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Host: Prof Dave Ullman, Mechanical Engineering Department

Background

Prof Ullman is teacher of mechanical design, a researcher in design methodologies, and a successful practicing designer. Several of his designs have been commercialized. His book [Ullman 1992] is a best-seller. His view of design, appropriately for his background, is an intensely personal one that focused until recently on the individual designer and the detailed thought processes that are brought to bear by a designer, especially during the most creative parts of the design process. Current work includes study of design teams. In his view, we need to understand the cognitive challenges faced by designers before we can develop really useful design tools. Current CAD is very far from being useful by these standards. Similarly, if one is to design better knowledge-support tools for designers, one needs to know better how designers think, organize their own knowledge, and search for ideas.

This emphasis should be contrasted with other approaches to design theory and methodology (DTM) which conceive of design as an activity engaged in by large groups of people working on a large and complex thing such as a ship or airplane. See for example my report on the U S Navy's design approach to warships [Whitney 1994].) In [Whitney 1990] I described these two views as

• *design in the small*: an individual creative process to be enhanced

• *design in the large*: a group process to be managed

Each of these views has its place, is relevant to its own phases of the design process, and applies to its own type of design activity. In order to place Ullman's research in perspective, some background information is needed which distinguishes three classes of design.

Three Classes of Design

Three kinds of design may be identified:

• <u>Concept</u> design of new products

• <u>Product improvement</u> and detailed design of both new and improved products

• <u>Reconfiguration</u> of existing products

New products are the most challenging because totally new technologies or scientific principles are often required. Examples include compact disks, room temperature IR sensors, new generations of semiconductor memories, and cellular telephones. Substitution of a revolutionary material in an otherwise traditional product also belongs in this category: use of composites in aircraft is an important example. A third type of new design comprises innovative combinations of materials, actuators, and geometry in order to provide a new kind of behavior or fill a previously unrecognized need. An example is a folding bicycle that can be manufactured to order to fit the buyers' measurements.

Design of such things is difficult because there may be only weak phenomenological models of the physical effects involved; perhaps only experimental knowledge is available. Processes for manufacturing the new item in quantity likely do not exist and must be created along with the product's function itself. There are probably no tested design principles or configurations of the product to rely upon. Early in the design process of such an item it is more important to get working models than it is to get them in large quantities or at low cost. The creative skills of individual designers are most important in this kind of design.

Product improvement is the next most challenging. It involves subjecting an existing product or technology to major rearrangement or subtle refinement. Examples are design of a new model car, improvement of three speed automatic transmissions to four or six speed, or of two valve-per-cylinder engines to four valves per cylinder. In these cases, the basic technology exists as well as engineering models for it. Also available are some tested design principles which can be varied systematically to arrive at the new configuration. Three, four, and six speed transmissions all have planetary gears and clutches, but they are interconnected differently. Product improvement applies to relatively mature products where competition is based on quality, customer features, cost, and rapid introduction of improved models rather than on novelty. For such items, cost and schedule play a large role in the design process, and manufacturers seek tools, algorithms, information, organizational techniques and production methods to support the effort. In this kind of design it is more important to manage the efforts of many designers. However, this emphasis tends to create essentially the same design over and over with little innovation. When radical change occurs, it is often the product of an individual.

Routine reconfiguration of existing products is the least technically challenging. The design of such items is essentially repetitive and occurs without innovation in response to customers' orders. Examples include heat exchangers, compressors, turbines, power plants, and other items, often in the capital goods industries. The basic technology is the same and the design methods are so thoroughly understood that they are said to be parameterized.

Specify the working fluid and amount of heat to be transferred, and one can design a single stage counterflow heat exchanger on a PC in a few seconds as a calculated variant of a stock design. A few keystrokes and out come the drawings and NC tapes; in a well run company, the finished unit will be on the shipping dock in 24 hours after the customer calls.

