2

Design as Experiment

A significant feature of the definitive method of computer modelling is the experimental nature of the interactions made by a user. It is that which makes it potentially attractive to the conceptual designer. In this chapter the idea of design as experiment is developed in order to draw out particular conceptual differences between the design process and the computational process. The aim is to explore what is required in principle to aid the conceptual designer and so provide the underpinning reasons for developing the definitive tools for design

2.1 Design and the Designer

Anyone attempting to give computer-based aids to design had better try to understand design and the role of the designer. These are formidable tasks. Even their definitions are unclear and virtually all writers on the subject seem obliged to formulate their own. Contrast the following examples: the academic Michael French; the industrial practitioner, Coplin of Rolls Royce; and David Ullman "a designer all my life".

> "Design is all the processes of conception, invention, visualisation, calculation, marshalling, refinement and specifying details that determine the form of an engineering product." [French, 1985].

> "Engineering design is a detailed planning process concerned with defining the package of product and service that will fully satisfy the customer while at the same time satisfying the expectations of the shareholders of the producer." [Coplin 1987]

> "The only way to learn design is to do it. A design process that results in a quality product can be learned, provided there is sufficient ability and experience to generate ideas and enough experience and training to evaluate them." [Ullman, 1992]

In these definitions design indicates purposeful activity, directed towards an end. Indeed some prefer the narrower definition of 'product realisation' as more accurately defining the task of the engineering designer. The phrase draws attention to the distinction between the process of designing, and the product of the process, whereas 'design' is used to describe both activity and result. Both French and Coplin imply that the process of design may be identified independently of the designer. Ullman is more sanguine. He sees all three, the designer, the design process and the resulting product, as closely bound up with one another.

We need to examine the relationship among these three: the product, the design process and the designer. Is the designer central to design? In an automated design system what is the role of the designer? Can we automate the process of design to the extent of excluding the human designer, or must the computer be a design support system with the designer in charge? If the computer and the designer are agents in the design process, how do they cooperate, and what if there are many agents, as in a concurrent design approach?

We consider first the relationship between the designer and the designed product. The ability to design is often thought of as arising from our human propensity to see order and pattern in the universe. Conversely where we perceive pattern we tend to regard it as somehow pointing to a designer. Indeed observing design and pattern in the universe as a whole, people from engineers to artists, physicists to theologians, speak of a "designer universe". Paul Davies, a professor of mathematical physics, writes the following.

> "The natural world is not just any old concoction of entities and forces, but a marvellously ingenious and unified mathematical scheme. Note, words like "ingenious" and "clever" are undeniably human qualities, yet one cannot help attributing them to nature too.
>
> According to Christian tradition, the deeper explanation is that God has designed nature with considerable ingenuity and skill ... so as to permit life and consciousness to emerge. Our own existence in the universe formed a central part of God's plan." [Davies, 1992]

The significant feature here appears to be the total involvement of ourselves with the universe. It seems that any definition of design that fails to include the agents of design is incomplete.

At first sight we may consider that demanding such a strong link between the design and the designer is unnecessarily restrictive. Even given a designer, may there not be a distancing of designer and product? Cannot parts of the design process be independent of the designer? For example, the more routine components of French's description of the design process are amenable to standardised approaches, even where the task is new. The correct specification of such "standard" problems quickly yields answers, as Roth's recent work shows [Roth, 1989]. Within a narrower definition of design, or perhaps downstream of the conceptual stage there will indeed be standard components and processes, but that begs the question of the need for a designer since those standard components must at one time have been conceived. Producing variants of existing designs is an extremely useful annex to the design process but can it claim to be 'design'?

The question centres on conception, invention and visualisation. If those could be independent of the designer then it should be possible to construct a computational system in which designs could be inferred. In that case a computational model, consisting essentially of symbols could create truly novel designs, *i.e.* designs that make new relationships and new patterns on observable data. There is little doubt that certain new relationships can be formed, but genuinely new pattern recognition requires a data base that is considerably larger than the biggest data system yet devised. The reason for that is in the contrast between the form of symbols and their 'content'. Cantwell Smith, in a paper entitled 'Two lessons from logic' [Smith, 1987], argues the 'irreducibility of content to form'. By this he means that there are two factors to be considered in any symbol system. The first factor involves the shapes of symbols, how they can be put together and the behaviour or operations defined over the systems. That would typically relate to operations in a computer based system. The second factor has to do with what symbols mean, what they are about: in other words their content.

