is embedded in the agent's reasoning mechanisms, and vice versa.[15]

However, we are not only concerned with individual designers. If we adopt Newell's characterization of knowledge as being what an agent needs to possess to have a particular competence,[16] we can consider the knowledge that teams possess that gives them the ability to accomplish things that are beyond any individual. We can, if we wish, draw a system boundary around the units whose knowledge we wish to consider, around individual people, around individuals plus the information artifacts they use and create, around teams, or around companies, and consider the unit as an agent possessing and using knowledge. In order to understand how physical objects and references to them function in the knowledge-using processes of engineering companies, we need to adopt a collectivity-centric perspective at least some of the time.

Schematic design chunks as elements of engineering knowledge

Much of what engineers know about products and systems comprises conceptualizations of structures, mechanisms and solution principles at varying levels of abstraction. In this paper we use the term *schematic design chunk* for concepts representing elements of designed artifacts such as components, subsystems, solution principles, or combinations of components linked by a common function, tied to their functions and behaviors, and the implications of using them; we intend this as a broad umbrella term covering a range of concepts that are familiar in different fields, such as *design pattern*.[17]

We will first explicate the notion of schematic design chunk, before elaborating on the schematic design chunks' relationship to engineering knowledge, and how references to objects – mediated by very specific schematic design chunks – are used in design processes. Much of the specialist expertise of experienced engineering designers is their stock of design concepts and features drawn from particular individual products. The focus of this paper is how individual engineers and engineering companies use these concepts and the objects they are drawn from. Existing products provide detailed concrete instantiations of categories of products and instantiations of solution principles, with known properties and known behavior; referring to them by name provides a vocabulary that enables terse expressions of highly complex information that cannot be described easily or briefly any other way. It is extremely difficult to describe the differences between products with the same basic architectures, such as diesel engines, short of referring to a product model or a product because the differences are more subtle than the gradation of the vocabulary of general terms; thus references to artifacts form an essential part of engineers' vocabulary by functioning as shorthand terms for clusters of properties and configurations that would otherwise be difficult to describe.

Designing a machine or a part of a machine involves considering the *structure* of the system (how it is composed of components, their shapes and connections, the form of the whole), the *functions* of the system and each component (what purposes they serve), and the *behavior* of the system as a whole and the behavior and interactions of its components.[18] Knowledge of the structures of systems and machine elements themselves is tightly associated with teleological knowledge of the functions of machines and components, and their properties and behavior, as well as what problems they can solve, and the advantages, disadvantages and consequences of using them. It is also tightly bound to knowledge of how to use them to achieve results. This comprises both 'procedural knowledge'[i] that a sequence of actions leads to the realization of a goal, and 'operational knowledge' – the skills needed to take these actions.[19] Of course, *using* a schematic design chunk requires the application of a lot of more general engineering knowledge.

Schematic design chunks: a terminological note

For our argument we need some terminology to talk about the pieces of designs that engineers know about, recognize and employ in new designs. We adopt the following new terms:

'schematic design chunk' for a conceptualization of a potential piece of a design, comprising a set of structural elements with particular functions that interact with each other in particular ways, so that the whole has particular behavioral characteristics, and can fulfil particular functions within a larger system. As well as its structure, function and behavior, a

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[i] In the terminology adopted by Houkes, whose use of the term 'procedural knowledge' fits the standard English meaning of 'procedural' but clashes with the usual use of 'procedural' in cognitive science to mean comprising or embedded in specifications for actions.)

schematic design chunk includes the consequences of using it for the larger system, and its advantages and disadvantages.

‘**schematic design knowledge’** for the collection of schematic design chunks possessed by the agent. (It would be a mistake to think of the schematic design chunks as entirely separate entities in human memory, as they are tightly interconnected and include schematic design chunks that are more or less abstract and general conceptualizations of the same systems.)

To clarify our use of more standard terms, objects are physical things (or sometimes information artifacts like programs); object references are elements of communication acts, usually but not necessarily verbal; schematic design chunks are elements of knowledge; and schemata are, according to psychological theory, mental representations of types of thing or situation specifying the elements that things or situations of a particular type include and the relationships between them, thus are how schematic design chunks are represented when humans use them.[20]

Notions of schematic design chunk familiar to designers

The notion of schematic design chunk encompasses a range of narrower concepts familiar to designers in different fields. Engineers make use of the concept of ‘machine element’ for generic elements that are used in multiple machines, such as bearings. They also use the far more abstract concept of ‘solution principle’ for how a part of a machine can carry out a particular function, for example diesel engines and electric motors are different solution principles to provide propulsion. We want the notion of schematic design chunk to cover both solution principles and concrete embodiments of them, thus both the idea of a ball bearing, and knowledge of the characteristics of a particular ball bearing supplied by a particular manufacturer.

