AN ABSTRACT OF THE THESIS OF

Tom A. Kuffner for the degree of Master of Science in
Mechanical Engineering presented on 1 February 1990.
Title: Mechanical Design History Content:
The Information Requests of Design Engineers

Redacted for Privacy

Abstract Approved: ______________________________
David G. Ullman

This thesis reports on research conducted to determine the information which should be included in a mechanical design history. This is part of a larger research effort aimed at developing a computer tool for storing and replaying mechanical design history information. Three question-asking protocols were conducted to determine what information should be stored in a design history. The subjects in these protocols were instructed to make modifications to existing designs in the presence of an examiner who was very familiar with the designs. The subjects were encouraged to ask the examiner questions about the designs. Analysis of the protocols focused on the questions that the subjects asked and the conjectures that the subjects formed. The questions and conjectures were classified according to a taxonomy presented in this paper. The information required to answer the questions asked and to confirm or refute the conjectures formed is information that should be included in a design history.

Mechanical Design History Content:
The Information Requests of Design Engineers

by

Tom A. Kuffner

A THESIS
submitted to
Oregon State University

In partial fulfilment of
the requirements for the
degree of
Master of Science

Completed 1 February 1990
Commencement June 1990

APPROVED:

Redacted for Privacy

David G. Ullman,
Associate Professor of Mechanical Engineering in charge of major

Redacted for Privacy

Gordon M. Reistad,
Professor and Head, Department of Mechanical Engineering

Redacted for Privacy

Dean of Graduate School

Date thesis is presented 1 February 1990

Acknowledgements

The author would like to take this opportunity to thank all those who made this research possible. Special thanks go to his advisor David G. Ullman and the other principal faculty member in the Design Process Research Group at Oregon State, Tom Dieterrich. Thanks too to the other members of his graduate council: Charles Smith, Andrzej Olas, and James Looney. The other student members of the research group who contributed include: Aihua Chen, Bruce Hwang, Steve Little, Brian McGinnis, Larry Stauffer, Juri Tikerpuu, Steven Wood, and Yukai Zhang. Thanks also to Skeeter Czimskey who puts up with an awful lot.

This research was funded by the National Science Foundation, Grant Number DMC 87-12091.

Table of Contents

Chapter 1: Introduction 1
Chapter 2: Related Work 6
Chapter 3: Model of the Design Process 13
Chapter 4: Research Methods 25
Chapter 5: Results 32
Chapter 6: Conclusions 58
Bibliography 63

Appendix A: Protocol Problems 66
Appendix B: Partial Design History 73
Glossary 92
Index 96

List of Figures

Page

Figure 1: Question and Conjecture Nature versus Topic 47

Figure 2: Validity of Conjectures by Category 48

Figure 3: Topics of Questions and Conjectures by Category 50

Figure 4: Age of Questions and Conjectures by Category 50

Figure 5: Nature of Questions and Conjectures by Category 52

Figure 6: Confirmation of Conjecture by Topic 53

Figure 7: Conjecture Validity by Topic 54

Figure 8: Validity of Conjecture by Topic 54

Figure 9: Source of Confirmation by Nature 56

Figure 10: Confirmation Source by Validity 57

List of Tables

Page

Table 1: Taxonomy of Questions and Conjectures 32

Table 2: Category of Questions and Conjectures by Subject 39

Table 3: Topic of Questions and Conjectures by Subject 41

Table 4: Topic Age of Questions and Conjectures by Subject 42

Table 5: Nature of Questions and Conjectures by Subject 43

Table 6: Confirmation of Questions and Conjectures 44

Table 7: Validity of Questions and Conjectures by Subject 45

Mechanical Design History Content:
the Information Requests of Design Engineers

Chapter 1: Introduction

Background

This thesis presents research performed at the Design Process Research Group at Oregon State University. This interdisciplinary group, formed in 1984, is dedicated to conducting research in the field of Design Theory and Methodology specifically by examining the process of mechanical engineering design.

Although mechanical engineering design has been practiced for thousands of years, the process that designers go through while performing design is not yet very well understood. A primary goal of the Design Theory and Methodology discipline is improving the understanding of the process of mechanical engineering design (Rabins 86). The two main reasons for studying the design process, besides the basic philosophical reasons, are that further understanding of the design process will both enhance design education and will enable the development of design tools.

Understanding the design process can serve to improve techniques of design education. Mechanical design ability is currently viewed by many to be an art, an intuitive skill that is difficult to teach. Design theory advances are being made in order to transform the art of mechanical engineering design to a science. Better understanding the science of design would enable the development of new methods of design education. Enhancing design education would ultimately produce better new designers and improve the skills of current designers. (Ullman 87, Ullman 88)

Another primary purpose for studying the design process is to guide the development of design tools, specifically computer tools, that will further enhance the performance of the design task. Computer tools are being developed to aid the designer throughout the design (see Chapter 2). Increased knowledge of the processes by which humans perform design is fundamental to the development of computer design aids.

With improved design methods and improved design tools should come better designed products. Such products would be designed in less time at lower non-recurring engineering costs and be better able to compete on the world market. (Bebb 89, Mostow 85)

With all this in mind, the National Science Foundation (NSF) initiated the Design Theory and Methodology Program in 1984 to foster research in design methodology. This NSF program is the result of, and has spurred, interest in the field. The research reported in this thesis was performed at Oregon State University under a grant from the NSF Design Theory and Methodology program.

Design History

This thesis presents research performed in order to find what information should be included in a complete design history. Here "Design History" is used as a medium independent term for a complete mechanical design notebook. Most practicing mechanical designers are familiar with design notebooks and others should not be unfamiliar with the concept. In the traditional sense, a design notebook is a bound notebook in which all of a mechanical engineer's work on a particular design is performed and recorded. The *ideal* design notebook contains every written or drawn artifact relating to a design, from concept through blueprint. The pages in such notebooks are permanently bound, numbered, and dated. With a clear and comprehensive design notebook, one could follow the progression of a design from the original germ of an idea through its various iterations to the final, completed design. Documentation, such as design notebooks, is held to be useful, even essential, during the initial design process (to record decisions) as well as in cases of patent law (claiming the originality of a design), liability litigation (proving the validity of a decision making process), and in subsequent design efforts. Subsequent efforts could include modification to the original design, using the original design as a model when designing a similar object, designing an adjacent component as in an assembly, or analysis of the design by management or in downstream efforts such as drafting or manufacturing (Buckley 89, Pare 63, Weber 84).

The problem with the current state of design notebooks is that very few (possibly none) are maintained to the above ideal level of completeness. Sketches are made on cocktail napkins and the backs of envelopes, groups work out ideas on chalkboards, realizations are made in the shower and on the way to work, decisions are made on the shop floor in response to unforseen conflicts or opportunities. This work seldom makes it into even the most meticulous of design notebooks. Additionally, notes that make perfect sense to the original designer when written may be unintelligible to any other person and jumbled even to the original designer months later.

Design Process Research Group at Oregon State University

A primary goal of the Design Process Research Group is the development of a complete mechanical design history tool. The ideal tool will store all of the requisite design history information in a computer knowledge base and provide for efficient retrieval. Ideally the tool will record the design history as the design process is underway and replay information as it is needed. The basic tasks in developing this tool are: 1) determine the content of the design history information stored, 2) develop a means of capturing the design history information, 3) determine an efficient manner in which to store the information, and 4) develop a method for retrieving the information.

This thesis research was performed to determine the information content required to be stored in such a design history tool, task 1, above. Development of a computer based design history browsing (or querying) tool is currently underway, developing methods for storing and retrieving design history information (see discussion of Hyperclass in Chapter 3). A related project team is working on a design history capture tool to record design histories.

The following chapter discusses a sample of related research both in the field of mechanical engineering design and in other design fields. Chapter 3 presents the model of the design process used (that of a series of decisions resulting in constraints on the features involved in the design). Chapter 3 also presents two formats used here for storing design history information. In Chapter 4 the research methods used to determine the level of information required for inclusion in a design history are discussed. In Chapter 5 the results of this research are presented. Chapter 6 concludes the thesis by summarizing some important results and indicating direction for further study. Appendices are included giving the design problems used for testing and showing one design history storage method in detail. A bibliography, a glossary, and an index are also included.

Chapter 2: Related Work

This chapter gives a brief overview of other research efforts concerned with the information contained in design histories. Discussed in turn are:

Jeff Conklin and Michael Begeman, MCC Corporation, "gIBIS: A Hypertext Tool for Exploratory Policy Discussion". This paper describes a computer tool that guides and records certain stages of design, especially group design. (Conklin 88)

Fred Lakin et al., Stanford University with NASA Ames Research Center, "The Electronic Design Notebook -- Performing Medium and Processing Medium". This is a report on the development of a prototype computer system called **vmacs**[1]. This system promises to be a flexible electronic medium for performing conceptual design while recording the design to allow subsequent processing. (Lakin 89, Sivard 89)

Stanley Letovsky, Yale University, "Cognitive Processes in Program Comprehension". This paper reports on an empirical study of the information requests and conjectures made by computer programmers while working on an unfamiliar program. (Letovsky 86)

---

[1] **vmacs** is a trademark of the performing graphics company

"gIBIS: A Hypertext Tool for Exploratory Policy Discussion"

gIBIS is a commercial system that structures and records group design deliberations (although its developers hasten to point out that it has proven to be useful in individual design situations as well). It is a software embodiment of IBIS, Issue Based Information Systems, an independently developed method for the resolution of complex design issues (Rittel 70). The IBIS method calls for the decomposition of a problem into key sub-parts called *issues* (IBIS is not limited to design problems). Each issue can have one or more proposed resolutions called *positions*. Each position may have *arguments* in support or opposition. This method promotes objective discussion of any problem. It gives structure to the presentation of all proposed solutions and to all arguments supporting or opposing the positions. This method promotes and structures discussion only; it does not directly address the resolution of conflicts nor does it provide any predetermined way to conclude the discussion. The IBIS method does not include a method to indicate which issues have been resolved or which positions have been adopted.

gIBIS is a computer tool that graphically displays IBIS discussions and allows networked users access to the gIBIS discussion blackboard. In this way, gIBIS "supports computer mediated teamwork." A major goal of the gIBIS development project was "to explore the capture of Design History: the decisions, rejected opinions, tradeoff analysis... the rationale behind the design itself."

A very complete user interface was developed for gIBIS allowing any user to browse the IBIS network and add links and nodes; color graphics are used to represent the various links and nodes. The system was tested by 33 groups at MCC and, according to its developers, proved to be useful for groups ranging in size from one to five users. Some groups used gIBIS to facilitate balanced group interaction; in other groups, one primary user led the gIBIS discussion with minimum input from other group members; and many groups consisted of a single person using gIBIS to structure and record individual design work.

gIBIS should prove to be a strong platform for performing IBIS discussions, and IBIS appears to be useful for many stages of mechanical engineering design. There are, however three significant shortcomings in the gIBIS system as it applies to mechanical engineering design: 1) IBIS may not be flexible enough to be used throughout the design, particularly in early conceptual stages of design (see discussion of **vmacs** below). 2) Graphical sketches, which are often the focus of mechanical design discussions, are not supported by the system. The graphics in gIBIS are limited to displaying the tree of the IBIS discussion. 3) While all of the design options considered are listed with arguments in favor and in opposition, the decisions are not shown. Unresolved issues are not highlighted and results are not recorded.

The gIBIS system does show promise for becoming a mechanical design history tool, but it falls short of this promise in significant ways. An IBIS system that graphically shows the options considered in making a decision, the arguments supporting and opposing each option, the resulting decision, and the effects of that decision would be a very useful design history tool.

"The Electronic Design Notebook -- Performing Medium and Processing Medium"

vmacs is a prototype electronic design notebook developed at Stanford University in conjunction with NASA Ames Research Center. This design notebook system promises to be a very fluid medium for electronically recording design work while providing capabilities for subsequent processing. The impetus for the development of **vmacs** was the hypothesis that most conceptual mechanical design is currently performed on paper and pencil, and it is translated to CAD only after substantial design decisions have been made. Paper and pencil are perceived to offer more "freedom and agility" than current state-of-the-art CAD systems. **vmacs** was developed to support conceptual design by giving designers the freedom and agility they find with pencil and paper while allowing for subsequent electronic manipulation of the images developed.

One system included in this project is the Design Rationale Inferencing System. This system was developed to infer the rationale behind design decisions and, integral to this task, to monitor the satisfaction of constraints. The motivation for this work comes in part from the belief that design decisions are important information to be included in a design history. It is conceived that the system will evaluate the constraint satisfaction in the present state of the design and compare this to the immediately previous design state. The constraints should be better satisfied in the latter case, thus the rationale behind the design change can be inferred to be the incremental satisfaction of the constraints. This portion of the project has been proven in limited empirical testing at NASA.

At this point in the development, the focus of **vmacs** has been in recording design work without impairing the user in any way. The link between **vmacs** and the Design Rationale Inferencing System is incomplete at present without a method for interpreting the sketches produced in **vmacs**. This link needs to be developed before the strength of **vmacs** is realized. Efforts toward computer recognition of rough sketches (Fang 88, and Hwang 90) will provide part of this link.

If all of a mechanical engineer's work were performed on and recorded by a computer, as **vmacs** was developed to enable, huge volumes of design history information would be retained. Ideally, an inferencing system such as that proposed could be used to structure the design history information. The developers of **vmacs**, however, do not propose a structure for design history information. Without this structure, the information stored would be very difficult to use. **vmacs**, in its current state of development, is an electronic design notebook with all of the disadvantages inherent in a paper design notebook as discussed in the previous chapter.

"Cognitive Processes in Program Comprehension"

This paper reports on an empirical study of professional computer programmers trying to understand an unfamiliar program. Six programmers were video taped as they were adding a feature to an unfamiliar computer program.

Analysis of the verbal protocols focused on the portion of the programming effort in which the subjects were understanding the existing unmodified code. Of particular interest were questions the subjects asked and conjectures the subjects formed while trying to understand the unfamiliar code. All questions were arranged into a taxonomy. The conjectures were also classified into a similar taxonomy. Questions and conjectures were each categorized according to their focus, what it is that they were focusing on. Questions were categorized as belonging to one of the following groups:

Why questions: Questions about the purpose of an action or design choice.