The problem that Smith identifies is that content is not intrinsic to the symbols. He gives the example of the word $PLANE_{17}$, a symbol that deals with the flight of a particular aircraft. No examination of the symbol within the air-traffic control system will reveal which aircraft in the air is referred to. To get that information one needs to look outside the system, to see how it is connected with the real world. The content of symbols outstrips the local assignment in a symbol system.

Worse, there is a whole world of reference bound up with symbols that can hardly be comprehended. What, for example, does one make of the following?

"Why does this sentence remind me of Agatha Christie?"

There is no reason for that sentence to bring to mind the whole fictional world of Agatha Christie, yet it does! 'Reference outstrips causality' is how Smith defines it.

Reference of that sort, or 'content' is a human thing. It depends upon memories, experiences, knowledge, understanding. These may be buried in the sub-consciousness, but ready to be triggered at a word, a smell, a picture, a sound. The "content" of a symbol may be huge, spreading its web of connections ever more tenuously to include perhaps one' s whole personal experience. The connection may be rational, it may be intuitive. It will also differ, depending upon the person.

Yet, it might still be argued, a 'content' may be large, but it can be regarded as finite in relation to a circumscribed model addressing a particular function. Is it not possible to construct a symbolic system that holds all that one might need for representing that model so that it has a one-to-one correspondence with the real world? The difficulty is in deciding whether one has 'all' that one needs. One cannot inspect that possibility, for one then comes up against what is called in computability theory the Halting Problem.

> "It is the question of whether there exists any computer program that can inspect other computer programs before they run and reliably predict whether or not they will go into infinite loops. The answer turns out to be "Definitely not" ... With that result there is no finite mechanism that can detect all patterns, patterns of patterns, patterns of patterns of patterns...." *On the seeming Paradox of Mechanising Creativity* [Hofstadter, 1979]

Any given logical system has to have a system outside; and that 'outside system' has to have a system outside it, and so on, to infinity. Whatever system one might construct to model the design process, its form must be limited - its content always connected to the real world by us as humans. It seems that 'agents are what matter' [Smith, *op cit.*].

If we wish to design a new object, the information enabling that object to be truly novel is likely to reside more in the mind and experience of the designer than in the forms that can be recorded in an automated system. Humans can make connections from among infinities of possibilities in apparently irrelevant experiences far beyond that which it would be reasonable to store in a comparatively specialised system for design support. We need to examine the ideas of symbol and content in more detail to see how those connections may be made.

2.2 Symbol and Content

The richness of 'content' in a symbol is illustrated in the widespread use of 2D CAD systems. While a rectangle might represent itself, it may be perceived, depending on the context, as a shaft, a box, a window, a zero symbol, a button or an information block. In other contexts it may be a kitchen cupboard, a tile, a sink; in yet another: a house, hotel or shop in plan view. The content is limited only by the imagination. A 2D CAD system permits the user to use imagination to its fullest: content is added by the user. The difficulty then is communicating the content to others: a difficulty that becomes acute in a multi-agent or con-current design. The traditional way out has been to have agreed conventions for interpretation such as BS308 Drawing Office Practice. It is well known that an engineering drawing conveys much more than that which is actually on the drawing. For example the presence of a fine-machining symbol on a dimension implies that the particular shape feature dimensioned is highly significant to the function of that object and drawing attention to it in a way that merely obeying the symbol to the letter may not be adequate. Another example is the tolerance on a hole position. That is specified in a way that cannot ever be measured: the centre of the hole is machined away; all you have is the rather inaccurate form of the circumference from which to infer the probable centre.