The concept of design pattern was introduced by the architect Christopher Alexander in the 1960s[21]. For Alexander, a design pattern is a component or emergent feature of a building or designed space that has a particular size or other characteristics that enable it to serve a purpose or achieve a benefit. The design pattern includes its uses and advantages as well as its disadvantages and consequences for the design of the rest of the building, so that buildings could be planned in outline by combining patterns. The concept of design pattern was later widely adopted in software development, to mean a standard solution to a class of problems,[22] with its advantages, disadvantages and consequences, expressed in a relatively abstract form that can be fleshed out differently for each instance of the problem. Following Gamma, Helm, Johnson and Vlissides' seminal 1995 book *Design Patterns*,[23] many subsequent authors have published collections of patterns for different aspects of software development. A description of a design pattern is formalized documentation of transferrable good practice, inferred by generalizing across many similar successful solutions to similar problems. To qualify as a design pattern, it needs to meet particular quality standards including the authority of repeated use. Like machine elements and solution principles, design patterns are special cases of schematic design chunks, but most schematic design chunks are more ad hoc and fluid, and some are very specific.

Architects make use of schematic design chunks drawn from what they term 'precedents.'[24] Similarly, fashion and knitwear designers make use of schematic design chunks drawn from sources of inspiration.[25] Oxman and Lawson both draw on schema theory[26] to account for how this works in architecture. Our account in this paper of how engineers employ actually-existing artifacts and how they carry knowledge also rests on schema theory. Schemata are mental structures that specify the elements that situations of a particular type include and the relationships between them. According to schema theory, humans learn schemata from different experiences with similar objects and situations, from which they generate mental representations of categories comprising the features the different objects or situations have in common. They then recognize objects and situations as members of categories for which they have schemata, and generate expectations that typical features of that type of object or situation will be present, such as a steering wheel in a car. When someone recognizes something as an instance of a category, slots in the schema are filled in with the corresponding features of the individual situation.

Schematic design chunks as knowledge

Since Aristotle distinguished craft knowledge, *techné*, from other forms of knowledge in the *Nichomachean Ethics*,[27] philosophers and other scholars have proposed and employed a wide variety of characterizations of what knowledge is, which are beyond the scope of this paper. Since the 1960s, scholars have increasingly considered what it is that engineers know, and whether there is anything distinctive about engineering knowledge.[28]

The space of different types of engineering knowledge has been mapped in a number of different ways.[29] Most famously, Walter Vincenti[30] stressed the importance of knowledge generating activities to the engineering enterprise, and put forward a typology of engineering knowledge, with six types of knowledge (fundamental design concepts, criteria and specifications, theoretical tools, quantitative data, practical considerations, and design instrumentalities), and seven types of knowledge generating activities (transfer from science, invention, theoretical engineering research, experimental engineering research, design practice, production, and direct trial). Anthonie Meijers and Peter Kroes put forward a taxonomy comprising structural knowledge, functional knowledge, prescriptive knowledge, design-related knowledge, and know-how.[31] They stress the centrality of functional aspects of design, normative claims about correct functioning, and the physical/chemical/structural makeup of things, along with know-how of developing and making things. Our concern in this paper is with aspects of engineering knowledge that Vincenti would file under fundamental design concepts, practical considerations, and design instrumentalities.

Schematic design chunks serve to connect and package elements of knowledge in all Meijers and Kroes' categories. In Vincenti's classification,[32] schematic design chunks come primarily under the heading of fundamental design concepts. However, Vincenti's discussion of fundamental design concepts talks about solution principles and configurations that cover types of machine, apparently unconnected to individual cases. We want to claim that not only is a lot of design concept knowledge quite specific and tied to individual cases, it is also tightly connected to a lot of what Vincenti terms knowledge of practical considerations. These are often learnt from experience and never codified, such as whether a particular feature can be manufactured using a particular machine. Schematic design chunks also serve to index some elements of what Vincenti terms design instrumentalities, knowledge of how to do designing.

Figure 1 illustrates the idea of schematic design chunks as elements of knowledge: an engineer at AgustaWestland saying 'like the one for the Italians' to refer to a complicated set of interconnected modifications of the EH101 helicopter to carry a larger and heavier radar understood as a coherent whole. While some are learned from abstractions, many are interpretations of elements of products. Seeing them and hearing a product mentioned can evoke the schematic design knowledge connected to its systems and components. It will also evoke episodic memories of positive and negative experiences, including problems and whether and how they were solved.