General Electric Co. calls this "purchase order engineering," and estimates that 85% of its design work really falls into this class. Many companies, among them General Motors and Boeing, have made use of software called ICAD to capture these routine processes.[1] ICAD supports graphics and rule processing, although classical rule chaining as used in expert systems is not available at the present time. A surprising amount of effort is needed to compile and rationalize the rules governing the design of seemingly simple things, but many companies are shocked at how much of their "design" effort is in fact in this category. "Designers" are really being used as clerks, indicating both a misunderstanding of the design process and a misuse of human talent.

New product creation poses severe challenges because there is so much risk and so much that is new and untested. Since the product is so new, it may be that there are no existing manufacturing processes. One cannot afford to develop a new concept without very rapid confirmation that a production and assembly process can be created as well. Yet it is very often the case that the product engineers must struggle so hard to get any working concept at all that they ignore the production issues. This has caused very serious consequences in the past. While it may be argued that inserting production issues early in this kind of design can only disrupt an already delicate process, there are formal studies [Iansiti] as well as lots of anecdotal evidence that it is especially dangerous to ignore processes in this situation. To do so often results in a basic concept that cannot be brought to production at all, requiring extensive and lengthy redefinition of the concept.

In the case of product improvement, the design process is likely to be more formalized because generic elements of it are repeated. Yet each improvement in the product not only can greatly rearrange the production processes but it offers the chance to improve them as well. The design process comprises exploration of a complex design space of well-recognized coupled product and process variables. Both generic and product-specific knowledge can be organized for this effort. Cost, schedule, quality, and yield are the major issues, and computer methods exist for attacking them. Examples include the Taguchi method, linear and integer programming, and simulation. The designers benefit greatly from getting early visibility into the effects of the many possible choices thay could make. Major research

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[1] Significantly, ICAD ws founded by a group of engineers after they wrote special software to support design of heat exchangers.

challenges here include improving engineering models of phenomena, understanding how to represent designs in computers consistently for all the different product and process designers, how to take account of variation in materials, processes and users, and how to convert the subjective needs of users into engineering specifications. Major organizational challenges exist as well, including defining the design methodology and providing design tools that provide technical support at specific points in the design process.

In the third type of design, the effort focuses on accessing the historically built-up parametrics and performing the repeated verified process steps quickly. These often are derived directly from laws, building codes, and tabular information. Missing in this class of design is the emphasis on exploration that dominates the second and invention which dominates the first. Here the issue is to coordinate databases, codes and regulations, records of past designs, customer specifications, price and bid information, vendor performance data, and so on. The methods of computer science are especially relevant here, whereas the methods of engineering characterize the second and those of science the first.

An important element missing in routine reconfiguration that often dominates new product design or reconfiguration is the element of conflict. Design is inherently about conflict: identifying and resolving conflicts over cost vs performance, efficiency vs flexibility, variety vs standardization, and so on. In new product design, one of the greatest risks is overlooking a basic conflict lurking within the interlocking constraints of an unexplored design space. Finding and quantifying these conflicts occupies much of the designers' time.

The same is true in reconfiguration design except that the same conflicts tend to recur. For example, several "real estate" problems can be depended on to occur in car design, of which the most difficult is allocation of space along the drive train line in a front wheel drive car. The styling department wants a sleek design, the marketing department wants a zippy power train, and the engine/transmission/suspension designers find they cannot fit the necessary elements into the available space. Successful companies recognize these recurring conflicts and provide institutional ways of addressing them. (See the reports on Nissan and Toyota.)

In reconfiguration design, the typical response to conflict is to "no-bid" the job: if the customer wants something outside the catalog, the answer is simply "No."

Based on the above distinction, Ullman's research can be said to concentrate on design in the small of new products.

Cognitive Issues in Individual Design

[Stauffer and Ullman] presents a theory of how engineers think while designing, based on the cognitive models of Newell and Simon. These models represent human thinking as a form of information processing which is reminiscent of the way computers operate. The model hypothesizes an external task environment, namely the design task itself plus external sources of knowledge, and an internal task environment inside the designer's head. The internal environment comprises an information processor containing short term memory, a controller, and a variety of mental operators. The processor interacts with the external task environment as well as with a store of knowledge in long term memory.