Despite the richness of possible *content* in a symbol the *context* of a symbol may provide certain avenues for exploring it in a rational way. Notwithstanding the intuitive connections, rational or experiential connections between symbol and content can be made by listing rules and relationships. It is the enumeration of finite groups of possibilities that underlies the taxonomic and the methodical approaches to Design. Characteristic of that is the recent abundance of research into *feature editors*. In mechanical engineering applications, for example, feature editors have libraries of features, such as holes, bosses, slots and pockets, that the user simply calls and assembles on the screen. It is claimed that all geometrical modelling could be based on such taxonomies, since other attributes can be added to standard features as required, and products designed that way can be readily linked with manufacturing activities. (See for example [Gu, *et al*, 1989], [Krause, *et al,* 1989], [Mantyla, 1990]. The latter gives a useful summary of feature editors).

The reasoning behind the taxonomic approach appears to be that one can construct commonly agreed vocabularies for referencing the world, or parts of the world. There appears to be an important concept here. Roger Trigg, a philosopher at Warwick University, writes:

> "Language must be understood to be about one world open to public inspection. Plato makes it clear that it is a precondition of language that the world has a certain stability. ... We must have the assurance that when we pick things out and draw other people's attention to them, they too can identify what we are referring to." [Trigg, 1973]

Trigg is appealing to the lowest common denominator of all languages: an understanding of the world that is common to all humankind. That understanding is in turn fed by a common set of basic conceptions of the world. So if one can isolate and classify such experiences there is a possibility that the taxonomic approach has some merit.

The problem of classifying these "basic experiences" and common language is that of disentangling the common from the other content. One only has to listen to politicians to see that the same words can denote very different things! And 'features' identified at one time suddenly invert and become the opposite (black on white rather than white on black for example).

It is thought by psychologists that conceptions of the world are formed by early childhood experiences, reinforced by experience. Those conceptions take the form of 'percepts', mental pictures of things and events that tie up with a world view. Every time a new experience is had, existing percepts are used to try to tie it in with the world as already understood. For example Yvonne Wærn illustrates the way a concept based around "an orange" can be understood in terms of percepts [Wærn, 1986]. *Fig 2.1* shows some of the percepts around that single object.

Percepts that are frequently used become reinforced and refined, and become "long-term memory"; less frequent or recent percepts are easily modified or displaced. The Swedish psychologist Professor Sandström made this observation of animals.

> 'The learning curve is not characterised by sudden leaps, revealing flashes of insight; learning takes place successively. When the animal has acquired a concept it becomes to a remarkable degree capable of altering the response pattern and adapting itself to the requirements of the situation.
>
> A so-called perceptive solution of a problem is here rather the result of extensive and versatile experience' [Sandström, 1968].

Sandström says that while this does not necessarily apply to human (as opposed to animal) insight, there does appear to be some evidence that percepts become the starting points for linking new experience.

Faced with a new experience new connections seem to be quickly established (first impressions) but later some regrouping of connections appears to take place as percepts get modified (second thoughts). A new experience is treated rather like the way the brain treats visual information from the eye. A literal data analysis of the retinal image yields a blind spot, but under normal circumstances the brain fills in extra information extrapolated from both visual and previously stored data. The new experience is like the blind spot, interpreted in the same way. New images, further experiences modify the extrapolated information and may later modify the longer term understanding. Donald Michie [Michie, 1986] mentions a startling illustration of this idea

> '[Fig 2.2] shows the result of asking a 3½ year old girl to copy a square. Her first attempt is on the left. Her second reproduced on the right, departs wildly from the