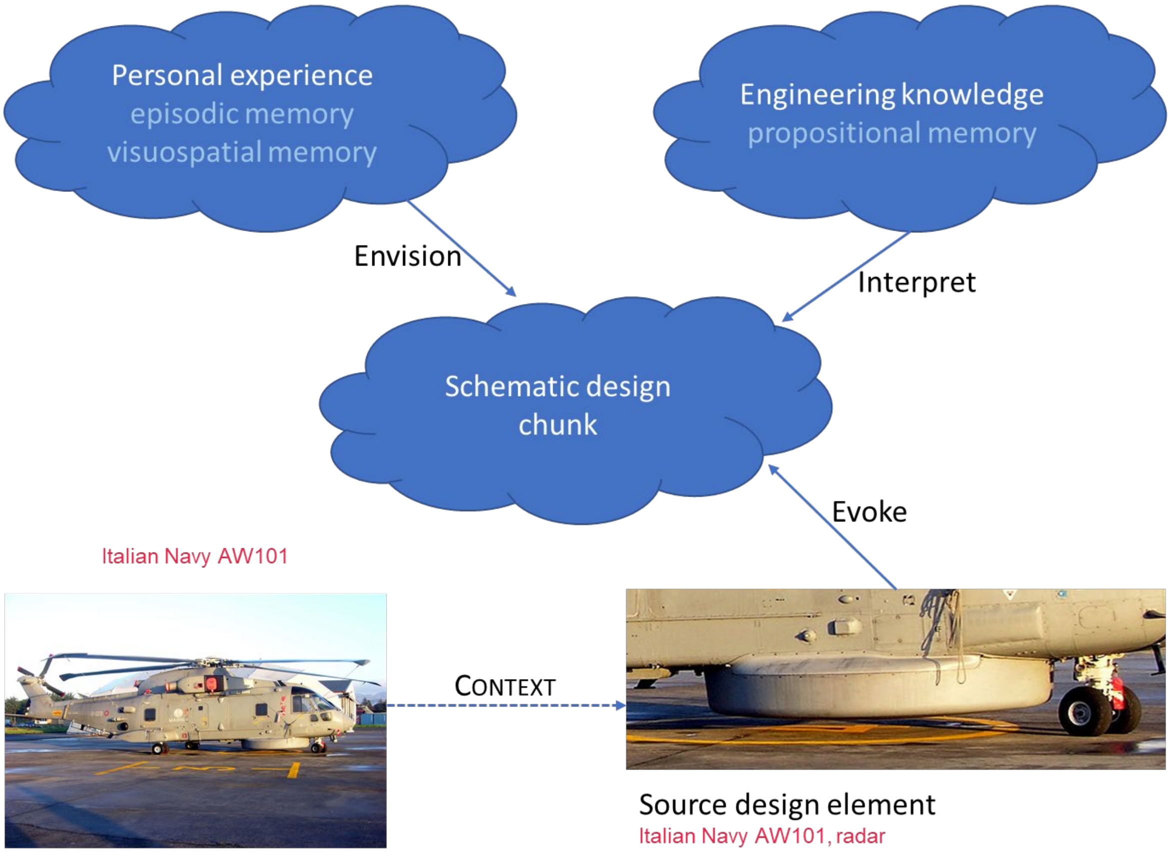

Figure 1 Schematic knowledge chunks constructed from general propositional knowledge, experiential knowledge and interaction with objects, for example concerning the radar installation on the AgustaWestland EH101.

Engineering expertise involves local knowledge

Using individual designed systems as carriers of engineering knowledge requires engineers to possess other forms of knowledge in all of Vincenti's categories. Engineers need to be able to read artifacts of the types they design: to understand structures and features and anticipate behavior. The knowledge required to interpret an object is general (across different designed artifacts) but is also personal, depending on the expertise and experience of individuals. As well as propositional knowledge of structures and properties and causal relationships, it includes teleological knowledge of the functions of machines and components, and how to achieve results.[33] It also includes experiential knowledge of the behavior of this and other objects, enabling the envisioning of its behavior (as illustrated in Figure 1). It is shared to different extents in overlapping communities: engineers sharing a particular professional training and thus sharing an object world,[34] engineers working on particular types of products, engineers working on particular types of components, or applying particular methods, and engineers working in one company. Similarly, the ability to interpret an object reference requires the combination of knowledge of the artifact itself with more general engineering knowledge.

Expert engineers

Expertise is built up by working on multiple designs. As complex engineering projects can take several years, an expert has to be in place for many years to build up sufficient understanding of what works and what does not work and under what circumstances. The objects that they have worked on serve as indices for the experiences associated with designing the product, as well as for the schematic design chunks associated with it and elements of situation-specific design skill. Previous designs also serve as indices for memories associated with them, not only their features and performance characteristics, but also memories for the practical considerations that influenced their design, when and why designing proved problematic, the relationship between the intended design process and how it played out in practice, and so on.

As well as knowledge of successful machines and useful solution principles, schematic design knowledge also includes solution principles and embodiments of them in specific designs that do *not* work, in particular contexts or at all, as well as the failure modes of potentially useful schematic design chunks. Engineers who have worked together on multiple product generations share not only an understanding of the product and the process, but also the problems that have occurred during the design process. They collectively know what to avoid (sometimes, excluding failed approaches that their competitors have success with). While there is certain amount of staff turnover in every organisation, companies think it is important that enough engineers stay to maintain this collective knowledge.

Communities of practice and the preservation of knowledge

Designed artifacts act as carriers of knowledge from the past as new designers learn about them and come to understand them and how they compare to similar designs. Schematic design chunks of varying degrees of specificity can be extracted from them by anyone with the general technical knowledge to understand how they work. Doing this is part of the development of product-specific expertise that working engineers acquire.

However, in practice, the knowledge of advantages, disadvantages and consequences that forms part of schematic design knowledge is passed on within local communities of practice.[35] It goes beyond what can easily be deduced from designed artifacts in isolation, and depends on experience of objects in context and on verbal report. So does knowledge of the reasons for the design decisions that the artifacts embody.