How questions: Questions about the way some goal of the program is accomplished.
What questions: Questions about what a variable is or what a subroutine does.
Whether questions: Questions asked to validate one of two possible inferred code behaviors.
Discrepancy questions: Questions asked to clarify a perceived inconsistency in the code.

Conjectures were categorized according to two independent taxonomies, one based on the focus of the conjecture (called content) and one based on the certainty of the subject in forming the conjecture (called certainty). The content taxonomy for conjectures parallels the taxonomy for questions i.e.

Why conjectures: Conjectures about the purpose of an action or design choice.
How conjectures: Conjectures about the way some goal of the program is accomplished.
What conjectures: Conjectures about what a variable is or what a subroutine does.
Word conjectures: Conjectures about the meaning of some word or other identifier in the code.

The *certainty* classification divided conjectures between *Guesses* which are tentative or uncertain and *Conclusions* which are firmly believed by the subject.

A model of programmers' behavior was developed based on this taxonomy. The model assumes that all programmers have basic knowledge about standards and practices in the field of computer programming. Conjectures are formed about an unfamiliar program when it seems safe to do so based on these standards. Conjectures are made in order to build up a mental model of the program. Questions arise when the mental model is contradicted and when it seems that the accepted standards have been violated.

Letovsky's research in computer science is significant in its parallels to the goals of this research in mechanical engineering. Accordingly, Letovsky's approach was modified for use in this research. Chapter 5 discusses the taxonomy used to classify questions and conjectures made by protocol subjects working on mechanical design problems. See Chapter 6 for a comparison of Letovsky's research to the current research project.

Chapter 3: Model of the Design Process

The design process is modeled as a series of design decisions, each decision involving a number of input constraints and one or more output constraints. The notions of constraints and decisions are discussed below. A history of these decisions including their associated constraints comprise a design history. Following the discussion of the design model, two methods used by the researchers for representing this design history information are presented.

Constraints

Constraints are the limitations imposed on the values of every feature of every object involved in the design.[2] Here a design object can be any assembly (such as a motor), component (such as a box), composite feature (such as a boss), or interface (such as a contact point) that exists in the design. *Composite* features are those features of a design that have their own sub-features. A hole may be a feature of some design object while its diameter is a feature of that hole. The hole then is a composite feature, its diameter is an *atomic* feature. Atomic features are the finest level of design information, those features without sub-features. Atomic features are the attributes of any design object such as a motor's torque, a wall's width, a boss' height, or a contact point's location. Atomic features can be represented as slots in a frame which can be assigned values (Tikerpuu 89). Some examples should clarify these definitions:

---

[2] This discussion follows the constraint format introduced by McGinnis et al (McGinnis 89).

Battery case -- is a design object
Battery case color -- is an atomic feature
Mounting tab -- is a composite feature
Mounting tab width -- is an atomic feature

A constraint is an atomic feature combined with its instantiated value (e.g. side wall width = .060") or a feature related to any other feature or list of features (e.g. isolating wall width less than side wall width). Constraints occur in these two basic forms: *instantiation constraints*, in which a feature is assigned a value (eg. side wall width = .060"); and *relationship constraints,* in which one feature, the dependent feature, is related to one or more independent features e.g.:

Battery case color = black - is an instantiation constraint
Cover color = Battery case color
- is a relationship constraint

Features can be *form* or *function* oriented as can relationships between features. A *function feature* could be the purpose of a design object, for example, or operational measures such as speed. *Form features* can be geometry, topology, material, etc.

Stepper motor torque - is a function feature
Stepper motor weight - is a form feature

Another way to classify constraints is by their source. The three important sources of constraints are: *given, introduced,* and *derived* as discussed below.

Given -- those constraints coming from outside of the design space. These can be from the problem's instigators in the form of specifications or from decisions made by other designers on adjacent parts of a large design. Given constraints are usually present at the beginning of the design and are often function oriented.

eg. "Assembly method to be automatic."[3]

Introduced -- those constraints brought into the design by the designer, from reference books or the designer's own knowledge base for example, that exist independent of the problem at hand. These are often brought into the design only because of certain other constraints extant in the design.

eg. "Adhesives do not lend themselves to automation."

Derived -- those constraints that are brought into the design as a result of design decisions (see below).

eg. "I will not use adhesives in this design."

Note the progression of the above examples. The *given* constraint "assembly method to be automatic" motivated the designer to *introduce* the constraint "adhesives do not lend themselves to automation". This introduced constraint would not have been considered if the *motivating constraint* did not exist in the design. If the motivating constraint were eliminated, the associated introduced constraint may no longer pertain to the design. (In this example, the motivating constraint is a given constraint, but any constraint can act to motivate an introduced constraint.)

---

[3] All entries in quotation marks are direct quotes from verbal design protocols (see chapter 5). Ellipses (...) indicate words omitted from the quotation for brevety, parenthesis () indicate additions for clarity.

These given and introduced constraints were both considered in the decision that resulted in the *derived* constraint "I will not use adhesives in this design" (see more on decisions below).

Another factor that can be tracked is a constraint's flexibility level, the ability of a constraint to change. *Given* constraints are generally considered relatively inflexible. *Introduced* constraints are similarly quite firm, although some may no longer pertain to the problem at hand. *Derived* constraints have widely varying flexibility levels from the very flexible to the very firm. It is important to realize that the flexibility level of a constraint can vary throughout the design process. For example, say that the length of some component is defined in a derived constraint that is initially somewhat arbitrary and quite flexible. As the design progresses, however, many other constraints may depend on the selected length. Changing the length at this later point would mean that a significant re-design effort would be required; the flexibility level of this once arbitrary constraint has gone from very flexible to firm. If later, for some reason, the dependencies no longer apply, then the flexibility level returns to its initial value. It is important in design to understand these dependency relationships and the flexibility of the constraints in a design.

Decisions

Decisions are the operations in which constraints interact resulting in new derived constraints. The input constraints to any decision are some subset of all the given, introduced, and derived constraints extant in the design. The result of a decision is one or more new derived constraints. This resulting derived constraint, then, can be used as an input constraint to subsequent decisions. Using this model, every derived constraint is said to be the result of a decision.

Design History

The researchers in this project have focused on the constraint propagation history as the fundamental information to be stored in a design history. A constraint based design history would convey information about each constraint in a design. The goal of this thesis research is to establish the level of detail required in a constraint history.

To this end, two graduate students pursued parallel projects each producing a constraint based design history from the same design performed in a video taped protocol session. The two researchers pursued disparate strategies using different media and storing different levels of detail of design history information. The author of this paper represented each constraint in a compiled paper design history. The other researcher used Hyperclass, a hypermedia environment developed by Schlumberger Corporation, to store a detailed decision based design history. The formats used in these two recording efforts are documented below.

Paper Design History

The paper design history project was initiated in order to get a useable design history in the hands of working designers for evaluation in less time than it would take to prepare an interface to a computer design history. This testing was never performed, but the format of the history should be understood as a basis for subsequent discussion on design history content.

The paper design history is constraint based. Every constraint in the design has an entry. Each entry has: an ID tag, a concise statement of the constraint, a verbalization of the constraint, and, if required, a sketch. The source of each constraint is identified as being given, introduced, or derived as defined above. The entry for each derived constraint shows the input constraints that went into the decision yielding that constraint. The entries for these input constraints bear a corresponding indication of those derived constraints that they affect. If a constraint entering the design contradicts or updates an earlier constraint, it is said to *supersede* that previous constraint. The obsolete constraint is noted in the entry for the new constraint. The obsolete constraint still has an entry in the design history, however, and that entry bears an indication of what constraint it is superseded by. The structure for each entry is shown below, a detailed explanation of each element follows:

ID Tag
Constraint Statement
    Dependent Feature
    Instantiation/ Relationship
    Independent Feature(s)
Constraint as spoken
Source (Given, Introduced, or Derived)
Input Constraints (If Derived)
Affects what Downstream Constraints
supersedes what Constraint(s)
superseded by what Constraint

The paper design history developed for this research was generated from a video taped protocol session (see Chapter 5). A portion of the paper design history appears in Appendix B.

ID Tag

The time and tape number at which a constraint first appears is used as the ID Tag for that constraint. The first digit is the number of the video tape, the next five digits show the time into the tape; hour, minutes, and seconds. For example a constraint labeled "2145.38" occurred on video tape two, one hour and forty-five minutes and thirty-eight seconds into the tape.

Some ID Tag is necessary as a shorthand reference for each constraint. This format of ID Tag proved to be useful in that it allows the researchers to easily find the constraint on the video tape and it allows for insertion of constraints without disturbing the numbering system. Other ID Tags considered but not used were absolute time in minutes into the protocol and a sequential numbering system.

Constraint Statement

The researchers gleaned the constraints from verbalizations and drawings made by a protocol subject during a video taped design session. The subject was instructed to speak as if to himself while working. The subject's verbalizations tend to be informal conversational English at best. For the purposes of uniformity, clarity, and ease of analysis, all constraints were abstracted from the verbalizations and recorded in a unified manner described below.

As previously discussed, all constraints act on a dependent feature and occur as either *instantiation constraints* or *relationship constraints*. *Instantiation constraints* give a value to the dependent feature, and *relationship constraints* define the relationship between the dependent feature and one or more independent features.

The constraints were recorded exploiting their composite nature with slashes separating the elements i.e.

Dependent Feature/ Instantiated Value
Dependent Feature/ Relationship/ Independent Feature(s)

for instantiation constraints and relationship constraints respectively. Examples of constraints from the protocol shown in this representational scheme are:

Isolating wall thickness/ thin
Isolating wall thickness/ less than/ Side wall thickness

In this paper design history, any apparent flexibility of the constraint is shown in the instantiation of relationship slot e.g.

Isolating wall width/ approximately .050"
Case material/ possibly ABS
Contact width/ desired to be greater than .250"

Note that in order to make the most of the constraints, the feature names must be clear, uniform, and unambiguous. For clarity, a drawing or textual description may be necessary to identify each feature. For uniformity, a single feature in the design must be referred to by only one name throughout the representation. To prevent ambiguity, each name must, of course, refer to exactly one feature.

Constraint as Spoken

Most of the constraints recorded in the design history were verbalized by the designer during the video taped protocol session (others were drawn without being verbalized). For these, the verbalization was retained in the entry. Retaining the constraint statement is invaluable during the manual construction of the design history to ensure that the full meaning of the verbalization is retained in the simplified constraint statement discussed above. If the language of the constraint statement is sufficiently complete, however, the *constraint as spoken* could be omitted from the finished design history without loss. For completeness, non-verbalized constraints are identified as such in this slot; this was necessary for just a few constraints that were drawn without being verbalized.

Source/ Input Constraints

As previously discussed, the source of a constraint can be identified as given, introduced, or derived. Given constraints are the initial problem specifications given to the designer by the problem's instigators. Introduced constraints are brought into the design by the designer or from outside sources such as handbooks. They exist independent of the design but are introduced as a response to constraints in the design. Derived constraints are the results of design decisions using other constraints as input. The source of each constraint in the design history is identified as being either given, introduced, or derived.

Input constraints are listed for each derived constraint and motivating constraints are listed for each introduced constraint. The constraints that were considered in the decision yielding a particular derived constraint are labeled *input constraints* to that derived constraint. *Motivating constraints* to an introduced constraint are those constraints that motivated the introduction of that particular constraint. Given constraints are not considered to have input or motivating constraints. The list of input constraints is critical in establishing the constraint propagation network.

Affects What Downstream Constraints

Each derived constraint is affected by the input constraints to its associated decision. Similarly the presence of an introduced constraint is affected by its motivating constraints. Input constraints provide insight into what existed upstream that influenced the derived or introduced constraint. A look downstream would show the region of influence of a particular constraint, i.e. what derived constraints this constraint acted as an input to, as is shown in the following examples.

<u>2127.40</u>
Case wall thickness/ .060"
Derived from: 1014.42, ...
Affects: <u>2113.38</u>, ...

<u>2113.38</u>
Case bottom thickness/ .060"
Derived from: <u>2127.40</u>
Affects: ...

Note that while only introduced and derived constraints have input constraints, any constraint can itself serve as an input constraint thereby affecting downstream constraints. Therefore, each constraint should have a slot for a list of downstream constraints that it affects.

The list of affected constraints can be generated from the lists of input constraints and any automated system for capturing and replaying design history information should be able to generate one from the other. Being able to look upstream as well as downstream along several levels of influence is the key to making use of the constraint propagation network.

supersedes what Constraint/ superseded by What Constraint

Any new constraint may contradict or update a previously extant constraint. If the new constraint is accepted into a design replacing another constraint, the new constraint is said to *supersede* the earlier constraint. Entries are made in both constraints to show that the new constraint replaces the previous constraint. In this way, obsolete constraints are so flagged but retained in the design history allowing the evolution of a feature to be traced. This evolution is demonstrated in the following sequence of constraints:

2139.12 isolating wall width / approximately .050"
    supersedes: ...
    superseded by: 2149.56

2149.56 isolating wall width / .030"
    supersedes: 2139.12
    superseded by: 2150.30

2150.30 isolating wall width / .030" plus a little
    supersedes: 2149.56
    superseded by: ...

In this example, the center constraint, 2149.56, supersedes the first constraint, 2139.12, and is itself superseded by the last constraint, 2150.30. Situations can be envisioned in which the superseding constraint is either given or introduced but these would be exceptions, most are derived. Similarly, since given and introduced constraints are generally quite firm, they are seldom superseded. The constraints that are superseded by other constraints are generally derived.

Hyperclass Representation

The Design History representation in Hyperclass is similar to the aforementioned paper representation in that both are *constraint based*. All of the information about the given, introduced, and derived constraints included in the paper design history also appears in the Hyperclass representation. The Hyperclass representation contains additional information not only about constraints, but also about the related decisions, including the operations contained in them, and about the design objects themselves.

The ability of Hyperclass to record links, or pointers, between associated entries allows efficient storage and retrieval of design history information. These links are used to: 1) determine constraint inter-dependency, 2) update the design object information to reflect new constraints, 3) develop the hierarchical structure of the design, and 4) reduce data storage requirements.