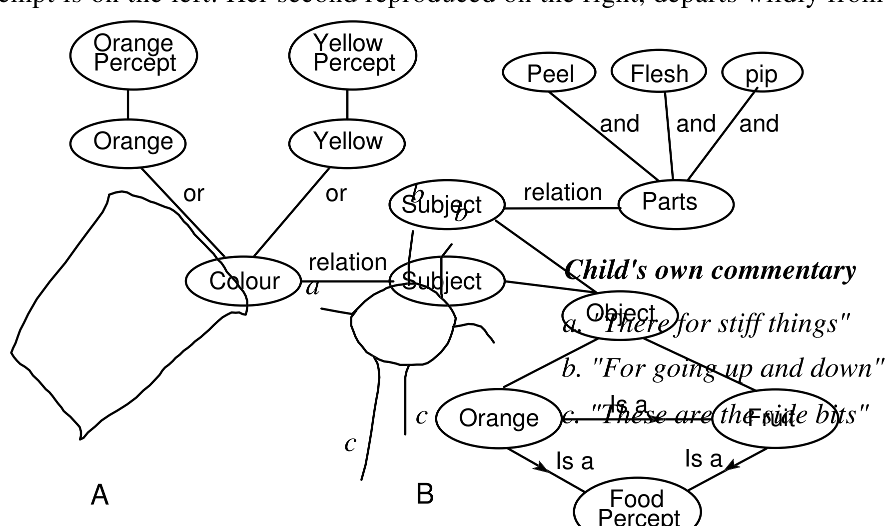

Fig. 2.2 Drawing of Square by a 3½ year old. From [Michie, 1986].
Fig 2.1 A Network of Percepts related to an Orange

> first, and from anything that the ordinary onlooker might have expected her to do. The child explained that her descriptions indicated the corners, uprights and horizontals of the square respectively The phenomenon reveals the normally hidden operation of a particular way of compactly encoding percepts of external reality.'

Marvin Minsky, an Artificial Intelligence specialist at MIT, uses the word *frame* for what appears to be the same idea described by *percept*. He uses frames as a basis for understanding visual perception, mainly for natural language dialogues.

> 'When one encounters a new situation (or makes a substantial change in one's view of the present problem), one selects from memory a structure called a *frame*. This is a remembered framework to be adapted to fit reality by changing details as necessary.' [Minsky, 1981].

According to this theory, frames are formed in the brain with default assignments, the details of which may not be warranted by a particular situation but are useful generalisations sometimes by-passing 'logic'. Defaults are easily displaced by new items that fit better. So a hierarchy of frames is formed that becomes more stable with increasing experience, with interconnections that form a kind of relational database. This view appears to reinforce the idea that it may be possible to capture these percepts or frames in a knowledge base that can be used in forming a design support system that is independent of the user. Minsky's idea of frames (introduced in 1975) as a basis for Artificial Intelligence was very popular in the '70s and early '80s where, by analogy, a 'frame' was defined as a cluster of procedures and data referring to the same topic that could be moved around as one piece. [See discussion in Ritchie & Thompson, 1984]. Using that idea a number of attempts were made at 'frame languages' for natural language parsing, even the word 'percept' being used in [Sobolewski, 1988]. In the latter it is argued that functions and relationships do not exist; rather only attributes and values, as atomic conceptual primitives, and attribute paths (slots) that have the value of the most recent value. Percepts here are built up from the set of slots. The attempts have had mixed success.

We are still faced with several problems. Given a new situation, how do we locate a percept to represent it? Second, what is the content of that percept? Does there have to be a set of percepts that is common to everyone? Minsky *[ibid.]* says, 'We cannot begin any complete theory outside the context of some proposed global scheme for the organisation of knowledge in general'. But we have already seen that global schemes tend to be will-o'-the-wisp. If content is common to all humans then sharing, mimicking, learning are terms that relate only to acquiring that common experience. No, ‘content’ is peculiar to each person. Although there are shared experiences it is likely that those common experiences are linked to different percepts in different people. It may be possible to generate artificial percepts perhaps, with common factors that to some extent can be formalised. For example many experiences are so common that they are rarely explicitly referred to; hence the famous conundrum ‘Does a falling tree make a noise if there is no-one to hear it?’, or the assumption that the hidden side of a cube is actually there and of an expected shape. Those assumed percepts could become micro-universes that have an agreed content. Even so that cannot mean that such percepts could be normative. World views do not remain unchanged in the light of increasing knowledge: compare the world views of Archimedes and Galileo, Newton and Einstein!