Becoming an expert design engineer in industry involves developing knowledge of the company's previous products, as well as related artifacts like the competitors' products, enabling understanding of object references as well as awareness of the company's standard design features and preferred solutions to problems. Having the right mix of this local knowledge is vital for engineering organizations developing successions of products over long periods. They can hire engineers or use consultants who have general engineering knowledge, but this local knowledge cannot be bought in. They have to make sure that they capture this local knowledge when members of staff leave or retire; and some industrial and governmental organizations have sunk a lot of money into trying to preserve specialist knowledge.[36] When this knowledge has been lost, reconstructing it from the artifacts themselves is extremely difficult or impossible. This has caused severe problems when engineers have needed to do this. Nonetheless the artifacts do preserve a lot of knowledge embedded in them when the communities are broken. Stories about problems, solutions and rationales for decisions are often propagated by communities of practice, and are lost and not recoverable without them.

Object references in engineering design

We examine how artifacts serve as carriers of engineering knowledge – from the past and between team members within development processes – by looking at the roles the artifacts play. These are roles that working engineers are well aware of, but which are often neglected by theorists, who have largely focused on the role of objects in idea generation.

Object references across design: analogies, precedents and inspirations.

Claudia Eckert et al.[37] have argued that "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." Eckert et al. suggest that object references reduce the overwhelming complexity of complex design tasks by offering parsimonious mental representations to which details can be added as needed.

The design research literature has largely focused on the role of objects in the generation of new ideas. Designers frequently reason by analogy to other designs to generate new ideas.[38] Saeema Ahmed and Bo Christensen[39] discovered in a study of aerospace engineers that novices tended to transfer information regarding geometric properties without considering their appropriateness in a particular context, whereas experts used analogies to solve specific problems and reason about the function of a component and predict its behavior.

Architectural design research has considered the role of precedents. These are often recent buildings from well-known architects, which have received wide critical acclaim and are well known, that designers use to give credibility to their own designs and from which they draw combinations of forms, materials and proportions.[40] In addition architects draw on a canon of historic designs. Goldschmidt drew a distinction between precedents providing the organizing principle for a new design, and references providing patterns or inspirations for particular elements.[41] In giving an account of precedents in cognitive science terms, focusing on the role of precedents as sources of ways to solve problems, Rivka Oxman pointed to the importance of design stories linking the design issues of the problem, a particular solution concept, and a related form description of an element of the solution.[42] For her, “Precedent knowledge is here considered as the explication of the relevant insights of particular designs and the appropriate linkages of information between multiple design precedents.” Similarly, Bryan Lawson stressed the importance of architects’ episodic memories for precedents as sources of solutions for problems, pointing out that precedents carry a concrete and situated form of knowledge rather than a theoretical and generalized one.[43]

While the idea of an architectural precedent is a design that has already been singled out as setting a trend, designers also make use of sources of inspiration. This is a much more pragmatic and diverse process of generating ideas based on objects that surround designers or that they seek out specifically. The term ‘sources of inspiration’ covers all conscious uses of previous designs and other resources, as the triggers or references for the solution to the current problem.[44] Sources of inspiration play a very important role in artistic design domains, such as fashion or product design, where the visual appearance of a product is important and highly dependent on the context of other products sold at the same time which collectively define a particular fashion. The inspiration can come from physical objects but also from descriptions[45] and other representations;[46] however professional designers confess to a preference for objects or images over text.[47] The use of sources of inspiration goes beyond generating ideas. Designers use references to identify the space of future designs and justify their choices.[48] Using other designs to generate ideas has its perils:[49] designers can get fixated on particular ideas, often without being aware of it, which biases their ideas towards known solutions.[50]

Modes of reuse

Most complex products are designed incrementally based on existing products.[51] Innovative design ideas are only introduced into complex products when they have achieved a high level of maturity,[52] which makes *ab initio* design, which has been extensively studied experimentally and theorized about, very rare. For example, the basic functionality of a diesel engine has changed little since the 1890s and had matured by the Second World War. Contemporary engines reuse the engine blocks and many of the basic systems like gears over many product generations. Companies have first put their effort into optimising the fuel consumption by optimizing fuel injection, and since the early 2000s on reducing emissions through after-treatments.

We can find the following modes of reuse.

Design by reuse: Companies strategically introduce new components or systems through planning product generations.[53] They try to minimise the use of newly designed elements, because making use of existing designs has considerable benefits, namely minimised development effort, reduced cost, and reduced risk, because the company knows the component works successfully in existing products.

Design by modification: Designers typically start by analysing the properties of existing designs. For example the diesel engine designers physically modify existing engines to see whether they can achieve the required performance and then modify the design of these engines to do so reliably and durably.[54] Changes to one component of a system can have effects on other parts, which will also need to be modified; predicting these change paths is notoriously difficult.[55] If engineering designers do not start from their own designs, they make use of feature-based component libraries.[56]

Reuse of solution principles: Abstract solution principles and the ways multiple different solution principles are deployed together are borrowed from particular designs as well as from more general categories of machines. These are then refined and instantiated differently for new designs. Often machines or components are required at different scales (contrast small outboard diesel engines and large ship diesels) but the solution principles they employ and the basic configurations are often the same, as engineers who have experience with them know how to design and test them.