The Hyperclass design history system under development is continuously being refined with regard to both data storage and user interface. The system is being prepared for future empirical testing which should give further insight to the information content to store in a design history and to storage and retrieval techniques. This is not a system on which design work is performed and recorded, the design history information is currently hand coded, but it is a step toward automating the retrieval of design history information.

Chapter 4: Research Methods

This chapter describes the verbal protocols used in this research and describes the techniques used to analyze the resulting data.

The Question Asking Protocol Method

The question asking protocol method is a form of Newell and Simon's verbal protocol method (Newell 72). In the standard verbal protocol, the subject is audio taped (and here video taped as well) while performing some task. There is little intervention by the examiner in this method, the examiner's main role is to keep the subjects verbalizing. This technique has been widely used in many fields including mechanical design (Stauffer 87).

The question asking protocol method as presented by Kato (86) is a method in which the subject works on some task and the examiner is present to answer any questions the subject may have. The question asking protocol method was appropriate for this study since there is interest in what information a designer would request from a design history. In these protocols, the examiner acted as a design history resource for the subjects. The subjects were given blueprints and original specifications for completed designs and instructed to make modifications to these designs (see below). As they worked, each subject sought certain information about the design. Not all of this information was available in the documentation provided, but the subjects were informed that the examiner was very familiar with the designs. The examiner had much of the design knowledge sought by the subjects. The subjects accessed the examiner's design history knowledge by asking questions. These questions were the primary focus of the analysis of these protocols. Also of interest were the conjectures formed by the subjects. Conjectures are formed when the subject does not have enough information to know things for certain. The information necessary to verify uncertain conjectures is additional information that should be considered for inclusion in a complete design history.

The Protocols in This Study

The data used in this research was obtained from three independent question asking protocols performed expressly for this research. The subjects were each practicing mechanical design engineers. They were each given complete specifications and drawings for a design completed by another engineer and instructed to make a series of modifications to the existing design. In all cases, an examiner was present who was very familiar with the design the subjects were working on and the subjects were encouraged to ask the examiner any questions they may have had about the design. The protocol sessions were audio and video taped; the audio portion was subsequently transcribed to facilitate analysis. The three protocol subjects are identified by number: S10, S11, and S12. The subjects worked on different problems and spent different amounts of time on their designs. The protocols ranged in length from just over 1 hour to 2 hours 45 minutes.

S10 was the first protocol subject. The protocol was performed in February 1988. This session was preceded by a brief warm-up design on an unrelated design topic. This warm-up served to test the equipment and to get the subject accustomed to verbalizing his thoughts while working in front of a camera and tape recorder. (See also Stauffer 87) The re-design protocol problem for this subject was based on the design of a piece of manufacturing equipment that dips aluminum plates into a water bath coating them with a thin chemical layer. This machine is known as the *Flipper Dipper* since it first dips one side of the plate into the chemical bath then flips the plate over and dips the other side. (All original and change specifications provided to the subjects are included in Appendix A.) The design given to this subject was that originally performed by another subject, S6, in a previous protocol study (Stauffer 86). The examiner for the S10 protocol studied the S6 video tape to become familiar with the design. S10 was given blueprints of the finished design, the original specifications, and four changes to these specifications. The changes were given to S10, as to the other re-design protocol subjects, one at a time, a manner which all three subjects said was "typical" of the way changes are introduced to them in industry. S10 was instructed to: 1) Change the flipper dipper to accept larger plates, 2) Facilitate loading and unloading of the plates, 3) Change the machine to fit on a smaller table than originally specified, and 4) More precisely control the manner in which the plate enters and exits the water bath. The S10 protocol was studied in some depth, and the protocol technique refined, before continuing with the S11 and S12 protocols in June 1989.

The S11 protocol was based on the same flipper dipper design as the S10 protocol. To streamline the process, however, S11 was given only two changes to make: 1) Change the machine to accept larger plates and 2) Change the machine to fit on a smaller table. These are identical to the first and third changes performed by S10. The S11 and S12 protocols differ from the S10 protocol primarily in the format of the preliminary warm-up session. During the warm-up session, S10 was given a set of specifications and instructed to develop an original design. This task was performed primarily as an equipment check and to get the subject accustomed to the verbal protocol process. The warm-up sessions for S11 and S12 involved re-design tasks that were similar to those they worked on during the actual re-design protocols. In these sessions, however, instead of only answering direct questions about the design, the examiner volunteered information thought to be helpful and in general worked with the subjects. The examiner thus tried to build up a rapport with the subjects during these warm-up sessions and worked to train the subjects as to how the information in the design history could be used as a re-design tool. This different approach resulted in the two later subjects asking more questions than S10. S11 used the examiner's knowledge 2.3 times more than S10 and S12 used the examiner's knowledge 3.5 times more than S10 to answer questions and verify conjectures. The other functions of the warm-up session, to ensure that the equipment was functioning properly and to make the subjects feel more comfortable verbalizing their thoughts while working, were also achieved by this procedure.

The warm-up re-design task given to S11 was based on the same design as S12 worked on during the main protocol: a plastic enclosure for three small batteries and the formed copper contacts for connecting these batteries in series. This design, known as the *Battery Contacts Problem*, was originally performed by yet a different protocol subject (Stauffer's S2). S12 was given finished blueprints and the original problem specifications for this design and instructed first to change the design to accommodate batteries of a larger diameter and then to change the design to accommodate taller batteries. S12 warmed-up with the problem of changing the plate size on the flipper dipper. S11, whose protocol involved the flipper dipper, warmed-up by changing the battery diameter on the battery contacts problem.

A different design was chosen for S12 in an attempt to obtain more general results than if all subjects worked on the same design.

Analysis Techniques

The analysis of the protocols focused on the questions that the subjects asked and the conjectures that the subjects formed, the hypothesis being that access to a complete design history would answer all questions and eliminate the need for unsupported conjecture.

The following definitions are used in this research:

Question: Interrogation by the subject or discussion initiated by the subject about any uncertain aspect of the design. These inquiries may be directed toward either the examiner, the designer's notes, drawings, given specifications, or the subject's own memory.

Conjecture: Conclusion about the design inferred by the subject from incomplete information. An interpretation, supposition, or assumption believed but not known for certain.

To find the questions and conjectures in the protocol, the transcripts of the protocol were examined for key words that typically identify questions and conjectures. Questions frequently occur in conjunction with the key words how, what, why, which, and where. In addition, the transcriber quite rationally included the question mark symbol (?) at points in which the subject's voice inflection seemed to indicate a question, these points were examined as well. Conjectures were sought in the environment of all instances of the key words:

> appear, assume, correct, guess, look, obvious, probably, right, say, see, seem, think, thought, understand, and worry.

This list of key words was determined empirically while examining the protocol. When a question or conjecture passage was located, those words that pointed to its existence as a question or a conjecture were identified as key words. The search for those words identified other potential key words to examine.

Enough of each passage was retained to understand the topic and the essence of the question or conjecture. Those passages that related to the design artifact or the requirements thereof were used to generate the taxonomy presented in the next chapter and then classified according to that taxonomy. The questions asked and the conjectures formed by the subjects were studied to evaluate the classes of information that should be stored in a complete design history. The results of this evaluation are also presented in the following chapter.

Limitations of the Research

This study is exploratory not definitive. The limited number of subjects and limited number of problems addressed by each subject give an indication of the design history information sought by mechanical design engineers, but this does not constitute a rigorous, thorough study. The protocols of the three subjects total over five hours. 372 questions and conjectures were identified from these protocols and studied. While the results of the study are not conclusive, they are revealing. Mechanical design engineers working on similar design problems will form the same types of questions and conjectures as formed by these protocol subjects. The taxonomy prepared to classify these questions and conjectures and the results of their classification are presented in the following chapter.

Chapter 5: Results

As discussed in the previous chapter, three protocol subjects were video taped while making modifications to mechanical designs that had been completed by a different engineer. Analysis of the resulting protocols focused on the questions the subjects asked about the designs and the conjectures the subjects formed about the designs.

This chapter presents the taxonomy used to classify these questions and conjectures and defines the taxonomic classes. Following this, the results of the taxonomic classification of questions and conjectures are presented.

An outline of the taxonomy appears on Table 1, below. A definition of each of the terms follows.

Table 1: Taxonomy of Questions and Conjectures

- CATEGORY:
  - Simple Conjecture
  - Conjecture with Verification
  - Verification Question
  - Open Question
- TOPIC:
  - Assembly
  - Component
  - Interface
  - Feature
- AGE OF TOPIC:
  - Old
  - New
  - Specification
- NATURE:
  - Construction
  - Location
  - Purpose
  - Operation
- CONFIRMATION:
  - Unconfirmed
  - Confirmed by:
  - Examiner
  - Drawings
  - Specifications
- VALIDITY:
  - True
  - False
  - Unconfirmed
  - No Conjecture

Category

Question and conjecture passages are classified as being either conjectures or questions according to the above definitions. Conjectures are categorized as being either *Simple Conjectures* or *Conjectures with Verification*; questions are similarly categorized as *Open Questions* or *Verification Questions* according to the following:

<u>Simple Conjecture:</u> A conjecture formed with no apparent, immediate attempt at verification. Formed when the subject feels confident in the validity of the conjecture.

e.g. "I think this is ****."

<u>Conjecture with Verification:</u> A conjecture immediately followed by a verification attempt. Formed when the subject is unsure of the accuracy of the conjecture.

e.g. "I think this is ****. Is that right?"

The verification attempt is added as an afterthought. While the verification attempt is usually in the form of a question, as in the above example, this question is not treated as a separate passage in the analysis. The conjecture may or may not actually be verified by the examiner or other outside source, the passage is classified here by its format only, not by the response.

<u>Verification Question:</u> A question formed such that a simple answer is all that is required by way of response. These are primarily yes or no questions formed when the subject wants to verify a single, conjectured, plausible answer

e.g. "Is this ****?"

Also in this class are disjunctive questions asked when the subject has conjectured two feasible answers.

e.g. "Is this **** or @@@@?"

Note that questions of this form are classified as *verification questions* whether or not they are explicitly verified.

Open Question: A question asked requiring a detailed answer. Formed when the subject has no clear idea of what the answer might be.

e.g. "What is this?"

Topic

The *topic* of each passage is also identified. The *topic* is defined as the design object which the question or conjecture focuses on. If the question or conjecture were in the form of a simple sentence, the topic would be the noun or the subject of the sentence. The four types of design objects (see Chapter 3) define the four *topics* used in the classification. All questions and conjectures are classified as belonging in one of the following four categories (all examples are from the protocols):

Assembly -- The topic of the question/conjecture is an assembly, either the complete assembly or a sub-assembly.

e.g. "What is this flipper dipper?" is a question about the entire *assembly* which is the focus of the re-design effort.

Component -- The topic of the question/conjecture is a single component of the whole structure.

e.g. "My clamp appears to be OK." is a conjecture about the clamp which is a single *component* of the design.

Interface -- The topic of the question/conjecture is the relationship or interface between two or more components or assemblies.

e.g. "How does this pivot arm seat in (the mounting brackets)?" is a question about the *interface* between two components of the design.

Feature -- The topic of the question/conjecture is some specific feature of some assembly, component, or interface.

e.g. "I've got 11 1/2 inches, it appears, on the interior of this frame." is a conjecture about a dimension which is a *feature* of a component.

Topic Age

The topic is further identified as to its relative age according to the following classifications:

Old -- The topic of the question/conjecture is some aspect of the original design as it existed before the current re-design session.

e.g. "Does the original flipper dipper work (well)?" is a question about some aspect of the *old*, or un-modified, design.

New -- The topic of the question/conjecture is some aspect of the design as modified by the current subject.

e.g. "Would it matter where I mount this micro-switch?" is a question about some aspect of the *new*, or modified, design.

Specification -- The topic of the question/conjecture is some aspect of either the original specifications or changes to the specifications.

e.g. "These are what kind of plates, aluminum plates?"

is a question about the design *specifications*, in this case the original specifications.

Nature

In addition to identification of the topic, each question and conjecture is characterized according to its *nature*. The *nature* is identified by the type of information that the subject either seeks (as in a question) or presumes (as in a conjecture). While the *topic*, discussed above, indicates which class of design object the question or conjecture is regarding, the *nature* indicates what about that design object the subject is interested in. The four natures of questions and conjectures are identified below. For each nature class, first an oversimplified example question is shown for illustrative purposes, then each class is defined, finally an example of each from one of the protocols is given:

Construction -- How is this built?

The question/conjecture concerns the physical structure of a design object, the manner in which a design object is made including material, shape, etc.

e.g. "I've got 11 1/2 inches, it appears, on the interior of this frame." is a conjecture about the *construction* of a component in the design.

Location -- Where is this (with respect to some reference)?

The question/conjecture concerns the position of a design object, where a design object is with respect to some other design object or in some reference frame.

e.g. "The plate comes within 1/8 inch from this edge. Right?" is a conjecture (with verification) about the *location* of one design object with respect to another.

Operation -- What does this do?
The question/conjecture concerns the behavior of a design object, the manner in which the design object performs its intended function.

e.g. "Does (the pivot arm) flip all the way out, or (are there) two positions?" is a question regarding the *operation* of the assembled mechanism.

Purpose -- Why is this here?
The question/conjecture concerns the reason a design object is included in the design, the function a design object is to perform.

e.g. "Why the two inch tubing?" is a question regarding the *purpose* of a feature of a component in the design.

Confirmation

Whether or not the question or conjecture is *confirmed* and the source of the confirmation is also noted. Here *confirm* is used in the general sense; for questions the term "answer" may be more appropriate, for mistaken conjectures, the term "refute" is more accurate. The categories of confirmation are:

Unconfirmed -- No immediate confirmation or answer.
Examiner -- Confirmed by the examiner
Drawings -- Confirmed by drawings supplied to or generated by the subject.
Specifications -- Confirmed by specifications or changes of specifications provided to

the subject.

Note: Questions and conjectures confirmed by the subject's domain expertise are considered unconfirmed for these purposes. The design expertise allowed the subject to form the conjecture but does not confirm the conjecture. Some questions in the form of verification questions, for example, were not answered by the examiner, drawings, or specifications, but by conjecture. These are labelled *unconfirmed* for the purposes of this category.