Content still outstrips symbol. If we could define a percept, its content would be impossible to limit. That is why ‘natural language’ is so often used in defining symbols. Readers of the symbol can interpret it with their own percepts. Symbols may be deliberately labelled in a system so that ‘content’ is appealed to that is not explicit in the system. Realism is implied, but is actually user defined. To refer back to the previous example, PLANE_{17} is a symbol in a system. It could easily be labelled ZIBKRLG_{17} and still do the same job, but without the same content implied by the word PLANE. In expert systems real-world vocabulary is commonly used although the system does not assign any ‘meaning’, merely the ability to access it according to some database management system. The advice ‘Sell your shirt to buy this computer”, from an expert system for assessing computer systems, is simply an output pre-programmed to occur with certain input values. It could equally be programmed as “The probability of uptake for this computer is 0.95.”, the result of a probability calculation from the same input values. Neither really expresses the real-world situation, where the expert might perhaps ask questions that depend as much on the customer’s personality as the specified requirement, using assumed experiences of the client to guide the level of questioning. Again, agents and processing cannot be ignored.

2.3 Design and Observation

The content of an event or situation is an interpretation in the universe according to personal experience. In that sense significance is not innate - it is in the mind of the beholder. Minsky suggests the following process for dealing with new situations in terms of frames (with my numbering).

1. EXPECTATION: How to select an initial frame to meet some given conditions.
2. ELABORATION: How to select and assign subframes to represent additional details.
3. ALTERATION: How to find a frame to replace one that does not fit well enough.
4. NOVELTY: What to do if no acceptable frame can be found. Can we modify an old frame or must we build a new one?
5. LEARNING: What frames should be stored, or modified, as result of the experience? [Minsky, 1981, *op cit*.]

What is interesting is the kind of ordering process that is going on: very akin to the design process. Replace the word *frame* with *design* and the connection is apparent. Contrast that with a General Design Theory suggested by Tomiyama & Yoshikawa, and developed in [Veerkamp, 1993]. Their basic idea is given as follows. From the given functional specifications a candidate for the design solution is selected (*cf.* Minsky, step 1) and refined in a stepwise manner until a complete solution is obtained. (2 & 3) The process is evolutionary, transferring the design object from one state to another to give a more detailed description. (3 & 4) To evaluate the state of the design various interpretations need to be derived to see if specifications are met. (Step 5).

Comparing some of the presentations at a 1988 Design Theory Workshop conducted by Sandra Newsome, Spillers and Susan Finger, further formalisations appear. Spillers and Newsome point out that conceptual design contains a cognitive, heuristic component. On that basis many theories can be developed around the design of products, but they claim that what is needed is a kind of principle that would apply to all design theories. That 'meta-theory' about design has as its starting points

- a high level of ambiguity
- a partially ordered structure of ideas.

A partial ordering lists ideas with links that are hierarchical. Operations over a partial ordering are therefore those of a hierarchical tree structure, with weights to indicate relative importance. Typical operations are simple search: to calculate the role or effect of special components by examination of the linking elements of the tree structure; imposing a structure; and representation of the system by partially ordered subsets [Spillers & Newsome, 1989]

Orderings of that nature, whether regarded as frame or design, are pattern seeking and abstraction of important identifying entities that may in turn be decomposed into other entities. Those orderings will be based on factors that are part of a person's 'content' for the particular entities. What is more they must be based upon observation of the real world, since content is highly dependent upon observation. The question of which observations is perhaps the crux of the design-designer problem. We have already seen that the number of possible observations is infinite and so content is infinitely variable. We have also seen that there are sets of observations that change very rarely (hence learned) or not at all (hence instinctive). Those settled observations are clearly the most easy to put into formal representations. Even so there remains the possibility that the representation may limit the implied content and so stultify creativity. What is required is that symbol and content be linked more directly by the user so that language and modelling are not treated differently.

One way that designers can get out of the difficulties of opinion and ambiguity is to make a physical prototype of the product. In [Pugh & Morley, 1988] the following conversation with an R&D director is recorded about the kinds of models used.