The design activity consists of a search whose goal is to convert a design problem into a solution. The steps in this search are actions in which the operators are applied, using short term memory, long term memory, and external information, to convert the design from one "state" to another.

To flesh out this model, Ullman and his colleagues have conducted a number of protocol analyses in which actual designers (some novices and some experienced) are videotaped while doing a design problem. The tapes are analyzed in detail and common elements are extracted. From these analyses, Ullman identified three main kinds of information: strategies, proposals, and constraints. The designer uses strategies to create proposals in response to issues identified in the design process, and uses constraints to limit the range of possible solutions. (Constraints consist of any information that act to limit or define a proposal.) This model is similar to one developed at MCC called IBIS, illustrated in Figure 1. [Yakemovic and Conklin] The IBIS model has proven useful to design teams as they try to keep records of their deliberations.

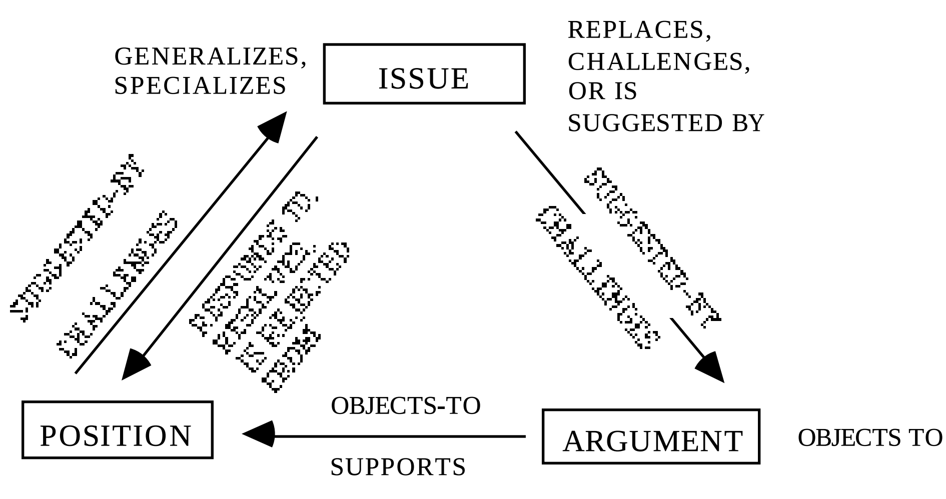

Figure 1. The IBIS Data Element Network. Issues, arguments, and postions interact in this model of decision processes. Issues must be resolved; positions or proposals are made in an effort to do so; arguments support or refute the proposals. Arguments can be used to support or refute arguments,

while issues can give rise to larger (generalized) or smaller (specialized) issues that must then be resolved as well.

Ullman has modified the IBIS model based on these experiments into the form shown in Figure 2.