Validity of Conjecture

Validity is a measure of the accuracy of a conjecture. The validity of all confirmed conjectures -- including conjectures implicit in verification questions -- was determined. The validity of unconfirmed conjectures and the validity of questions without an implicit conjecture was not established. The validity of most unconfirmed conjectures (such as "I don't know which option is better, but this one looks easier to solve") is impossible to measure with any certainty, while the validity of an explicitly confirmed conjecture is readily determined. *Open questions* and disjunctive *verification questions* do not contain a single conjecture so validity, in these cases *validity* has no meaning. The four categories of validity therefore are:

True -- The conjecture formed by the subject is a valid conjecture.

False -- The conjecture formed by the subject is not a valid conjecture, it is incorrect.

Unconfirmed -- The question or conjecture was not immediately confirmed.

No Conjecture	-- There is no clear single conjecture implicit in the question. The passage is a confirmed open or disjunctive question.

Note that a listing of *unconfirmed* here corresponds directly to a listing of *unconfirmed* in the preceding *confirmation* category. If an open or disjunctive question is not immediately confirmed, it is listed as *unconfirmed* rather than *no conjecture* even though no clear single conjecture is present.

Results of Taxonomic Classification

The 372 questions and conjectures identified in the three protocols were classified according to the above taxonomy. The results of this classification follow. First each classification in the taxonomy is discussed individually, then important combinations of these classifications are presented.

Category

The question and conjecture passages observed in the protocol were classified according to the form of the question or conjecture as *Simple Conjectures*, *Conjectures with Verification*, *Verification Questions*, and *Open Questions*. The number of questions and conjectures in each of the four categories formed by each of the three subjects appear in Table 2, below.

Table 2: Category of Questions and Conjectures by Subject

	S10	S11	S12	Combined
Simple Conj.	116 (57%)	32 (33%)	18 (25%)	166 (45%)
Conj. w/ Verif.	15 (7%)	34 (35%)	30 (42%)	79 (21%)
Verif. Question	37 (18%)	15 (15%)	16 (22%)	68 (18%)
Open Question	34 (17%)	17 (17%)	8 (11%)	59 (16%)

The three protocol subjects each formed approximately two questions for every one conjecture. This ratio was fairly consistent among the subjects. Similarly, the ratio of Verification Questions to Open Questions is not inconsistent for the subjects, varying from about one to one to two to one. There is a striking difference, however, in the ratio of Simple Conjectures to Conjectures with Verification among the subjects. S10 formed 7.7 Simple Conjectures for every Conjecture with Verification; for S11, this ratio is roughly one to one; S12, however, formed more Conjectures with Verification than without, forming only 0.6 Simple Conjectures for every one Conjecture with Verification. There are three plausible reasons why S11 and S12 were more likely to verify their conjectures than S10. First, S10 worked longer on the protocol than the other two subjects changing more and forming more *new* conjectures (see below). Since the examiner was present expressly for purposes of helping with the *old* design, these *new* conjectures are more likely to be Simple Conjectures. A second factor may be the difference in the format of the warm-up sessions of the subjects as described in Chapter 4. Because the examiner worked more closely with subjects S11 and S12 during these warm-ups, they may have been more confident of the design knowledge available from the examiner. Third, the different personalities of the three subjects must also be taken into account in making any comparisons.

Topic

The *topic* of a question or conjecture is the design object that is the focus of that question or conjecture. The four classes of design objects (see Chapter 3) define the four possible *topics* in the taxonomy of questions and conjectures: *assembly, component, interface*, and *feature*.

The number of questions and conjectures in each of the four topics by each of the three subjects appear in Table 3, below.

Table 3: Topic of Questions and Conjectures by Subject

	S10	S11	S12	Combined
Assembly	40 (20%)	18 (18%)	7 (10%)	65 (17%)
Component	74 (37%)	37 (38%)	12 (17%)	123 (33%)
Interface	31 (15%)	18 (18%)	10 (14%)	59 (16%)
Feature	57 (28%)	25 (26%)	43 (60%)	125 (34%)

The proportions were surprisingly consistent among the three protocol subjects with one exception. S12 tended to focus more questions and conjectures on the *features* of the design than the other subjects. This is most likely due to the different character of the design problem that S12 worked on.

Age of Topic

The age of the topic of each question and conjecture passage was established as being either *new, old*, or *specification.* As shown in Table 4, below, 13% of the questions and conjectures observed relate to the *specifications;* this indicates that specification information belongs in a complete design history. 51% of the questions and conjectures had to do with *old* topics, topics which would necessarily be addressed by a complete design history of an existing design. The remaining 36% of the passages related to the changed design (in other words, *new* topics). A static design history would not address new topics, but a design tool that recorded design histories as the design was in progress would.

Table 4: Topic Age of Questions and Conjectures by Subject

	S10	S11	S12	Combined
New	100 (50%)	29 (30%)	5 (7%)	134 (36%)
Old	81 (40%)	51 (52%)	58 (81%)	190 (51%)
Specification	21 (10%)	18 (18%)	9 (13%)	48 (13%)

There are great differences between the subjects in this area. While 50% of the questions and conjectures that S10 formed focused on new topics, these were the interest of only 7% of the questions and conjectures formed by S12. Conversely, S12 focused on *old* topics 81% of the time, S10 40%. S11 came in between the other subjects with *new* topics the focus of 30% of the questions and conjectures, and *old* topics the focus of 52%. The differences in *specification* questions and conjectures are less dramatic. As previously stated, S10 worked longer during the protocols and generated more *new* design that could serve as the topic of questions and conjectures. For whatever reason the subjects were concerned with old or new topics, it is important to note that design history information is potentially useful to both the original designer, who would only be concerned with *new* topics, as well as to any subsequent designer working primarily on an *old* design.

Nature

The *nature* of a passage is an indication of the type of information sought by the subject in a question or presumed by the subject in a conjecture. While the *topic*, discussed above, indicates which class of design object the question or conjecture is regarding, the *nature* indicates what about that design object the subject is interested in. The four natures identified are: *construction, location, operation*, and *purpose*. The number of questions and conjectures belonging to each of the four natures formed by the three subjects appear in Table 5, below.

Table 5: Nature of Questions and Conjectures by Subject

	S10	S11	S12	Combined
Construction	105 (52%)	46 (47%)	24 (33%)	175 (47%)
Location	37 (18%)	19 (19%)	26 (36%)	82 (22%)
Operation	47 (23%)	22 (22%)	5 (7%)	74 (20%)
Purpose	13 (6%)	11 (11%)	17 (24%)	41 (11%)

175 of the 372 questions and conjectures observed in the protocol, nearly half of the total, were regarding the *construction* of some design object. This emphasis is consistent among the three subjects; from over one-half to one-third of the interest is in the *construction* of design objects. This information is primarily contained in individual form constraints. 22% of the questions and conjectures were about *location*, which is also addressed by individual form constraints. 20% of the questions and conjectures were about the *operation* of some design object. Operation questions and conjectures are addressed by sequences of form and function constraints. The remaining 40 questions and conjectures, 11%, were about the *purpose* of some design object. These are addressed by individual function constraints.

There is surprising correlation in the *nature* of the questions and conjectures formed by the three subjects. As with Topic, S10 and S11, who worked on the same design, asked questions and formed conjectures about the four natures in roughly the same proportion. S12 formed far more questions and conjectures proportionally about the Purpose and Location of design objects than S10 or S11 and proportionally fewer questions and conjectures about the Construction and Operation of such objects. This distribution points again to the differences in the designs which the subjects worked on, but of course with this sample size, no conclusions can be formed with certainty.

Confirmation

Questions and conjectures are labelled as *confirmed* if, immediately following the passage, the question is answered or the conjecture is either confirmed or refuted. Confirmed passages have the *source* of their confirmation noted. The sources used by the protocol subjects to confirm questions and conjectures were *Drawings, Examiner*, and *Specifications*. The number of questions and conjectures confirmed by each of these three sources along with the number of unconfirmed questions and conjectures appear in Table 6, below.

Table 6:
Confirmation of Questions and Conjectures by Subject

	S10	S11	S12	Combined
Drawings	29 (14%)	9 (9%)	2 (3%)	40 (11%)
Examiner	46 (23%)	53 (54%)	58 (82%)	158 (42%)
Specification	5 (2%)	1 (1%)	0 (0%)	6 (2%)
Unconfirmed	122 (60%)	35 (36%)	11 (15%)	168 (45%)

45% of the questions and conjectures went Unconfirmed; of the confirmed passages, 77% were confirmed by the Examiner, 20% were confirmed by Drawings, and 3% were confirmed by the Specifications.

As mentioned in the section discussing *category* of questions and conjectures, S10 formed far more Simple Conjectures and fewer Conjectures with Verification than the other two subjects. This behavior is seen again in analyzing the *confirmation* of questions and conjectures. 60% of S10's questions and conjectures went unconfirmed (or unanswered) compared to 36% for S11 and 15% for S12. Conversely, S10 was more likely to confirm questions and conjectures by reference to the *drawings* or the *specifications* than the other two subjects were. S11 and S12 seemed to be more comfortable referring to the design history knowledge of the examiner than S10. They frequently asked about information which was also available on the drawings or in the specifications provided. One prime factor in this may be the additional training these two subjects received using the design history during the warm-up sessions, as described in Chapter 4. Because the examiner worked more closely with subjects S11 and S12 during these warm-ups, they may have been more confident of the design knowledge available from the examiner. The fact that the protocol subjects referred to the examiner's stored design history at all indicates that mechanical designers would use a design history tool if available.

Validity of Conjecture

Validity is a measure of the accuracy of a conjecture. The *validity* of all confirmed conjectures -- including those conjectures implicit in verification questions -- was determined. All question and conjecture passages in the protocols are labelled as being either *true*, *false*, *unconfirmed*, or *no conjecture*. The number of questions and conjectures belonging to each of the four validity classes formed by the three subjects appear in Table 7, below.

Table 7: Validity of Questions and Conjectures by Subject

	S10	S11	S12	Combined
True	32 (16%)	42 (43%)	41 (57%)	115 (31%)
False	20 (10%)	6 (6%)	13 (18%)	39 (10%)
Unconfirmed	122 (60%)	35 (36%)	11 (15%)	168 (45%)
No Conjecture	28 (14%)	15 (15%)	7 (11%)	50 (13%)

S10 confirmed far fewer questions and conjectures than the other subjects, as was discussed in the *confirmation* section above, and formed far fewer *true*, confirmed conjectures. This subject had approximately the same percentage of *false*, confirmed conjectures as the other subjects. This would indicate that S10 only confirmed conjectures when the validity was uncertain.

Note again that a listing of *unconfirmed* here corresponds directly to a listing of *unconfirmed* in the preceding *confirmation* category.

It is theorized that if a complete design history were available with the data structured such that retrieval was facilitated, more conjectures would be verified and fewer incorrect conjectures would be incorporated into the finished design. This hypothesis has not been tested as part of the current research project. This could, however, serve as a testing criterion for future research aimed at finding the utility of a design history.

Combinations of Taxonomic Categories

The taxonomy presented at the beginning of this chapter divides the questions and conjectures formed by the three protocol subjects according to six defined taxonomic classes: Category, Topic, Age of Topic, Nature, Confirmation, and Validity. The results of the classification of questions and conjectures for each taxonomic class is discussed above. These six classes can be combined into fifteen possible pairs. Ten of these combinations that show interesting results are presented below. Discussed are Question and Conjecture:

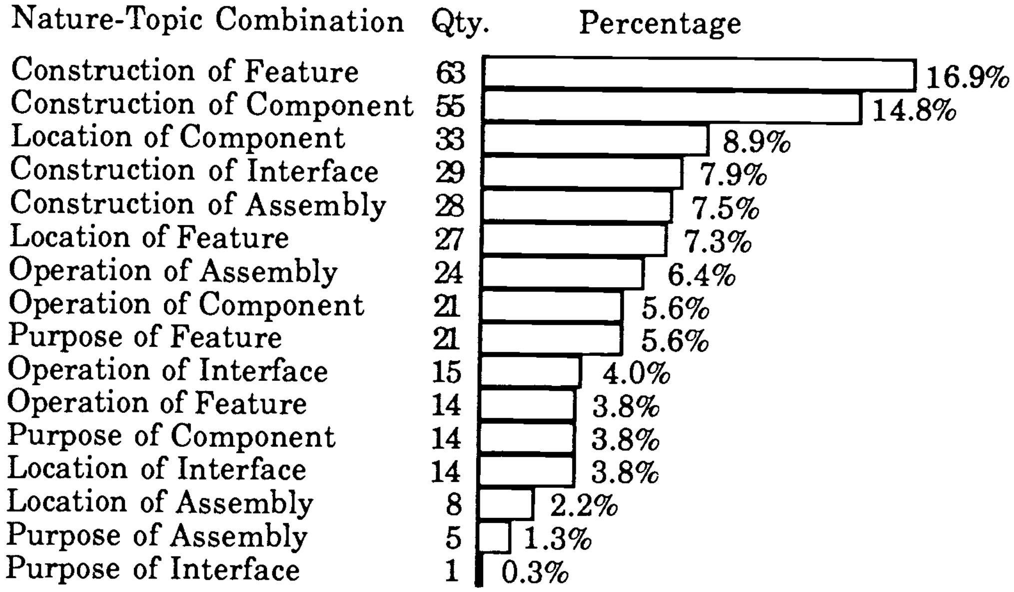
Nature versus Topic
Category versus Validity
Category versus Topic
Category versus Age
Category versus Nature
Topic versus Confirmation
Topic versus Validity
Age versus Validity
Nature versus Confirmation
Confirmation versus Validity

Analysis of the five remaining pairs (Category versus Confirmation, Topic versus Age of Topic, Nature versus Age, Confirmation versus Age, and Nature versus Validity) does not yield any remarkable results.

Question and Conjecture Nature versus Topic

Comparing the *nature* (Construction, Location, Operation, and Purpose) of the question and conjecture passages versus the *topic* (Assembly, Component, Interface, and Feature) of these passages yields some interesting patterns. The number and percentage of questions and conjectures for each combination of nature and topic is shown in Figure 1, below.