Object references in design discourse

Engineers often bring up references to existing objects in meetings. Through these references, the objects carry design information between the participants in the development process, about possible developments regarding the current design, as sources of intended analogical mappings to elements of the new design as well as sources of elements to be reused.

These references are often almost impenetrable to outsiders, but seem to be entirely clear to the people who are also familiar with the objects.[57] However, there is little guarantee that what the people themselves and observers interpret as a form of shared understanding is in fact a congruent understanding. In some cases they might think of different versions of a quite specifically named product in a situation where the differences matter. There might not even be an original unmodified version to constitute the core meaning of the reference; for example there is no ‘standard’ version of the EH101. To minimise potential misinterpretation, engineers often carry smaller components such as bearings or pumps with them to meetings or to discuss issues with colleagues. Specifying what is different from a reference design is easier than explaining fully what a new design entails. For example, “use a bigger version of the four cylinder engine” is a concise way of expressing an idea. This is assuming that the other person knows the reference product and understands the scope of the reference being made.

Varieties of objects used as object references

Designers are entirely opportunistic in the object references that they make. They use similar objects as reference points for features[ii] and configurations that can be mapped to the new design. We have observed engineers referring to the following categories of objects.

Own past designs: Past designs serve as a starting point for new designs either by basing a new product on past designs or by combining features from multiple past designs. The designers are most familiar with their own old designs and have complete documentation for them. Companies also keep physical examples of some of their own designs and refer to them during the design process and as illustrations of potential designs.

Competitor products: Engineers regularly look in detail at their competitors' products. They buy them and take them apart. Competitor products provide useful insight into how particular features can be addressed and what solution principles would work. For example, the diesel engine company we studied used the competitor engine to corroborate their own ideas.

Products embodying solution principles: Engineers also look beyond their own field for objects that use features or solution principles that might be included in a new design. For example, off-road diesel engine designers look at car engine design and pick up ideas from that.

References to objects, pictures, models and memories

How designers interact with the objects they refer to depends on whether the objects are physically present, or whether the designers rely on their memories, or they have images or models of the objects. Often the physical object itself serves as its own representation.

[ii] The term 'feature' is used widely by engineers to mean an element or aspect of a product that does not align neatly with the component breakdown.

Designers either make verbal references to an existing object or an aspect of it by its proper name or a commonly understood denominator, or gesture towards it. Often engineers just refer to an object by its name, such as the "same piston configuration as in the four cylinder engine", with the implicit understanding that both the sender and recipient know the details of the most recent four cylinder engine design. Sometimes objects are referred to by their market sectors, so that "like an engine for Africa" is a shorthand for a robust older design with lower emission requirements and maybe some current updates; or by a specific customer, where the reference implicitly includes details about the packaging of the engine, for example where the fuel intake is located.

Thinking with objects / knowing through objects

Much of the knowledge and experience built up in a company over decades is embodied in objects and accessed through references to objects. Thinking with object references enables designers to think in big chunks of design information that they can connect as and when required. For example, they can imagine combining components from two different objects without needing to specify either in detail or at that point worry about how they are linked. Object references enable designers to retrieve and use connected schematic design chunks from one design; the object references provide a context and a coherence to otherwise fragmented constituents of designs by binding together sets of structural elements, parameter values and behaviors in ways that are known to fit. Being able to use objects or images or diagrams of them, as external memory and as a source of triggers for making inferences, often enables engineers to reason (by recalling or generating and applying schematic design chunks, and filling in details by direct observation) in more precise detail about how to use elements of the existing design in a new design.

Thinking about existing objects gives the designers the flexibility to switch between the product itself, the processes by which it is designed and manufactured, and the use of the product, because the identity of the object acts as an index for information about all of these, as well as a route to find out information the designer cannot remember. While all these aspects of a new design could be formulated and explained without object references, this would be time consuming, and the effort and the choice of sequence and representation would also bias the design process, though differently from the object references.

Object references work on different levels of detail, triggering the recall or construction of schematic design chunks for elements of the product at different scales. Designers can think about the entire product or focus on a small element of the product. They can also think about the physical structure of the product, its function, behavior or use. Object references also allow them to pull together different levels of hierarchy in a way that no product description would.

Implicit features

Object references help designers to reason by analogy to think through some very important aspects of a design, which are usually only implicit in models and descriptions, are often hard to express, and difficult to reason about for an incompletely specified, evolving design:

Relations: Object references enable people to think about the relationships between different elements of a design, because all the elements of a concrete object have defined relationships with each other and with the environment the object is in. It is difficult to think this through for an evolving design, as different elements are designed in parallel and remain fluid for long periods of time. For example, when dealing with issues like vibration it is important to look at neighbouring elements and gaps between them, since vibration is often caused by components expanding due to heat and thereby coming into contact with each other. A particularly important form of relations is the system architecture, i.e. “the arrangement of the functional elements into physical blocks.”[58] Generally, relationships between the elements of the product, such as configuration, clearance, and so on, are implicit in CAD models, etc., but are often very obvious when looking at objects. These cannot be conveniently expressed as a set of statements or as design rules, because they depend on the context. Object references can also be convenient shorthand terms for clusters of features or system architecture. System architectures can be expressed as connectivity matrices[59] or as network diagrams; however these become hard to follow with a large number of elements and are difficult to read, whereas a physical object enables designers to appreciate the object holistically and in addition see the details of special relationships between the elements.