> 'Director So we would then make a feasibility, and what we mean there is that we've identified the broad product concept and approach. But now we've got to see in technical terms. Can it achieve cost objectives and time objectives, and can it meet marketing and performance requirements? For example, if we want the product to operate in a particular way, can the technology achieve it? So there must be compatibility in achieving the requirements.
>
> Interviewer: You do more engineering there?
>
> Director Yes, there's engineering at this stage. For example, the type of feasibility items that came out of this is some very crude model .. nothing necessarily to do with our business - it's simply got the right technology in it. We pull out modules and start writing software and doing some tests
>
> Interviewer: It's literally a bit of kit lashed together?
>
> Director Sometimes yes; the aim is to quickly demonstrate functional possibility in areas of high risk. We also prepare industrial design models - because we have to sell.
>
> Interviewer So the bread-boards, lego models, prototypes, whatever you're doing here - you're learning from it to refine the spec.?
>
> Director Yes.

Here the reason that the models are physical rather than computer based is clear, especially with the point about industrial design models. The latter points directly to the different set of understandings that a customer has compared with the designer; but both can inspect a model. Both can, to quote the fictional schoolboy, Billy Bunter's famous phrase, "jab a fat thumb into the works". That is because both share the same reality despite differing perceptions. That would be much more difficult with a computer model for the reasons already discussed.
The conclusion is that the design process is best served in the same way as the original perception or cognitive process is, by the designer having direct contact with the real world, being able to make observations experimentally. That way the 'content' or significance is made immediately relevant to the observer.

2.4 Models and Prototypes

'Experiments' in conceptual design may be thought of as the tests made by designers on possible solutions that they have constructed on the basis of experience, using the initial specification. But experiment may have a deeper sense: the casting around for the idea itself can be thought of as experiments on alternative realities. That spinning out of ideas has a similar motivation to that at Minsky's 'Expectation' stage of perception: trying to match the specification with a possible reality. In that respect the ability to try out things is important. As the new reality - the new design - begins to take shape then aspects of the problem become apparent. This is the process of partial ordering and breaking up of the problem into smaller entities. At that stage modelling becomes useful.

Modelling a problem is not normally an attempt to replicate the design - rather it is to simplify aspects of it for closer examination. Consider the following definition of 'model'.

> "**Model** *[n]* **1.** A representation, usually on a smaller scale, of a device, structure, etc.; **2.** A representative form, style, or pattern."
> *(Collins Concise English Dictionary)*

While *representation* has the connotation of equivalence, it could alternatively suggest some selectivity. A model may have salient features that symbolise the represented design while other features of the model may be irrelevant or even misleading. (Materials used in a physical model are often highly inappropriate to what is modelled, chosen more for ease and speed of manufacture.) 'Smaller scale' may mean smaller in scope or content rather than size. The reduction in scope could be quite drastic, as in a mathematical model. In that case the model is at the extreme end of the modelling spectrum having virtually nothing innate in the symbolism other than a mapping of perceived relationships. Such symbolic models are deceptive as one can confound the model for the thing itself, or else think the model is actually better than reality. The latter is akin to the Platonic idea of Forms.

> "We distinguish between the many particular things that we call beautiful or good, and absolute beauty and goodness. Similarly with all other collections of things, we say there is corresponding to each set a single, unique Form that we call an "absolute" reality. .. And we say that the particular are objects of sight but not of intelligence, while the Forms are the objects of intelligence but not of sight." [Plato, *Republic,* VII,6]

That idea can lead us into real difficulty if we think of the model as somehow representing the Form rather than the substance. For example, mathematics itself has been regarded as a fundamental Form. Platonists have opined that mathematics is *discovered*, not invented. Galileo declared "The book of Nature is written in mathematical language". In that case which is the *real* "reality"? An abstraction of a *triangle* models but one aspect of three sticks fixed together at their ends, but we can think of the three sticks as a not only a representation of the abstraction but with an infinite other 'content'.