Figure 1: Question and Conjecture Nature versus Topic



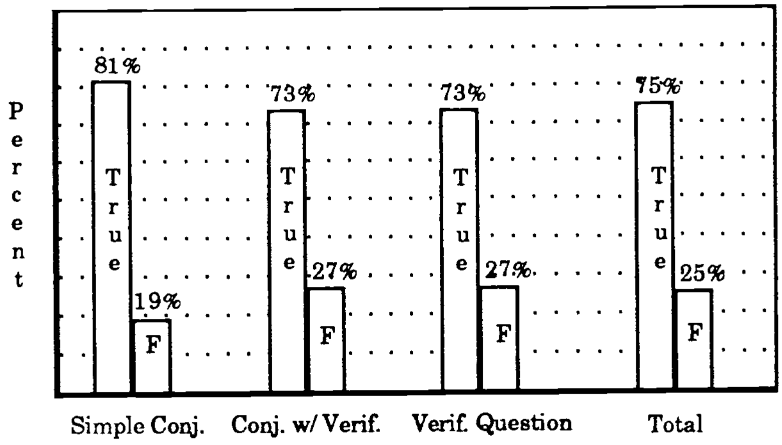
High percentages of questions and conjectures were formed concerning the *construction* of both features and components. Also of high interest were the location of components and the construction of both assemblies and interfaces. Uncommon were questions and conjectures concerning the *purpose* of assemblies or interfaces.

This distribution should guide the information content of design histories. The subjects of this study were interested in the construction of design objects, especially features and components, so this information must be included in and readily obtained from a design history. Less important is information on the purpose of assemblies and interfaces. Though the data from three subjects is far from conclusive, the trend is clear.

Question and Conjecture Category versus Validity

41% of the questions and conjectures in the protocols contained conjectures which were externally confirmed (Simple Conjectures, Conjectures with Verification, or Verification Questions with a single implicit conjecture which were confirmed). The validity of these conjectures was determined as either *true* or *false*. 25% of these *measurable* conjectures were false. This result is quite flat across the three question categories that can be deemed true or false as is illustrated in Figure 2, below.

Figure 2: Validity of Conjectures by Category

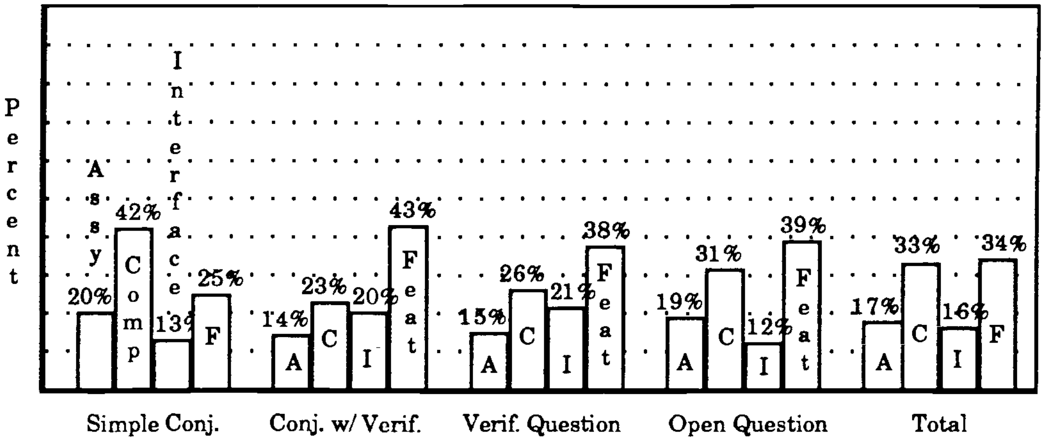


The fact that this curve is flat runs counter to the hypothesis that Simple Conjectures are formed when the subject is fairly confident in the accuracy of the conjecture, Conjectures with Verification when less sure, and Verification Questions when still less sure. This result would indicate that the three conjecture types are all about equally likely to be valid. Of course, due to their nature, Simple Conjectures are less likely to be confirmed; the validity of unconfirmed conjectures can not be determined with any certainty. 81% of the Simple Conjectures went unconfirmed versus 6% of the Conjectures with Verification, 19% of the Verification Questions, and 27% of the Open Questions. The Unconfirmed *questions* (of both the Verification and Open type) could usually be classified as rhetorical questions, questions that did not require an answer.

Question and Conjecture Category versus Topic

In analyzing the *topics* of interest in the questions and conjectures of each category, a fairly broad distribution is seen. All topics (Assembly, Component, Interface, and Feature) are addressed by roughly equal percentages of question categories (Simple Conjectures, Conjectures with Verification, Verification Questions, and Open Questions). This is shown in Figure 3, below. Slightly more Simple Conjectures about Components were formed than average at the expense of Simple Conjectures about Features, but not to any degree to warrant particular inspection.

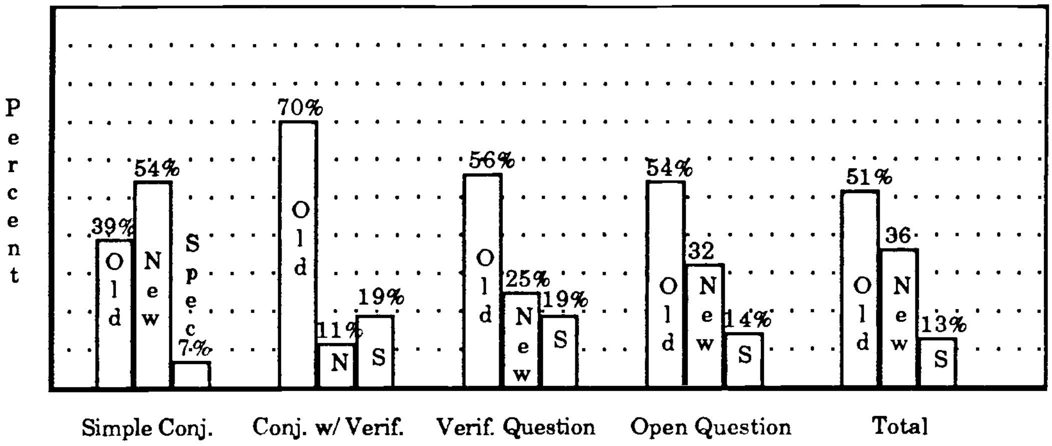
Figure 3: Topics of Questions and Conjectures by Category



Question and Conjecture Category versus Age

The *category* of questions and conjectures (Simple Conjectures, Conjectures with Verification, Verification Questions, and Open Questions) versus the *age of the topic* (Old, New, and Specification) in those questions and conjectures are plotted on Figure 4, below.

Figure 4: Age of Questions and Conjectures by Category

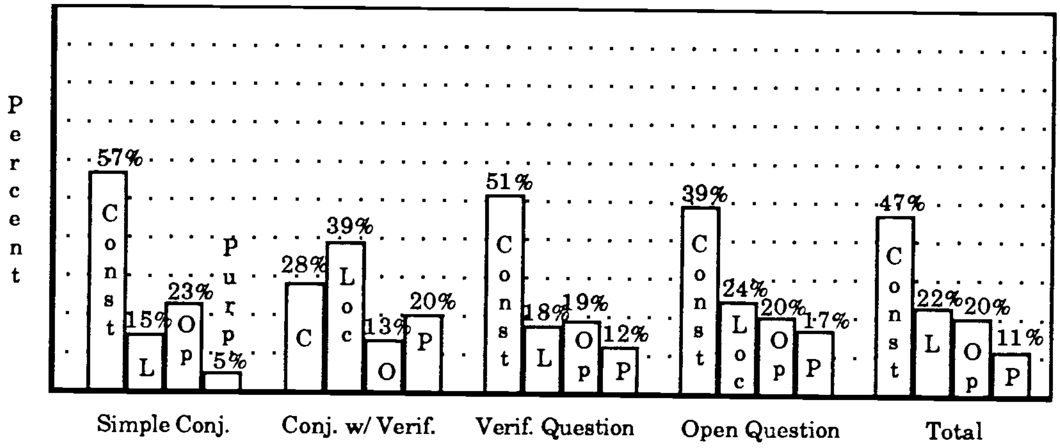


Note that Simple Conjectures are typically formed about *new* topics and that other question and conjecture categories are proportionally more likely to be concerned with *old* topics. It should encourage design history researchers that while protocol subjects are likely to conjecture without verification about their own work, they will refer to design history information when working on *old* topics. This conclusion does not disregard the fact that designers make inquiries about *new* topics as well. The presence of these inquiries should encourage those interested in a design history tool that would incorporate recent design work into the knowledge base.

Question and Conjecture Category versus Nature

In examining the *nature* (Construction, Location, Operation, and Purpose) of the passages in each question and conjecture category (Simple Conjectures, Conjectures with Verification, Verification Questions, and Open Questions), as shown in Figure 5 below, some interesting trends become apparent. There are high instances of Conjectures with Verification about the Location and Purpose of the various design objects and relatively few Simple Conjectures about the Purpose of design objects. (The trend in Location is especially strong in S12 for whom 50% of the Conjectures with Verification concerned location.) This behavior indicates that the protocol subjects were less sure of their *location* and *purpose* conjectures and are therefore more likely to seek verification.

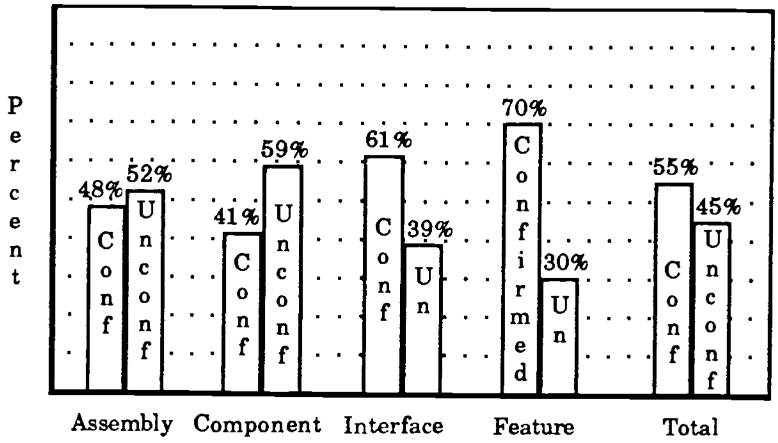
Figure 5: Nature of Questions and Conjectures by Category



Question and Conjecture Topic versus Confirmation

Next consider the *topics* of the questions asked and the conjectures formed (Assembly, Component, Interface, and Feature) versus the *confirmation* of these questions and conjectures (Examiner, Drawings, Specifications, and Unconfirmed) as shown in Figure 6, below. The source of confirmation of the questions and conjectures across all topics is fairly flat proportionally, with 77% of those confirmed, confirmed by the examiner, 20% confirmed by drawings, and the remaining 3% confirmed by the problem specifications. The proportion of confirmed questions and conjectures by any source to unconfirmed questions and conjectures, however is not as well behaved. Feature based questions and conjectures are confirmed 70% of the time, compared to an average 55% confirmation rate. This higher confirmation rate would imply that *feature* information, information at the finest level of detail, is more critical, therefore more likely to be confirmed than other, coarser design information.

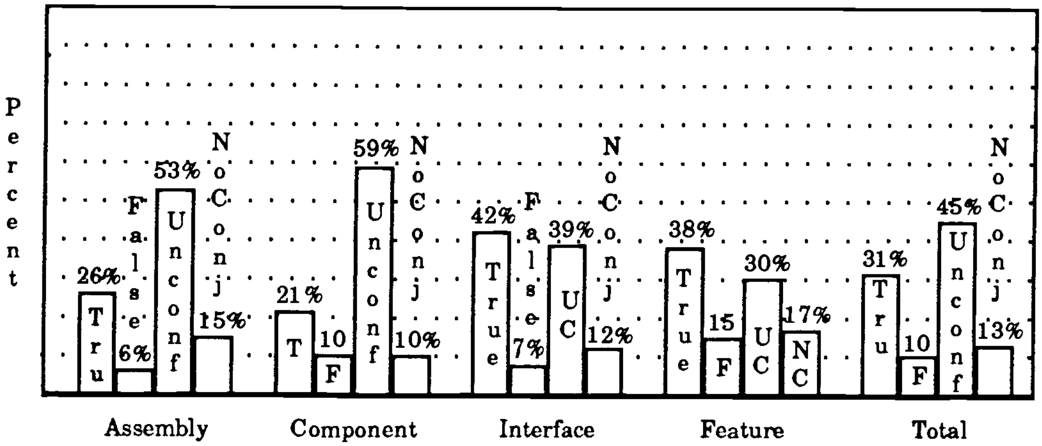
Figure 6: Confirmation of Conjecture by Topic



Question and Conjecture Topic versus Validity

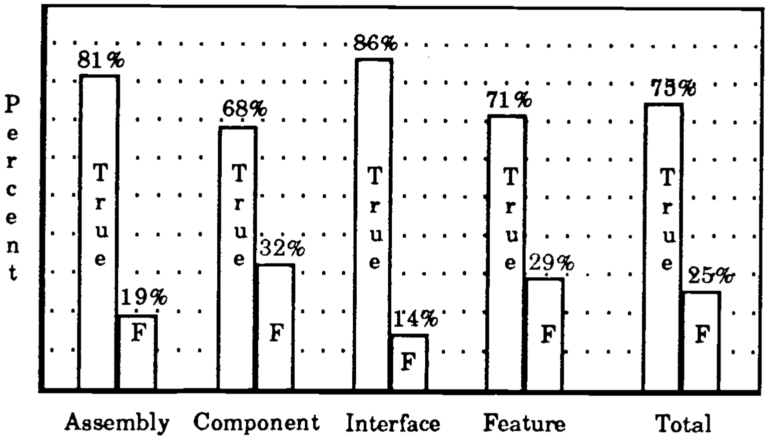
In looking at the *validity* of questions and conjectures (True, False, Unconfirmed, and No Conjecture) of various *topic* (Assembly, Component, Interface, and Feature), two interesting, conflicting results emerge. While the subjects appear to be more comfortable conjecturing about *components* than about other topics, conjectures about components turn out to be false more often than other conjectures. The subjects' confidence in making component based conjectures is evident in two ways. First, as shown in Figure 7 below, fewer component questions are asked with no implicit conjecture (Open and Disjunctive Questions) than in the other topic classes which suggests that the subjects formed more single conjectures about components than about the other topics. Second, more *component* based questions and conjectures went unconfirmed than any other topic meaning that the subjects were more sure of the conjectures they had formed.