Emergent properties: Sometimes, combinations of design elements in particular relations generate emergent properties that are important for the functioning or human experience of the artifact.[60] Considering previous similar artifacts can enable designers to recognize that particular emergent properties are likely to be important, and anticipate what they are likely to be. Sometimes these are the consequences of adopting particular solutions to technical problems. For some products, these choices of technical solutions and characteristic details of features play an important role in defining brand identity, sometimes by generating emergent perceptual properties that are very difficult to specify. Companies designing and producing a range of consumer products use common styling features to maintain a clear identity in the market.[61] Brand identity is a combination of tangible and intangible elements,[62] which makes it particularly difficult to describe. Only by a detailed study of a range of specific objects can new designers understand the perceptual features that characterize a brand and how they depend on structural features of the designs.

Behavior: In designing parts of the product, designers need to think about how the part behaves on its own and contributes to the overall behavior of the product. While it is now possible to simulate much of the behavior before a physical prototype is built, such a simulation requires the design to be worked out in considerable detail. By looking at existing products, designers see the behavior of similar products and the effect of the interaction of different behaviors, so can anticipate likely behaviors and problems before the design is complete enough to simulate. This is particularly important in the context of problems or failure modes, where designers often think through potential problems with a new design by reference to problems they had to sort out in past designs. One example of this is engine noise, a highly subjective property of a diesel engine, which is determined by the details of the engine configuration and the way an engine is deployed in a machine. Most of the time the experts in the engine noise team build up their expertise by working on multiple generations of engines, but a new engineer can only learn about this by interacting with existing engines and applying their general knowledge about acoustics.

The ambiguity of object references

Abstractions, such as solution principles and other abstract and general schematic design chunks, underspecify details and thus allow alternative instantiations. In design it is seldom the case that the context provided by the rest of the design entails all the details of the instantiation of an abstract schematic design chunk. A named object might also have alternative interpretations: it might be abstracted in different ways to form different schematic design chunks, so naming a specific concrete source object introduces potential ambiguity in what features should and should not be transferred. But some abstraction will be needed for talking and thinking about complex designs in skeletal and qualitative terms.[63] Object references can be hazardous because their scope and focus can be unclear. There is scope for ambiguity in a reference to a specific object, and object references are interpreted through the individual lens of one's personal experience and expertise. It is not explicit what exactly is referred to. How much of the object should be included in the mapping to a new design, and how much should the mapping include concrete detail as well as abstract solution principles? For example, does "configuration like the four cylinder engine" imply all the peripheral components, that is, the options for connecting the engine to the products they are deployed in? The referent itself can be unclear or ambiguous.

Engineering companies often develop an internal vocabulary, where insiders know what it is included in the reference. However, the boundaries are still not clear. For example, one of the authors carried out a modeling exercise with six diesel engine engineers who insisted that the gudgeon pins, which connect the piston to the rod, were mentioned explicitly in a product breakdown as part of "piston, rings and gudgeon pins".[64] They had been overlooked in the past, because as connecting parts they could be part of two systems and were ignored as everybody had assumed they would be implicitly covered by the other system.

Using elements of existing objects in new designs involves finding a match between the structural and functional features of the existing object and the new design, so that corresponding features pertinent to the current problem to be solved are aligned. There is a danger that too much of an earlier design is carried over, when some aspects of it are chosen for good reasons and other aspects are adopted because they are never questioned. The rationale for *why* particular aspects of a product are the way they are is often lost, in the absence of easy and convenient ways to capture design rationale. Combined with design fixation, this leads designers not to question particular design decisions, so that object references can push engineers to solutions that are no longer appropriate. This is particularly an issue for relationships between different elements of the objects and between the product and the outside world, that people might not be aware of. For example, the exact location of the pipe linking the engine and the fuel tank can be critical.

Clusters of objects as sources of schematic design chunks

As well as isolated individual objects carrying knowledge, groups of objects collectively serve as carriers of knowledge. Designers abstract over their shared features to form schematic design chunks that are more abstract and skeletal than those they form from individual designs. In some cases, the objects belong to categories that can be named and given clear definitions, such as engines with integral sumps, or engines for the African market. In other cases, more commonly in artistic design industries such as fashion and knitwear, clusters of designs that are juxtaposed and share common characteristics function as groups, but the groups may not have clear definitions or boundaries. Such clusters are typically identified by referring to exemplary members.[65] These clusters can share identifiable and describable features that are characteristic of the cluster, and that are invoked by referring to the cluster. It will usually be apparent from context which of these features should be mapped to a new design, but this is not always the case. Interpretations of references to ill-defined groups of objects may differ in the scope of the groups and in which properties are taken to be central to it, and thereby become a significant source of miscommunication in engineering processes.