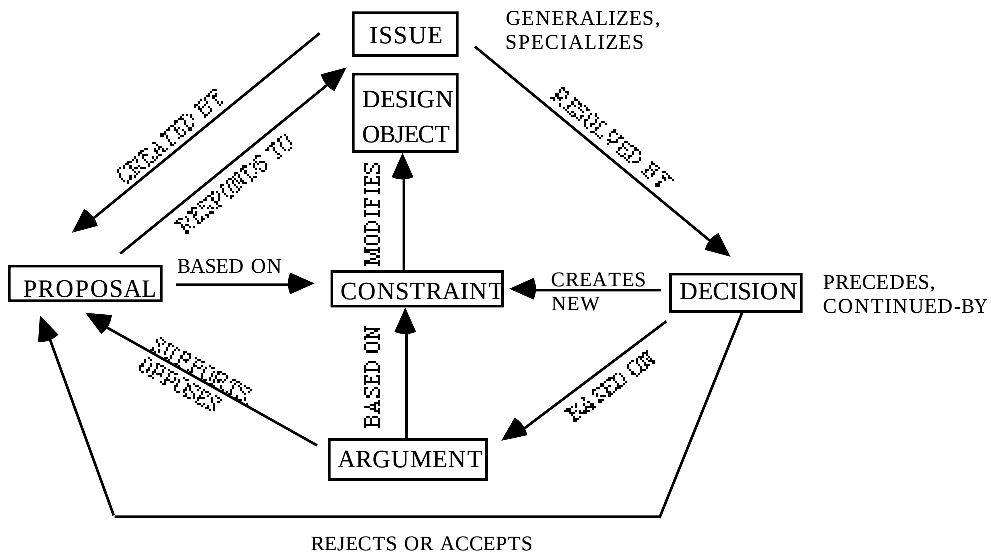

Figure 2. Data Element Nework for Capturing Design Activity

Ullman has found from protocol studies that designers appear to use three kinds of operators: generate, evaluate, and decide. These are combined via the strategies into four approaches for identifying and resolving design issues: Generate and test, Generate and Improve, Means-end analysis, and Deductive thinking. These approaches are also found in various artificial intelligence approaches to computerized problem solving. In each case, the strategy will involve the designer identifying an issue (say, choosing the material for a part), then generating a series of proposals, applying various constraints to them, evaluating the result, and continuing until the issue is resolved. New issues are usually generated along the way representing either subproblems to be solved first, or recognition of larger problems that are put on an agenda to be dealt with later. In fact, Ullman found that 75% of the constraints used by the designers in one set of experiments were derived during the process rather than being imposed from the outside as part of the design specification.

Stauffer and Ullman argue that designers' behavior as evoked in their experiments should be used to guide the creation of computerized design aids. They summarize their findings as follows:

• designers seem to repeat the same thinking activities using the same cognitive tool set

• they tend to work over a given proposal rather than generating a range of proposals (this tendency has been observed by other researchers as well as managers in industry)

• issues are resolved primarily by applying internal knowledge rather than by systematic searches or a global procedure

On this basis they conclude that intelligent CAD tools should conform to and support these modes of design. One could argue the case the other way, of course, noting that better designs might emerge if more alternate proposals were generated first, providing a richer array to evaluate. Additionally, one might challenge the CAD and research communities to come up with methods that would make generation of proposals easier, support systematic searches, and reduce the dependence on individual knowledge. Individual designers could be helped to produce designs that adhered better to standards of various kinds, or their hunches could be explored systematically.

Ullman's way of representing the thinking process of an individual designer can be contrasted with the Design Structure Matrix (DSM) method of representing interactions between designers in a large project. [Eppinger, et al] In this technique, designers are asked how they fit into a large project by describing the information they receive and from whom, plus the information they generate and for whom. In addition, they describe their design tasks. The results are plotted as a matrix like that shown in Figure 3. The DSM provides a convenient way to map the information flows but it does not detail the thought processes of individual designers or the group as a whole.