Figure 7: Conjecture Validity by Topic



Interestingly enough though, as shown in Figure 8 below, there were proportionally fewer true *component* conjectures than for any other topic of conjecture. This result is particularly surprising considering that the subjects seemed to be more comfortable forming conjectures about components and seemed to be more confident in such conjectures.

Figure 8: Validity of Conjecture by Topic



Question and Conjecture Topic Age versus Validity

Not much can be said about the *age* of question and conjecture topics versus the *validity* of conjecture. One surprising finding is that S10 made five *false conjectures* about *new topics*. S10 was alone in this respect. S10, who worked longer and on more problems than the other subjects, made far more conjectures about new topics as was discussed earlier. These five anomalies occurred rather late in the design after working for an hour and twenty minutes. One such transaction is shown below:

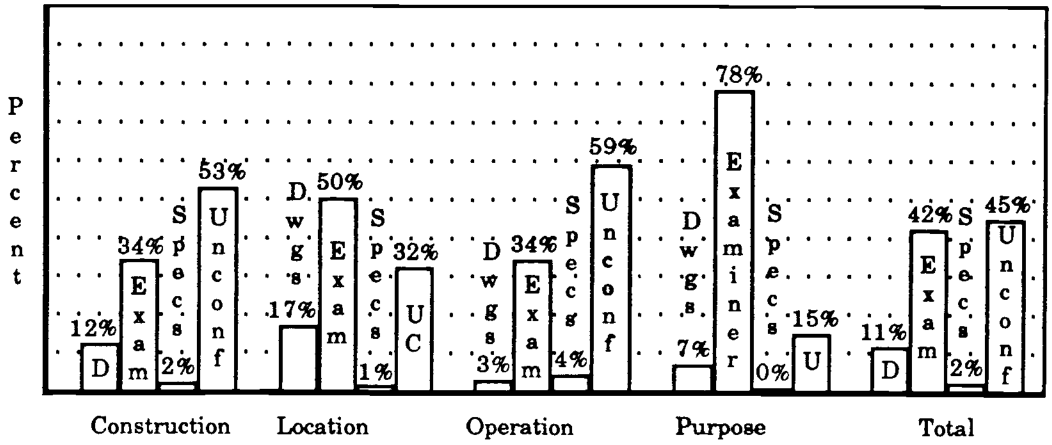
> [S10 pg 35 line 6] (Point) D is in the center of the bath (in the new configuration). Is that right? No, (point) F is in the center of the bath.

This example is typical of the five conjectures, all with verification, about new topics that were refuted.

Question and Conjecture Nature versus Confirmation

In studying the Nature of questions and conjectures (Construction, Location, Operation, and Purpose) versus Confirmation (Examiner, Drawings, Specifications, and Unconfirmed) one significant trend becomes apparent. As shown in Figure 9 below, questions and conjectures pertaining to the *purpose* of a design object tend to be confirmed, and confirmed by the examiner, in higher proportion than questions and conjectures regarding the other Natures.

Figure 9: Source of Confirmation by Nature

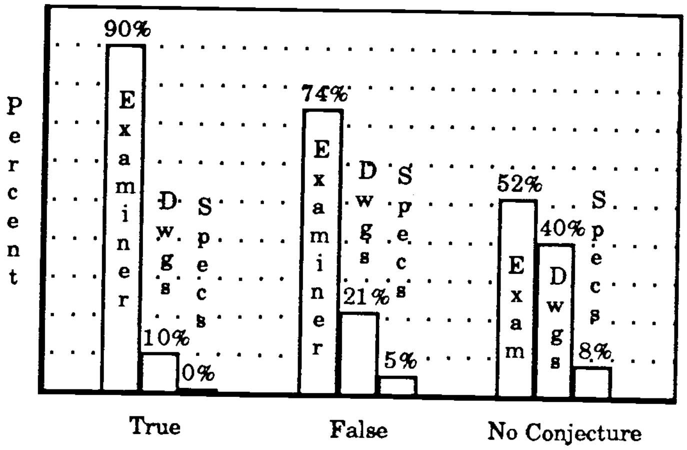


85% of the *purpose* oriented questions and conjectures were confirmed, 91% of these were confirmed by the examiner. This compares to 55% of all questions and conjectures which were confirmed, 77% of which were confirmed by the examiner. This result was consistent for all subjects. The reliance of the subjects on the examiner's knowledge about the design in confirming *purpose* questions indicates two things: 1) the subjects were uncertain of any purpose conjecture they were able to form, and 2) the other forms of design documentation available (i.e. drawings and specifications) are unsatisfactory in answering *purpose* oriented questions and confirming *purpose* oriented conjecture. This being the case, design histories must provide *purpose* information to supplement the other documentation forms.

Question and Conjecture Confirmation versus Validity

The Confirmation of questions and conjectures (Examiner, Drawings, Specifications, and Unconfirmed) compared to their Validity (True, False, Unconfirmed, and No Conjecture) readily indicates the confirmation source used to confirm questions and conjectures. Figure 10, below, shows the confirmation source used for all confirmed questions and conjectures.

Figure 10: Confirmation Source by Validity



The *true* category of the Validity class contains all accurate conjectures that were verified. The *false* category contains those mistaken conjectures that were refuted or corrected by outside sources. The *no conjecture* category is reserved for *confirmed* questions with no single inherent conjecture. It is interesting that the examiner verified 90% of the true confirmed conjectures, refuted 74% of the false confirmed conjectures and answered only 52% of the confirmed Open and Disjunctive Questions.

It is far more important to refute inaccurate conjectures than to confirm accurate ones. Open and Disjunctive Questions are asked when the subjects could not form a single conjecture about the problem at hand; answers to these questions generally must be found. The subjects, however, relied less on the examiner's design history knowledge for these more critical inquiries and more on the other sources of design information, the sources that are usually more readily available.

Chapter 6: Conclusions

This thesis has explored the information that should be included in a mechanical design history. The two hypothesis that guided this research are:

1) A thorough mechanical design history would contain sufficient information to answer all questions and confirm or refute any likely conjecture.
2) A complete design history would consist of a list of constraints which resulted from every decision in the design as well as a list of input constraints to every decision.

From the information included in 2), above, a complete constraint propagation network for a design can be built. This constraint propagation network would be sufficient to fulfil the goals listed in 1); to answer any question and confirm or refute any conjecture likely to be formed by anyone interested in the design.

Three protocols were performed in which practicing engineers made modifications to fairly realistic, existing designs. The knowledge gained by analyzing these protocols allows a focus of effort from recording the constraints involved in every decision to recording the portions of the constraint propagation network that are likely to be examined during a re-design effort.

Of the questions and conjectures observed in the protocols, 69% focused on either the construction or the location of design objects, information that is generally available from the blueprints for a design. This information should also be included in a design history, however, since the last two subjects, S11 and S12, who received more training using the examiner's knowledge as a design history, referred to the examiner to confirm a total of 63% of their construction and location questions and conjectures. Operation and purpose questions and conjectures are not addressed in blueprints and can only be partially inferred from specification documents. These forms of questions and conjectures were confirmed by the examiner 73% of the time for the latter two protocol subjects. Questions and conjectures about the purpose of design objects were confirmed more frequently than other conjecture natures (85% versus 55% for all conjectures by all subjects). The source of confirmation for purpose conjectures was also more likely to be the examiner than for other conjectures (91% versus 77%). A design history must contain the information necessary to address operation and purpose questions and conjectures in order to be considered complete.

78% of the conjectures formed by the subjects which were confirmed by the examiner were true conjectures. For these conjectures, reference to the design history was only of marginal benefit. The design history was necessary, however, to refute the remaining 22% of the conjectures that were false. Design history reference is also critical reference in answering open and disjunctive questions, 52% of that were answered by the examiner.

Questions and conjectures regarding features of the design were more likely to be confirmed than questions and conjectures concerning other topics (70% compared to the average 55%). And while component questions and conjectures were confirmed less often than questions and conjectures concerning other topics (41% confirmed versus 55%), these proved to be false more often than questions and conjectures relating to other topics (32% versus 25% false). A concentration on features in a design history is an appropriate focus. Feature information is the finest level design information. The information included would necessarily indicate what higher level design object the feature relates to (component, assembly, or interface).

Comparison to Related Work

The **natures** of questions and conjectures identified in this study correspond fairly closely to the **content** of conjectures identified by Letovsky and discussed on page 10.

Letovsky classified Questions and conjectures by separate content taxonomies. These taxonomies, however, have three common classifications:

Why: about the purpose of an action or design choice.
How: about the way some goal of the program is accomplished.
What: about what a variable is or what a subroutine does.

These three classes of questions and conjectures correspond to the three **nature** classes: purpose, operation, and construction. Purpose directly defines why a feature is included in the design. Operation covers the goal oriented how of Letovsky's work as well as the action portion of Letovsky's what (what a design object does rather than what it is). Construction relates to the balance of Letovsky's what class: what a design object is.

The one nature classification observed by this study of mechanical designers that Letovsky did not observe was location. Mechanical design is far more spatially oriented than computer programming. If one of Letovsky's programmer subjects had asked where a certain operation were performed, Letovsky would have labelled that a <u>how</u> question since the subject is actually seeking information on <u>how</u> an operation is performed.

Letovsky included two question classes not included in the present <u>nature</u> classification: <u>whether</u> questions and <u>discrepancy</u> questions. <u>Whether</u> questions correspond to disjunctive questions of any nature (a subset of the <u>verification question</u> category), asked to determine which of two conjectures is accurate. <u>Discrepancy</u> questions were not prevalent in the current study and were not given a separate classification here.

Letovsky's taxonomy for conjectures included <u>word conjectures</u>, conjectures about the function of a bit of code based on a meaningful variable or sub-routine name. Mechanical designers make similar conclusions about the purpose or location of a component based on a meaningful name on the drawing (such as "Left Mounting Bracket"), but these are conclusions known with confidence not uncertain conjectures.

Along with conjecture **content**, Letovsky also judged the **certainty** of conjectures as being either <u>guesses</u> or <u>conclusions</u>. No attempt was made in the current study to judge the certainty of the conjectures observed. It is hypothesized, however, that the subjects verbalized simple conjectures when most certain of their conjectures, conjectures with verification when less sure, asked verification questions when still less certain of their conjectures, and asked open questions when they could not form a conjecture.

Letovsky did not include in his study an evaluation of the topic, topic age, confirmation, or validity of the questions and conjectures observed in his study, nor did he include the percentages of the questions and conjectures for the content or certainty classifications identified.

The correspondence between these two independent studies indicates that the taxonomies are reasonably complete and fairly domain independent. Computer programmers ask the same classes of questions and form the same types of conjectures as mechanical designers.

Bibliography

(Bebb 89) Barry Bebb, Keynote Speech, NSF Design Theory and Methodology Workshop, Amhurst Massachusetts, June 1989

(Buckley 89) Patricia G. Buckley, "Product Liability: Industry's Solutions", Design News 19 June 1989.

(Conklin 88) Jeff Conklin and Michael L. Begeman, "gIBIS: A Hypertext Tool for Exploratory Policy Discussion" in Proceedings of the Conference on Computer-Supported Cooperative Work, September 1988, Portland, OR. Copyright Association of Computing Machinery 1988.

(Fang 88) Roger C. Fang, "Intelligent CAD Tool: 2D Free Hand Sketching Recognition System", MS Project Report, Oregon State University, April 1988.

(Graesser 85) Arthur C. Graesser and John B. Black eds <u>The Psychology of Questions</u>, Lawrence Erlbaum Associates, Hillsdale, New Jersey, 1985.

(Hwang 90) Bruce T.S. Hwang, PhD Dissertation, Oregon State University, in preparation.

(Kato 86) Takashi Kato, "What 'Question Asking Protocols' can Say About the User Interface", International Journal of Man-Machine Studies Academic Press Inc. London 1986.

(Lakin 89) Fred Lakin, John Wambaugh, Larry Leifer, Dave Cannon, Cecilia Sivard, "The Electronic Design Notebook: Performing Medium and Processing Medium" to appear in "Visual Computer: Internatioonal Journal of Computer Graphics", Ranjit Makkuni ed. Springer Verlag pub. 1989.

(Lehnert 78) Wendy G. Lehnert, The Process of Question Answering: a Computer Simulation of Cognition, Lawrence Erlbaum Associates, Hillsdale, New Jersey, 1978.

(Letovsky 86) Stanley Letovsky, "Cognitive Processes in Program Comprehension" in Proceedings of First Workshop on Empirical Studies of Programmers, June 1986, Washington DC. Eliot Soloway and Sitharama Iyengar eds. Ablex Publishing, Norwood NJ. 1986.

(McGinnis 89) Brian D. McGinnis and David G. Ullman, "The Evolution of Committments in the Design of a Component" in Proceedings of the ICED Conference, Harrogate, Great Britain, August 1989.

(Mostow 85) Jack Mostow, Toward Better Models of the Design Process, "The AI Magazine" Spring 1985.

(Newell 72) Alan Newell and Herbert A. Simon, Human Problem Solving Prentice Hall, Englewood Cliffs, New Jersey, 1972

(Pare 63) E. Pare, L. Francis, and J. Kimrell, Introduction to Engineering Design, Holt, Rinehart and Winston Inc., New York, 1963.

(Pugh 87) Stewart Pugh, "Design Decisions -- How to Succeed and Why"

(Rabins 86) Michael Rabins, David Ardayfio, Steven Fenves, Ali Serig, Gerald Nadler, Herbert Richardson, and Howard Clark, Design Theory and Methodology -- a New Dicipline, "Mechanical Engineering" August 1986, American Society of Mechanical Engineers, New York.

(Sivard 89) Cecilia Sivard, Monte Zweben, David Cannon, Fred Lakin, Larry Leifer, and John Wambaugh, "Conservation of Design Knowledge" in Proceedings of 27^{t}h Aerospace Sciences Meeting, Reno, Nevada, January 1989, American Institute of Aeronautics and Astronautics pub.