In other cases, the members of a cluster can share a range of emergent or experiential characteristics, so that it is not obvious which features or emergent characteristics really determine group membership, and which are merely shared, nor exactly how the structural features of the objects produce the important experiential characteristics.[66] Different generalisations could be made, to produce different schematic design chunks, and knowledgeable designers might legitimately disagree on how to interpret the clusters. The scope of such groups can often be unclear. As well as artistic designers of various sorts, needing to recognize categories characterized by undefined emergent characteristics affects engineers concerned with the customer-visible elements of consumer products such as cars, where the maintenance and development of brand identity matters for the success of the product.

Designed artifacts as carriers of design knowledge

Actually existing designed artifacts, like documentation of designs, actually exist: their existence is independent of anyone's mind. Extracting from an artifact an understanding of how it works, what its components and features and emergent characteristics are, and the design choices it embodies, sometimes even the reasons for choices, requires extensive general engineering knowledge. But the artifact contains this information for people with the skill to read it, in an independent objectively-existing form; in particular, it embodies the brute fact that it exists and is so and not otherwise. (In practice, reading an artifact in enough detail to replace it or reverse engineer it without knowing about its history or use context is very difficult and people seldom do it. However, people do read artifacts using some situation-specific knowledge to extract information they cannot easily recall or construct.)

However, the central thesis of this paper is that designed artifacts, like a diesel engine, play important roles in design processes – this is an empirical observation – and that the way to understand these roles is by examining how they serve as carriers of information. As we have observed, company archives of both their own designs and products and their competitors' products play a significant role in both the development of local expertise and in development of new designs.[iii] Designers interact with them in the course of creating new designs and discussing them in meetings, and refer to them to describe new ideas as variants of old ones. Engineering companies like the diesel engine company we have observed are dependent on them as locations, internal to the company but independent of any particular human, from which parts of the knowledge used and constructed in new product development are drawn. Drawing knowledge from them involves *reading* them as structures with properties, behavior and purposes. Thus, past designs and past artifacts have a dual nature as

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[iii] The proponents of actor-network theory argue that objects of this sort have agency in social processes like the development of a new product. This view is of course controversial.

physical objects whose physical structure causes their meaning for their interpreters, and as embodiments of information about ways to solve engineering problems that were used in the past, with their consequences and problems. The embodiment of information in artifacts is not unique to engineering. Davis Baird[67] has developed the argument in far more detail that physically existing apparatus and experimental setups play an important role in science, by embodying and conveying information beyond themselves about the nature of reality, and often in ways that mirror transmissions of scientific information through texts.

Designed artifacts as components of designing organizations

The previous designs and actual products that play various roles in a product development process are independent of human brains, but are internal to the organization that physically possesses them. The product development process is a collective sociotechnical process with collective goals, requiring a collective competence extending beyond the capacities of any one designer. The designing and knowledge generating activities that the process involves include previous designs as important contributors. If we take a collective view of engineering knowledge, as what enables a design team to create designs for new artifacts, we see existing objects acting as part of the team's collective memory, serving as holders of design knowledge, both shaping the team's skills and providing many of the schematic design chunks that are employed in constructing designs by using and adapting existing elements at various levels of abstraction. The company's archive of artifacts and designs functions as part of the company as a designing system, carrying knowledge that is shared between people, or available to be shared between people, but internal to the company.

Conclusion

Engineers frequently refer to or point to existing designed artifacts when designing or discussing a new design, most commonly earlier similar products. Object references are an extremely powerful way to express specific engineering knowledge. They provide terse expressions for highly complex information that cannot be expressed easily and effectively otherwise. In particular, relationships between elements and behavior are difficult to express at all unless through object references. However, how references to objects are interpreted depends on individuals and their general engineering knowledge and personal experience.

Becoming an expert engineer involves acquiring a lot of local knowledge that is embodied in one's employer's past designs. It enables the expert engineer to make and understand references to them. Collectively the history and identity of a company is expressed through the objects it keeps: not just characteristic ways to solve technical problems but in many cases also the perceptual properties of the company's products that contribute to brand identity – sometimes these perceptual properties are created by characteristic technical features.

Object references provide triggers for the knowledge of individual engineers, who recall past designs or experience with earlier designs or other artifacts when they are named or when they see them. They construct analogies between the existing artifact and the new design to map elements of the artifact to the design, at varying levels of abstraction.[68] We have argued for regarding what we have termed *schematic design chunks* – combining structural knowledge of the elements of part of a system and the relationships between them with teleological knowledge of its functions and awareness of its advantages, disadvantages, potential failure modes and consequences for the rest of the design – as important units of designers' knowledge. Schematic design chunks vary in abstraction and generality, but many are drawn from experiences of specific objects and are closely related to memories of them. The concept of schematic design chunk encompasses a range of notions familiar to engineers, architects and other designers, including solution principle, machine element, design pattern and precedent.