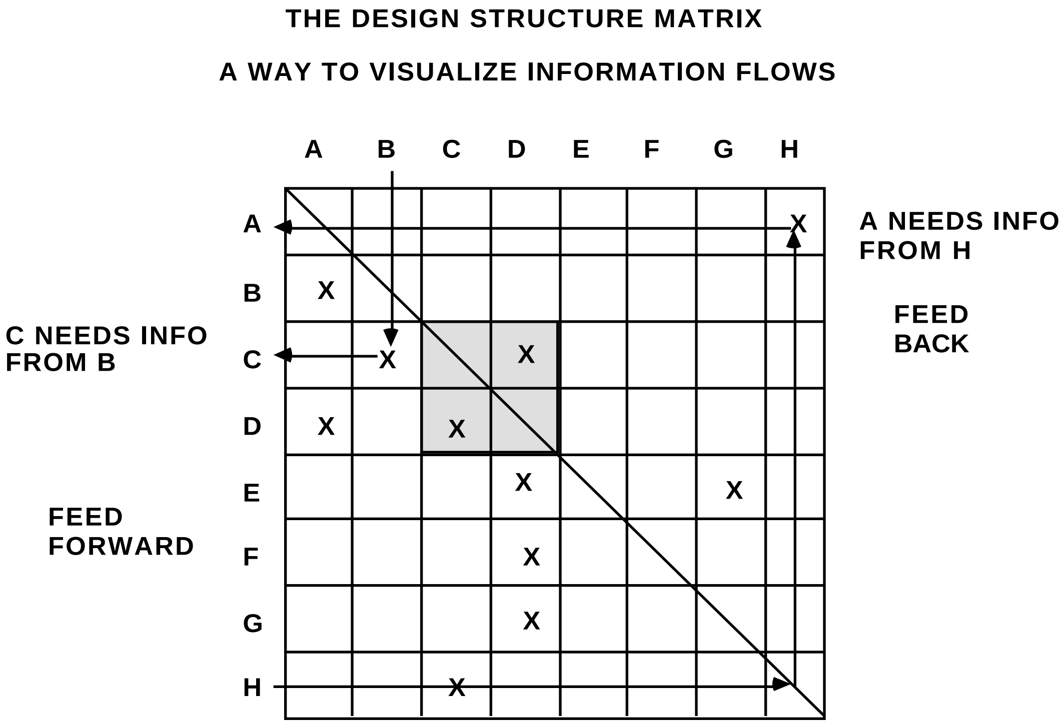

Figure 3. The Design Structure Matrix. The tasks (A - H) in a complex design process are listed horizontally and vertically. The Xs represent the fact that one task feeds information to another. Such information may represent constraints, analysis results, material choices, dimensions and tolerances, test results, and so on.

The DSM represents a rather high level way of capturing the interactions of large groups of designers. The IBIS model as modified works to capture what individual designers do. The DSM appears to Ullman to be too gross in the detail it captures while his version of IBIS appears too fine. Other researchers have attempted to capture in detail what designers do. Lukas Reuker, a student of Warren Seering at MIT, has selected a number of existing information modeling schema from the literature and tried to use each one in turn to represent one decision made by an experienced designer, another professor at MIT. In this case the item being designed was the foundation of a robot. Each of the information modeling schema chosen comprised a standard format in which decisions were modeled according to a required set of data and their interactions. Reuker first interviewed the designer extensively and then attempted to represent what he found in each of these schema. He found first that the information, when represented as completely as the designer was willing to elaborate, could not be captured in less that about 27 square feet of paper on which the writing was rather small. (Often the interview would dead-end when the designer merely said, "That's the way it is," or some such indefinite reason. In Ullman's terms, the designer had reached a boundary or memory limit within his own internal knowledge at which he could no longer produce another reason, source, or authority.)

Each of Reuker's attempts to display the results within the format of a schema resulted in one or both of the following:

1) the schema demanded kinds of information, justification, or logical flow that was irrelevant to the decision being represented; demanding the missing elements from the designer would have been counter-productive

2) the decision process contained steps or methods that could not be represented concisely with the given schema; this could mean that not every step in the designer's reasoning was in fact rational

As detailed as Reuker's original data were, they were not detailed enough for most of the schema. His conclusion at this point in his research is that such detailed studies produce a lot of detail, probably too much, and that the schema are unsuited to representing designers' reasoning.

Up to now no attempt has been made to link models of individual designers with the information flows captured by the DSM. That is, no attempt has been made to link design in the small with design in the large. This remains an interesting and important challenge.

Recent Research by Ullman

Ullman has recently tried to bridge this gap by adding entities to his models, by being more specific about what aspects of the object itself needed to be included in the model in addition to the processes engaged in by the designer. [Ullman 1993] This approach seeks to capture three kinds of information: objects being designed, relationships between objects, and the operating steps of the thing being designed (roughly speaking the performance specifications).