(Stauffer 87) Larry Stauffer, "An Empirical Study on the Process of Mechanical Design" PhD Dissertation, Oregon State University, September 1987

(Tikerpuu 89) Juri Tikerpuu, "General Feature-Based Frame Representation for Describing Mechanical Engineering Design Developed from Empirical Data", Master's Project, Oregon State University, March 1989

(Ullman 87) David G. Ullman and Larry A. Stauffer, "Toward Expert CAD", in Computers in Mechanical Engineering November/December 1987.

(Ullman 88) David G. Ullman, "How Understanding the Mechanical Design Process May Change Engineering Education" in Proceedings of 1988 ASEE Annual Conference, Portland, Oregon, June 1988.

(Weber 84) Bernard R. Webber, "Product Liability -- Some Ounces of Prevention" SAE paper 841050 summarized in Automotive Engineering, Vol 92, September 1984.

APPENDICES

Appendix A: Protocol Problems

Electrical Contacts -- Original Specifications

A high-tech electronics company is manufacturing a new portable computer. As part of the overall design, three batteries are needed to power a time clock. We need you to design a housing and the electrical contacts for holding these batteries and connecting them to a printed circuit board. The specific requirements are:

1. Batteries
- 3 required
- connected in series
- type LR44, see Figure 1 for specifications.

2. Envelope
- The components must fit within the walls of the plastic case you design. The walls may have slots for contacts, locating features, etc.
- The maximum interior dimensions for the plastic case are given in Figure 2.
- Maximum wall thickness, .060".
- The case is to have five walls. The sixth side (where the batteries go in) must remain open.

3. Contacts
- The contact force shall be 0.1 lb. minimum and 1 lb. max. at the batteries and at the printed circuit board.
- Contact plating to be nickel.
- Printed circuit board contact area diameter .100 +/- .005
- Contact locations shown in Figure 2
- Any contact locations for X1 and X2 will be compatible

with the printed circuit board. (The design of the board has not yet been finalized)

- The contacts cannot extend below the bottom of the envelope.

4. Assembly

- The computers will be assembled by robots: the contacts will be handled and fit into place by a 1/4" suction type robotic end effector.
- After the contacts are installed in the case, the cover and the printed circuit board will be set in place. The batteries are inserted last and must be removable.

5 Quantity

- 50,000 units will be assembled per month for three years.

Flipper Dipper -- Original Specifications

Our manufacturing company needs a machine to coat thin, aluminum plates. A thin chemical layer will be cast on the surface of a water bath for coating the plates. The machine needs to dip both sides of the plates into this chemical bath. We need you to design three of these machines. There is a large machine shop on the premises for building these machines in-house.

Specifically, the process for coating the plates will be as follows:

A worker loads the machine with a .063 X 10 X 10 inch aluminum plate (see Figure 1). Since the worker needs to load and unload these plates all day from a standing position, fatigue should be kept to a minimum.

The worker visually insures that the surface of the water is clean and then uses a syringe to inject a pre-measured amount of chemical in solvent solution on the surface of the water. The chemical solution spreads as an oil slick over the surface. When the solvent evaporates (just a few seconds) the 500 Angstrom thick chemical layer is ready to be applied to the surface of the plate. The chemical is non-toxic and safe to handle.

The chemical is applied to the surface of the plate by gently lowering the plate onto the water where surface tension will cause bonding instantly. The plate should not go in more than half of its thickness. Once the plate is coated, it is moved away from the surface and the process is finished for that side of the plate. The excess chemical left on the surface of the water is cleared from the bath manually by the worker (the layer is very thin and sticky).

The process must be repeated to coat the other side of the plate. After coating both sides, the plate is then presented to the worker for unloading. The entire process should take a maximum of 40 seconds.

There are a few constraints to the problem, namely:

(1) The plates can only be edge handled. Only the edge 1/4" around the periphery of the plate can be touched by either the worker or the machine at any time, see Figure 1.

(2) The water must be kept clean because any impurities can affect the integrity of the chemical. This is especially true of organic materials.

(3) Parts of the machine that hold the plate can enter the water, outside of the periphery of the plate, to a depth of up to 1/2" as shown in Figure 1.

(4) It is anticipated that the machine will mount on the table surface in the areas shown in Figure 2. The machines cannot extend to within 1.5" of the edge of the table.

(5) The water bath level is automatically maintained 0.5 inches below the surface of the table, plus or minus 0.01".

Re-design Protocol Instructions

During the following session I am going to ask you to make some modifications to some existing designs. Please work through the problem as you would any other problem. However while you are working on this design I would like you to think out loud. Please try to verbalize your thoughts constantly as if you are talking to yourself during the entire session. If you are thinking about something non-verbal, just say something like "I'm trying to see how this would work". Don't plan what you are going to say, don't explain to me what you are doing, just talk, as if to yourself.

I will be here to work with you throughout the design effort. I am very familiar with the designs you will be working on, and will serve as an information resource for you. You will be performing the actual design, but I will be available to answer any questions during the session. If you need any tools or would ordinarily use any references, just ask.

Again, please work on this design as you would any other except think out loud.

Our company hired a consultant to design an assembly for us. The original specifications and his drawings are attached. We are preparing to build the parts but some changes are necessary. The original designer is no longer available and we would like you to implement these changes for us. For purposes of this experiment, I will give you these changes one at a time. Please sketch your designs to the point that you would feel confident sending them either to our drafting department or directly to the shop.

Flipper Dipper problem (see original specifications)

1) Different plates are proposed which measure 10" by 14". Make the necessary changes to the design to accommodate the new plates.

2) In analyzing the design, the production engineer was concerned that it may be difficult to load and unload the plates. See if you agree with her concern. If you do, what changes would you propose?

3) Rather than have new tables built, we would like to use some existing tables that were part of a different process. Their dimensions are 18" X 60" as shown. Modify the design to mount on the area indicated.

4) We need tighter control on the process than originally specified. We need the plate to contact the chemical with one edge first and then level out on the surface so that the entire plate is in contact. Also one edge must lead as the plate is withdrawn from the water. Please add this feature to your design.

Note: S10 was given all four of these tasks, S11 worked on tasks 1 and 3 only, S12 worked on task 1 as a warm-up exercise only. All re-design problems were given one at a time.

Battery Contacts problem (see original specifications)

1) The batteries we had originally intended to use do not provide enough power. New batteries have been found that are the same diameter and construction but have a height of .263" +.000/-.016 Make the necessary changes to the design to accommodate these taller batteries. The envelope height may increase if necessary.

2) Even more powerful batteries have been identified for this project. The new batteries have the same height as those in the previous change (.263") but the diameter is now .556" +.000/ -.012. The anode cap diameter has also increased to .380". The construction of the new batteries otherwise matches the original batteries. Make the necessary changes to the design to accommodate these larger batteries. Corresponding changes to the size of the envelope will be acceptable.

Note: S12 was given both of these problems, S11 worked on task 1 as a warm-up problem only.

Appendix B: Partial Design History

This appendix shows a portion of the paper design history developed for this project followed by the transcript of the protocol from which the design history was created. The format of this paper design history is discussed in chapter 4

Paper Design History Excerpt:

2140.25 case material
possibly ABS
Spoken: And, one general category of material I could use would be ABS.
Source: Derived
Input constraints:
Affects: 2140.51, 2140.58, 2141.19
Superceeded by: 2140.51

2140.51 case material
possibly polycarbonate
Spoken: if strength is a problem, polycarbonate might be preferable.
Source: Derived
Input constraints: 2140.25, 2140.52
Affects: 2140.58, 2141.19
Superceedes: 2140.25
Superceeded by: 2140.52

2140.52 polycarbonate strength
greater than
ABS strength
Spoken: if strength is a problem, polycarbonate might be preferable.

Source: Introduced
Input constraints: 2140.25
Affects: 2140.51

2140.58 UL flammability
not a problem
Spoken: I'm going to have no problem with uh, UL, flammability, of any of this with my ABS Polycarbonate or even nylon
Source: Derived
Input constraints:
Affects: 2141.04

2141.04 case material
possibly nylon, 30% glass filled
Spoken: Uh, if the part really, uh, is strength intensive, I'll go to a glass filled nylon,
Source: Derived
Input constraints: 2140.58, 2141.05
Affects: 2141.19
Superceedes: 2140.25
Superceeded by: 2140.52

2141.05 nylon, 30% glass filled, strength
very high
Spoken: Uh, if the part really, uh, is strength intensive, I'll go to a glass filled nylon,
Source: Introduced
Input constraints:
Affects: 2141.04

2141.19 case material
ABS
Spoken: But let's start with ABS.

Source: Derived

Input constraints: 2140.25, 2141.20, 2141.23, 2141.25, 2141.51, 2142.53, 2142.57, 2143.05, 2143.12, 2143.24, 2143.41, 2143.48, 2146.00

Affects: 2142.35, 2142.41, 2144.05, 2148.07, 2148.08, 2148.54, 2149.29, 2149.56, 4031.13

2141.20 ABS attributes
good
Spoken: But let's start with ABS. It's a very nice material to use;
Source: Introduced
Input constraints:
Affects: 2141.19

2141.23 ABS mold-ability
high
Spoken: it (ABS) molds well,
Source: Introduced
Input constraints:
Affects: 2141.19

2141.25 ABS price
low
Spoken: it's (ABS) economical.
Source: Introduced
Input constraints:
Affects: 2141.19

2141.27 case volume
small
Spoken: The volume used in this part is not going to lend itself to being price competitive.
Source: Derived

Input constraints: 1025.50, 1026.01, 1026.07, 2127.40, 2139.18

Affects: 2141.45

2141.45 case material price
insignificant

Spoken: because of volume, there'll be a slight difference.

Source: Derived

Input constraints: 2141.27

Affects:

2141.51 ABS capabilities
high

Spoken: But there really nothing that ABS can't do.

Source: Introduced

Input constraints:

Affects: 2141.19

2141.58 case color
not an issue

Spoken: Uh, we're not worried about color, for instance.

Source: Derived

Input constraints: 1011.52, 4031.26

Affects: 2142.35, 2142.41

Superceeded by: 2142.35

2142.35 case color
black

Spoken: But we're going to probably mold this out of, uh, black material.

Source: Derived

Input constraints: 2141.19, 2141.58, 2142.41

Affects: 4031.14
Superceeds: 2141.58

2142.41 black ABS availability
high
Spoken: And that's (black material is) very generic and easy to get hold of.
Source: Introduced
Input constraints: 2141.19, 2141.58
Affects: 2142.35

2142.53 ABS dielectric
very good
Spoken: Also dielectric of, of ABS is very good.
Source: Introduced
Input constraints: 2140.25
Affects: 2141.19

2142.57 ABS water absorption
low
Spoken: It (ABS) doesn't absorb moisture, nylon does a little bit.
Source: Introduced
Input constraints: 2140.25
Affects: 2141.19

2143.00 battery voltage
1.5 volts
Source: Given
Input constraints: N/A
Affects: 2143.01

2143.01 battery series voltage
4.5 volts

Spoken: But the voltage is what I'm talking about. 4-1/2 volts.

Source: Derived

Input constraints: 1012.56, 1012.57, 2143.00

Affects: 2143.05

2143.05 case material requirements
not very severe

Spoken: The, the, the, uh, material requirement of the case, let's just say, are, are not very severe

Source: Derived

Input constraints: 1136.58, 2049.07, 2049.52, 2146.39, 2143.01

Affects: 2141.19

2143.12 case material availability
should be high

Spoken: Let's use a material that's commonly available, that any house in the country would have

Source: Derived

Input constraints:

Affects: 2141.19

2143.24 ABS availability
high

Spoken: And that's ABS.

Source: Introduced

Input constraints: 2140.25

Affects: 2141.19

2143.41 ABS mold shrinkage
common

Spoken: mold shrinkage... very common 7 to 9 thousandths mold shrinkage.

Source: Introduced

Input constraints: 2140.25

Affects: 2143.53, 2141.19

2143.48 ABS mold shrinkage
predictable

Spoken: it's very predictable (ABS mold shrinkage), 7 to 9 thousandths.

Source: Introduced

Input constraints: 2140.25

Affects: 2143.53, 2141.19

2143.53 ABS dimensional stability
good

Spoken: You can really hold your case dimensions.

Source: Derived

Input constraints: 2143.41, 2143.48

Affects: 2144.05

2144.04 case overall tolerance
+/- .004

Spoken: you can control the plus or minus 4 thousandths very easily in the die

Source: Derived

Input constraints: 1055.35

Affects: 2144.05

Superceeded by: 2144.05

2144.05 case overall tolerance
possible

Spoken: you can control the plus or minus 4 thousandths very easily in the die and even a

Source: Derived

Input constraints: 2143.53, 2144.04, 2141.19, 1026.07

Affects: 2141.19

Superceedes: 2144.04

2146.00 case material

not structural foam

Spoken: We don't want structural foams.

Source: Derived

Input constraints: 1136.58

Affects: 2141.19

Superceedes: 2141.04

2146.39 case stress

quite low

Spoken: My psi's are going to be quite low.

Source: Derived

Input constraints:

Affects: 1136.58, 2143.05

2148.07 ABS wall thickness

.060 to .180

Spoken: "Wall thickness: Prevex polymers injection molded parts will range from .060" to .180"

Source: Introduced

Input constraints: 2141.19

Affects: 2148.31

Superceeded by: 2148.08

2148.08 ABS wall thickness

<.060 possible

Spoken: "Lesser thicknesses have been used over short distance and small parts.