We have argued for viewing physical objects, examples of designed artifacts, as holders of design knowledge. They are external to the brains of individual engineers, but engineered products and designs for them that are referred to in engineering design are typically possessed by and thus internal to engineering companies. They can be read, and knowledge of how to design extracted from them, by someone with sufficient general engineering knowledge. However, the schematic design chunks that are evoked by designed artifacts may include awareness of problems and ways to solve them, rationales for decisions, failure modes, and so on, that is propagated within a community of practice and is difficult or impossible to reconstruct just from the artifact itself.

We are often not concerned with the knowledge of individuals – as a company does not particularly care who in an organisation has specific knowledge, as long as the knowledge is available collectively – but with the knowledge possessed by design team or a company, or even a multi-company structure. We have argued for a competence characterisation of what knowledge is – that which enables an agent to carry out particular tasks[69] – as equally appropriate for an individual, team-centric or company-centric view of engineering knowledge. Existing objects contribute to the teams' collective designing competence.

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[2] See Stacey et al, “From Ronchamp by Sledge” for a somewhat idiosyncratic example.

[3] See Latour, Science in Action; Reassembling the Social.

[4] See Law and Callon, “Life and death of an aircraft”; Jarrahi and Sawyer, “Networks of innovation” for applications of actor-network theory to engineering.

[5] Eckert et al. “Change and customization”; Jarratt et al., “Development of a product model”; and Keller et al., “Using an engineering change methodology”.

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[6] Eckert and Clarkson, “Planning development processes”.

[7] Eckert et al., “Hidden issue”; Eckert et al., “Design margins in industrial practice.”

[8] Eckert and Stacey, “Sources of inspiration in industrial practice”; and Eckert and Stacey, “Language of design”.

[9] Lave and Wenger, *Situated learning*.

[10] Cox, “What are communities of practice?”

[11] Wenger, Communities of practice.

[12] See Eckert and Clarkson, “If only I knew.”

[13] Ryle, “Knowing how and knowing that”; see Löwenstein, *Know-how as competence*.

[14] Newell, “The knowledge level”.

[15] See Russell and Norvig, *Artificial Intelligence*.

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[17] See most famously Alexander et al, *A Pattern Language*; Gamma et al, *Design Patterns*.

[18] Gero and Kannengiesser, “Situated FBS framework”, “FBS ontology”.

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[24] Oxman, “Precedents in design”; Lawson, “Schemata, gambits and precedence”; see also Goldschmidt, “Reference versus precedence”.

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[26] Schank and Abelson, Scripts, plans, goals and understanding.

[27] Aristotle, *Nichomachean Ethics*, Book VI, chapters 3-7.

[28] See Kant and Kerr, “Taking stock of engineering epistemology”, for a survey.

[29] Houkes, “Technological knowledge”.

[30] Vincenti, What engineers know.

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[31] Meijers and Kroes, “Extending the scope”.

[32] Ibid, chapter 7.

[33] Zwart, “Prescriptive engineering knowledge”.

[34] See Bucciarelli, *Designing Engineers*.

[35] See Lave and Wenger, Situated Learning; Wenger, Communities of practice.

[36] See McNamara, *Ways of Knowing*, on the knowledge of nuclear weapons designers.

[37] Eckert et al., “References to past designs”.

[38] See Linsey et al. “A study of design fixation” for engineering solutions; and Gonçalves et al. “What inspires designers?” for industrial design.

[39] Ahmed and Christensen, “An *in situ* study of analogical reasoning.”

[40] Goldschmidt, “Reference versus precedence”.

[41] Ibid.

[42] Oxman, “Precedents in design”.

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[46] Cai et al., “Extended linkography”.

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[48] Eckert and Stacey, “Language of design”.

[49] See Jansson and Smith, “Design fixation”; and Linsey et al, “A study of design fixation”.

[50] Vasconcelos and Crilly “Inspiration and fixation” ; and Crilly and Cardoso, “Where next for research”.

[51] Cross, Engineering Design Methods.

[52] Mankins, “Technology readiness levels”.

[53] For instance, Albers et al, “iPeM”.

[54] Tahera et al., “Testing”.

[55] Eckert et al, “Change and customization”.

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[56] Vajna et al, “CAx”.

[57] For examples in an idiosyncratic situation, see Stacey et al, “From Ronchamp by sledge.”

[58] Ulrich and Eppinger, “Product design and development”.

[59] See Eppinger and Browning, Design Structure Matrix Methods and Applications.

[60] Johnson, “What are emergent properties?”.

[61] Warell, “Design syntactics”.

[62] De Chernatony et al., “Modelling the components of the brand”.

[63] Maier et al., “Model granularity”.

[64] Jarratt et al, “Development of a product model”.

[65] Eckert and Stacey, “Language of design”.

[66] Stacey, “Psychological challenges for the analysis of style”.

[67] Baird, Thing Knowledge

[68] See Stacey et al, “From Ronchamp by sledge”; Ball and Christensen, “Analogical reasoning and mental simulation”.

[69] See Ryle, “Knowing how and knowing that”, Löwenstein, *Know-how as competence*, See also Newell, “The knowledge level”.