Objects include the thing being designed and its immediate surroundings. If people are involved in the thing's operation, then people are additional objects. These objects have physical properties, including geometric shape. Early in the design process the objects are indistinct, and they get additional detail as the process advances. Additional information about the object is also considerd to be an object or objects, such as energy states, material conditions, and changing relationships with other objects.

Relationships describe interfaces of all kinds between objects, such as assembly, energy exchange, relative motion, and logical relationships. These relationships may change as the designed object operates in either normal or abnormal activities (failures, for example).

Operating steps represent discrete or continuously varying states that the designed thing can occupy in the course of normal or abnormal operation.

These steps represent changing relationships among the objects, such as open, closed, locked, broken, and so on.

Among other ways of representing physical systems, Bond Graphs [Paynter] come to mind. But Bond Graphs capture only the energy exchange relationships between objects, says Ullman, and this is too limited to represent all the complexities of a design problem.

In these terms, the process of designing something consists of iteratively defining and decomposing objects, their relationships, and their operating states starting from a broad goal statement and ending up with a complete geometric description. The process by which this evolution takes place lacks the structure that is assumed by researchers such as Pahl and Beitz, who assume that a fairly structured process can be followed. [Pahl and Beitz]

Pahl and Beitz recommend a process by which functions are defined first, then implementations are suggested, and finally geometric instances of hese implementations are created. This method seems to work in cases that follow the pattern of reconfiguration design as defined above. It also appears to be suited to designs which are made up at some level of fairly standard elements such as pumps, gearboxes, and other familiar elements. The design process often consists of resizing these elements and determining how to interconnect them. It is a sort of building-block method and in some ways is similar to the way VLSI items are designed.

Many mechanical design researchers have reached another conclusion, including Ullman. These researchers are interested in more integrated designs whch are made up of innovative geometry rather than innovative assemblages of familiar geometries. In such cases, Ullman says that "the form and function of a device evolve concurrently" and no strict sequence of function first, then geometry can succeed. This is often the case when the design is required to meet stringent conditions on weight, volume, or energy consumption.

Concluding Remarks

Ullman's research method consists of observing designers and seeking to generalize from what they do to obtain both models of designers' cognitive processes as well as specifications for design tools that aid design. Such aids include methods for capturing the sequence of decisions by which a design was arrived at so that an accessible history can be captured for use by later designers. Other methods include tools that are aimed directly at helping designers execute these thinking processes.

An interesting alternate approach called TRIZ was developed in Russia over the last 40 years. Its developer did not observe designers but instead examined the Soviet patent literature over a century, observing how the same basic idea evolved in successive patents by the same or even different inventors. From this information, he developed a "systematic procedure" for coming up with inventions, which in many cases comprise innovative designs.

While Ullman's research has identified a number of generic thought operations such as generate and test, TRIZ has identified a series of specific thought-steps that are intended to help a designer identify and focus on the core problems in the design. Each "issue" as identified in Figure 1 is called a "conflict" or "contradiction" in the TRIZ method. The designer's job is to resolve the contradiction by finding a resolution through application of opposites.[2]

The contradiction is first stated physically ("material melts to soon") and then abstractly. An "ideal" solution is then postulated ("material can be brought to the right place and then melting begins") and as many blockages to achieving that ideal are identified as possible. The deadlock is broken not by trying to avoid the source of contradiction but rather by attacking it head on. Some systematic conceptual blockbusters are used for this purpose, including kinematic inversion, separation in space, and separation in time. For example, kinematic inversion systematically reverses inside and outside, or stationary and moving, in order to generate new configurations or resolve conflicts. Separation in time is invoked when things undesirably happen at once. And so on. The designer still has to be innovative, but these specific guidelines are often helpful. Two Russian emigres have started a company that sells software to help apply the method.

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[2]It is interesting to note that the mode of thinking represented here is precisely that of the Marxist Dialectic. It is not surprising that this style of thinking was applied by a Soviet citizen in the 1940s. However, the results appear to have value anyway.

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