These are the hard questions of artificial intelligence, a major source of ideas for implementing designer support systems. Bound up with modelling in AI is the idea that 'modelling by Turing machines can be taken to be "free" in that the model of X is interchangeable with X itself' [Smith, *op cit.*]. That agrees with the Platonist but rather goes against all we have discussed up to now. If we accept the Platonist view we get stuck with a Universal Turing machine as a model of the universe itself, a suggestion refuted by the self-reference argument already rehearsed. Despite the philosophical problems of parallel universes and alternative realities the 'safest' approach is to take the universe as it appears and to make observations as near first-hand as possible. We have seen earlier that that is the conclusion taken as obvious by those nearest the problems of design.

The kind of reality one can have seems to be in the mind of the designer when sketching out ideas. One only has to watch a designer sketch a line, pause, delete the line and then redraw the line in the same place to realise a pattern of thought has occurred that says *this* line is quite different from *that* line and a whole 'content' is implicit in that one line. The line represents the *intention* of the designer. The thought is well explained by Takala.

> "In philosophical terms, the implicit requirements [of a design] are called *intensional* descriptions of the product, whereas explicit models of the product are *extensional.* Designing proceeds in two opposite directions: *top-down*, starting from implicit functional descriptions and synthesising an explicit model, and *bottom-up*, analysing and combining explicit realisations and trying to find useful implicit properties in them" [Takala, 1989] .

The ability to record or model intensional ideas is essential if we wish to construct support systems that help designers to design the way that they actually design. For despite many attempts to codify design methods the process is still implicit, cognitive and abstract; it is still perhaps best described by the design folio: a logbook of ideas, sketches, half thought out concepts, back of envelope calculations that follows the designer's progress towards solutions. That folio tends to reflect a 'three steps forward, two steps back' movement rather any kind of block diagram stages of progress beloved of text-book authors of design.

A considerable number of approaches have been tried to deal with intensional ideas. The simplest is not to attempt to record them, but to leave them entirely with the designer. As indicated earlier, the 2D draughting system is a suitable tool to do that and its continued popularity is witness to the success of that approach. Constraint based methods go to the opposite extreme, being pursued to give fully logical synthesis of the intention. [*e.g.* Chan & Paulson, 1987, El Dahshan & Barthes, 1989]. Although numeric *constraint solvers* are well suited to problems amenable to analytic formulations, they severely limit human intervention and often prove to be unnecessarily global. In an effort to model such human intervention the *expert system* approach is invoked so that constraints can be written as rules. Such systems are only currently able to cope with fully constrained problems and both approaches are computationally expensive. The latter two approaches can sometimes by found as tools within bigger packages. (*e.g.* Pro-Engineer)

Another approach is to encourage the designer to record what intentions are around a given line or geometrical object. This was in part the idea behind Object-Oriented Programming - recording the purpose as well as the geometry of parts. The computer model is built up from the descriptions given by the user, forming objects with 'meaning' in the real world that have real-world connections. The difficulties in principle of doing that are apparent from our discussion. Practical difficulties will be discussed in the next chapter. What is important here is the idea of modelling real life relationships explicitly when such models are intended to convey implicit or intensional ideas.

Finally we consider how intensional ideas are conveyed by the building of a physical prototype. With a physical realisation the experimental approach implicit in the sketched ideas can be extended by allowing observations to be made and experiments performed. A physical prototype is more than just a replica of the designer's thoughts; it embodies reality and so carries more 'content' than the idea. It is that which gives the prototype its superiority over other modelling methods. Properties of the prototype remain to be discovered. Also amendments and additions can be made to the prototype using features not in the original specification. (The industrial designer's ideas of colour are difficult to conceptualise, but a prototype in a different environment might suggest a very different colour. Successive bridges on the M6 motorway were painted in different colours because the wife of the architect suggested it would reduce boredom of motorists, a factor quite remote from the function or form of the bridge in its own locale.)

2.5 Concurrent Design

Many tasks in design overlap or can be done concurrently. This was well understood in the West at one time but forgotten: probably due to the high degree of specialisation and differentiation in job functions. In recent times the automating of certain separate functions gave rise to 'islands of automation' that were difficult to connect together let alone permit concurrency.

The Japanese never had that particular problem since they were used to multi-disciplinary teams with very high levels of communication. The difficulties of that communication are identified by Daniel Whitney in his seminar on Japanese methodologies.

> 'Success at product-process integration requires identifying just what information the downstream process designers will need from the upstream product designers, and vice-versa. In the absence of a structure for this data exchange, integration degrades into arguments and confusion.
>
> The research community has barely recognised this issue, Potential approaches include information analysis of design processes, cost structure analysis of fabrication and assembly and modularization methods for products' [Whitney, 1992]

[Wilson & Greaves, 1989] discussed very much the same issues on a broader front, coining the phrase 'Forward Engineering' for the activity based upon early manufacturing involvement, the management of technological uncertainty, quality function deployment, design for manufacture, and assembly and process control. Forward Engineering demands cross-functional teams representing these specialisms as well as conventional engineering design. On that model many core people participate in the early stages of product design

Technical developments in CAD have reinforced the demand for wider participation. At one time, comprehension of technical drawings was a prerequisite for appreciating an engineering design. Even after the draughting process was automated, the interpretation of computer-aided drawings remained a task for the specialist. Only in recent years, when sophisticated computing resources for graphics have become more widely available and more powerful techniques for visualisation have been developed, has it become feasible to animate a design realistically at a very early stage. As a result, more people are now able to appreciate a designer's proposal; marketing mangers, visual designers, service personnel, accountants - even conservators - all wish to interact with the design and express their view of the product requirement. [Cartwright & Beynon, 1992].

The focus of concurrent engineering is on a pattern of interaction that is more complex than that of a single designer. Design activity corresponds to passing a consultative document around between human agents. In that context design activity passes through phases that are product-oriented: specifications and schemes are hard-copy outputs that become inputs for the next phase. Evaluation goes on at all phases of design often being iterative. Evaluation criteria must be available on the basis of incomplete designs and possibly also on incomplete data. It is essential therefore that the roles of the different agents are circumscribed so as to avoid the 'arguments and confusion' Whitney observed.

Given the incompleteness of partial designs it is essential that constraints on a design are seen as provisional. For the engineering designer the space in which the solution to a particular design problem is normally limited by functional constraints. The designer team will want a host of other constraints: cost, quality, manufacturing feasibility, appearance, etc. One way of enabling progress on all these fronts is first to identify areas of the design that are exclusive to each expert and then the areas of overlap and interfaces to other areas. Normally the expertise of the design manager will cope with that: the whole purpose of team briefings is to delineate those areas. But if we try to automate the procedure what may happen is the simultaneous developments of different models of the same product, with all the dangers that brings! A sketched design becomes the solid modelled shape that is tested for stressing at the same time as it is being knocked into a better aesthetic shape and the manufacturer is trying to put in draught angles for casting. That done as a sequence is bad enough but if a series of slightly different designs emerges from concurrent actions there is a recipe for discord. It is then easy to see that a single prototype lends itself better to group design. Something of that is possible using communications on computer systems, but then constraint management has to be built in. The idea of experiment even for constraints is then worth considering. Constraints would become things to be tested, modified or over-ridden rather than being written in stone as the easy way to control interaction. So all constraints would need to be explicitly justifiable, whilst preventing the non-expert from making unsuitable changes to areas that are central to another's area.

The main idea of experimental constraints is that different agents acting on a design can feel at liberty to try out 'what-if?' scenarios, knowing the na ture of the monitor placed on the constraint. A design support system based on that idea would mean the model being tested would be the same for all agents and the agent clashes would emerge in the setting up of appropriately actioned monitors.

In our argument for experiment in design we conclude the following.

1. *The designer is an integral part of the design*
2. *Content depends on the designer not the model*
3. *Content is filtered through percepts that help to organise the world into hierarchies, but these percepts are different for each individual.*
4. *Observation and experiment are fundamental to our organisation of the universe, even to reference itself*
5. *Models cannot stand in place of reality, although some standard frames can be codified for bottom up design*
6. *Supporting intent is best done nearest to reality - physical prototypes invite experiment*

7. *Concurrent engineering requires good communication between independent agents. It is best done where different agents have access to the same model.*