Source: Introduced
Input constraints: 2141.19
Affects: 2149.56, 2148.31
Superceedes: 2148.07

2148.31 ABS wall thickness typical
0.06
Spoken: Telling me that 60 thousandths is the thickness that typically I ought to use
Source: Derived
Input constraints: 2148.07, 2148.08, 2127.40, 1025.50, 1026.01, 1026.07
Affects: 2148.55

2148.54 ABS fillet radius
1/4 times
ABS wall thickness
Spoken: Oh, here's a guideline of, uh, one fourth of the material thickness or .015 to be the fillet radius to use throughout.
Source: Introduced
Input constraints: 2141.19
Affects: 2149.29, 2148.55
Superceeded by: 2148.55

2148.55 ABS fillet radius
0.015
Spoken: Oh, here's a guideline of, uh, one fourth of the material thickness or .015 to be the fillet radius to use throughout.
Source: Derived
Input constraints: 2148.31, 2148.54
Affects: 2149.29
Superceeded by: 2148.54

2149.29 case fillet radius
0.015
Spoken: Fillets .015
Source: Derived
Input constraints: 2127.40, 2141.19, 2148.54, 2148.55
Affects:

2149.56 isolating wall width
0.03
Spoken: I'm going to go around 30 thousandths for much of that wall.
Source: Derived
Input constraints: 2139.18, 2141.19, 2148.08
Affects: 3104.35, 3150.30, 2150.13
Superceeded by: 2150.30

2150.03 isolating wall height
0.25
Spoken: It's not very high, 200, roughly 250 thousandths high,
Source: Derived
Input constraints: 1025.50
Affects:

2150.13 cavity width
0.487
Spoken: I am going to go 30 thousandths and that would, uh, make it 487 thousandths.
Source: Derived
Input constraints: 1059.36, 2149.56
Affects: 2150.40
Superceeded by: 2150.40

2150.30 isolating wall width
.030 + a little
Spoken: A little more than 30,
Source: Derived
Input constraints: 2150.40, 2149.56
Affects: 2151.07
Superceedes: 2149.56

2150.40 cavity width
0.485
Spoken: 485 thousandths that's the cavity width...
Source: Derived
Input constraints: 2150.13, 3014.25
Affects: 3003.02, 2158.07, 2157.10, 2150.30
Superceedes: 2150.13
Superceeded by: 2157.10

2151.07 Contact 2 positive contact space width
.035 +/- .010
Spoken: Huh, what I really ought to do is subtract 485 that leaves me with 35 thousandths plus or minus 10.
Source: Derived
Input constraints: 2150.30, 2138.55
Affects: 2156.57, 2152.25

2152.25 Contact 2 positive contact space width tolerance
+/- .010
Spoken: I'm using up 10 thousandths...
Source: Derived
Input constraints: 2151.07
Affects: 2152.31

2152.31 Contact 2 positive contact deflection tolerance

0.02

Spoken: The spring is allowed 20 thousandths variation in height in addition to its height plus or minus 0.008.

Source: Derived

Input constraints: 2135.19, 2152.25

Affects: 2153.19, 2153.18

2153.18 Contact 2 positive contact deflection minimum 0.008

Spoken: and that means the spring is going to be 0.008 to .028 in deflection

Source: Derived

Input constraints: 2152.31, 2135.17

Affects: 3037.58, 2156.20, 2154.57

2153.19 Contact 2 positive contact deflection maximum 0.028

Spoken: and that means the spring is going to be 0.008 to .028 in deflection

Source: Derived

Input constraints: 2152.31, 2135.11

Affects: 3037.58, 2156.20, 2154.36

2154.36 Contact 2 positive contact force maximum .84 lb

Spoken: Then, 28 thousandths deflection is .84 pounds.

Source: Derived

Input constraints: 1117.13, 2153.19

Affects: 2155.05

2154.57 Contact 2 positive contact force minimum .24 lb

Spoken: So, I am going to end up with a spring that, uh, will vary predictably...
Source: Derived
Input constraints: 1117.13, 2153.18
Affects: 2155.05

2155.05 Contact 2 positive contact force
predictable
Spoken: So I'm going to end up with a spring that is predictable.
Source: Derived
Input constraints: 2154.36, 2154.57
Affects:

2155.20 contact deflection nominal
equals half
contact defl. minimum + contact defl. maximum
Spoken: Whatever is left of the system has 35 thousandths plus a nominal up here equals 2836.
Source: Derived
Input constraints:
Affects: 2156.20

2156.20 Contact 2 positive contact deflection nominal
.018 +/- .010
Spoken: I will dimension the height of the spring as 18 thousandths plus or minus 10 relaxed.
Source: Derived
Input constraints: 2153.18, 2153.19, 2155.20
Affects: 3026.12, 2156.57

2156.32 Contact 2 positive contact relaxed height
equals

Cont. 2 pos. cont space width cont 2 pos cont defl

Spoken: Wait a minute. No, no, I'm wrong. 18 thousandths plus the 35 space that's left over so that's uh, 45, 53 thousandths, excuse me.

Source: Derived

Input constraints:

Affects: 2156.57

Superceeded by: 2156.57

2156.57 Contact 2 positive contact relaxed height
.053 +/- .010

Spoken: 53 thousandths, plus or minus 10 will be the prebend on that spring.

Source: Derived

Input constraints: 2156.32, 2156.20, 2151.07

Affects: 3046.18, 3045.37

Superceedes: 2156.32

2157.10 cavity width
known

Spoken: Now, I have this dimension of the cavity.

Source: Derived

Input constraints: 2150.40

Affects:

Superceedes: 2150.40

2158.07 contact 2 retention pocket
may hit
battery

Spoken: I had a space limitation on that (contact 2 retention pocket)

Source: Derived

Input constraints: 1013.38, 2109.38, 2150.40
Affects:

2158.25 battery diameter
approximately 0.45
Spoken: The radius of the spring (read battery) is 450 thousandths.
Source: Derived
Input constraints: 1013.38, 3014.25
Affects: 2158.31

2158.31 battery radius
approximately 0.225
Spoken: 225 and 145, 159 thousandths in both directions.
Source: Derived
Input constraints: 2158.25
Affects: 3003.02

4030.57
cover wall thickness / .060 typical
.060 typical wall thickness,
4031.13
cover material / ABS
ABS let's er make it black, um,
4031.14
cover color / black
ABS let's er make it black, um,

Excerpt of S2 Protocol Transcript

The asterisks (*) indicate pauses.

Subject: And, uh, one general category of material I could use would be ABS. Uh, before I say that, let me, let me maybe look at a sheet of uh... Oh, I don't have it in this book. In my other book I have a general sheet of plastic properties. Nylon, polycarbonate. Uh, if strength (3:40:54) is a problem, polycarbonate might be preferable. I'm going to have no problem with uh, UL, flammability, of any of this with my ABS or polycarbonate, or even, nylon. Uh, if the part really, uh, is strength intensive, I'll go to a glass belt nylon, oh say 30 percent. But let's start with ABS. It's a very nice material to use: it molds well, it's economical. The volume used in this part is not going to lend itself to being price competitive. Uh, are we running over time here?

Examiner: That's ok.

S: Yeah. It's not going to lend itself to being price competitive. Uh, because of the volume, it might be a slight difference. But there really nothing that ABS can't do. Uh, we're not worried about color, for instance. So it would be a trade-off there if, if ABS, we had to have a certain color, uh, a custom blended color, we would worry about the colorfastness. And, uh, U, for instance, UL, uh, ultraviolet. not the other UL Underwriter's Laboratories, ultraviolet, uh, can degrade the colorfastness in ABS. But we're going to probably mold this out of, uh, black material. And that's (black material is) very generic and easy to get hold of. So I'm going to look at some properties and find out if they discuss any... Also dielectric of, of ABS is very good. It doesn't absorb moisture, nylon does a little bit. But the voltage is what I'm talking about. 4-1/2 volts. The, the, the, uh, material requirement of the case, let's just say, are, are not very severe. Let's use a material that's commonly available, that any house in the country would have on their warehouse shelf. We can competitively bid; it's very common. And that's ABS. Ah, now, impact grade * volume, density, old shrinkage, inch per inch. Say again, very common 7 to 9 thousandths mold shrinkage and then it's very predictable, 7 to 9 thousandths. You'll like that. You can really hold your case dimensions. Uh, the whole thing being an inch and a half long, and 7 to 9 thousandths, you can control the plus (3:44:07) or minus 4 thousandths very easily in the die and even allow for wear in the tools. It's very nice. Uh, impact rates flame retardant ranges... They don't talk about minimum wall thickness. I have to go hunting. Minimum wall thicknesses has not been a problem for me before. * I'm just going hunting for a while. You have to do that. Flow data, viscosity, shielding. All right, maybe there's something back up in their design manual. Material behavior. We don't want structural forms. Let's see. Material data. Small index here. Some charts here. Flexural creep data, applied stress, 1000 psi, apparent modules, changing modules over time. Hum interesting. My psi's are going to be quite low. Uh, * tensile stress strain, 1/4 inch thick specimens, nothing on thickness. Oh, well, a dry run on that. * Uh-h, Machine Design, design plastic parts. * It's a very nice article. Stress versus time. They talk a lot about creep * I'm not worried about creep because I don't want to face that problem.

E: That's usually the way it goes.

S: Ah-h, all right, Table of Contents. Section Thickness. Oh, boy, here we go. Page 22. "Wall thickness is a prime consideration. Prevex polymers injection molded parts will range from 60 to 180 thousands of an inch. Lesser thicknesses have been used over short, short floor distances and small parts. There's no optimum wall thickness." All right. Telling me that 60 thousandths is the thickness that typically I ought to use but that I can get thinner over small areas. Oh, here's an interesting note here giving me a guideline of, uh, one fourth of the material thickness or 15 thousandths as being the fillet radius to use throughout. Might as well copy that down here. Well, I'll just have to go where no man has gone. Fillets .015 (3:49:45) Where was I? There's a little bit of Kentucky windage on picking my, uh, material thickness. I'm going to go around 30 thousandths for much of that wall. It's not very high, 200, roughly 250 thousandths high, I am going to go 30 thousandths and that would, uh, make it 487 thousandths. A little more than 30, 485. * 485 thousandths that's the cavity width... * And that's 485. * Huh, what I really ought to do is subtract 485 leaves me with 35 thousandths plus or minus 10. I said I had a total of 30 thousandths for the system. And, uh, my nominal compression height is, uh, instead of 17, I'll use 16 thousandths. And... Oh, What I'm doing now is trying to figure out what the bend in the height in the spring would be. And I have 30 thousandths for the system. * But I've got to come in from those extremes. I'm using up 10 thousandths... * Uh, all right. So, if the system was only 20 thousandths because I have here on page 1, I have 10 thousandths of tolerance consumed. The spring is allowed 20 thousandths variation in height in addition to its height plus or minus 0.008. So then, I've got to come up with some dimensions here that have only 20 thousandths variation tolerance for the sys..., tolerance for the spring. And, uh, that comes in 5 thousandths from each end there and that means the spring is going to be 0.008 to .028. Ah, in deflection. * And, ah, why don't I just take those particular dimensions and figure out what what force is. Have, uh. * Uh-h, oh, yeah, I need to, touch base here. * Coming back to my s..., nominal 17 thousandths, if that's .5 pounds 1 pound is 33 thousandths. Then, uh, 28 thousandths deflection is .4 pounds and 8 thousandths is

.24 pounds. So, I am going to end up with a spring that, uh, will vary predictably... Well, I'm still going to get the 3 to 33 thousandths. It was an unnecessary exercise. * Whatever is left of the system has 35 thousandths plus a nominal up here equals 2836. I need 18 thousandths. I now know what my spring has to be shaped like. Somewhere here should have enough detail of the spring and can put that in. I put it on one of these sheets for the spring seems to be fairly clear. * I'm going to put it on sheet 5. Since I have chosen the site for this version * I will dimension the height of the spring as 18 thousandths plus or minus 10 relaxed. Wait a minute. No, no, I'm wrong. 18 thousandths plus the 35 space that's 10 left over so that's uh, 45, 53 thousandths, excuse me. 53 thousandths, plus or minus 10 will be the prethinned on that spring. Now, I have to dimensional cavity. I'll need to call out that little region there that I'm putting the lance in. * Ok. I had a space limitation. But, ah, * The radius of the spring is 450 thousandths. 225 and 145, 159 thousandths in both directions. * Now, what's left of that 125? It's going to be a 6 thousandths material that's lanced to grab into that punch. * Just ocurred to me a slightly different way to lance it. Rather than a little tooth that comes out. I can more or less cut it from the end. Let's look at this spring from another view. ** Ok, now, the way I can do it is by cutting a lance out the side. I just showed it in the wrong direction, it should lance out that way.

Glossary

Conjecture: a conclusion inferred by the subject from incomplete information. Interpretation, supposition, or assumption believed but not known for certain.

Conjecture with Verification: A conjecture immediately followed by a verification attempt. Formed when the subject is unsure of the accuracy of the conjecture.
e.g. "I think this is ****. Is that right?"
The verification attempt is added as an after-thought. While the verification attempt is usually in the form of a question, as in the above example, this question is not treated as a separate passage in the analysis. The conjecture may or may not actually be verified by the examiner or other outside source, the passage is classified here by its format only, not by the response.

Simple Conjecture: A conjecture formed with no apparent, immediate attempt at verification. Formed when the subject feels confident in the validity of the conjecture.
e.g. "I think this is ****."

Constraints: the limitations imposed on the values of every feature of every object involved in the design.

Sources of:
<u>Given</u>: those constraints coming from outside of the design space. These can be from the problems instigators in the form of specifications or from decisions made by other designers on adjacent parts of a large design. Given constraints are usually present

at the beginning of the design and are often function oriented.
eg. "Assembly method to be automatic."

<u>Introduced</u>: those constraints brought into the design by the designer, from reference books or the designer's own knowledge base for example, which exist independent of the problem at hand. These exist independent of the design but are often brought into the design only because of certain other constraints extant in the design.
eg. "Adhesives do not lend themselves to automation."

<u>Derived</u>: those constraints which are brought into the design as a result of design decisions (see below).
eg. "I will not use adhesives in this design."

Downstream Constraints: Those derived constraints for which a certain constraint acted as an input to.

Flexibility of Constraints: the ability of a constraint to change: flexible, firm, immutable

Form Constraints: constraints acting on form features defining the geometry, topology, material, etc. of a design object.

Function Constraints: constraints acting on function features defining the purpose of a design object or operational measures such as speed.

Motivating Constraints: those constraints extant in the design which prompt the introduction of a constraint.

Input Constraints: those constraints which are considered in a decision are input constraints both to that decision and to the constraint resulting from that decision.

Superseding Constraint: If a constraint entering the design contradicts or updates an earlier constraint, it is said to *supersede* that previous constraint.

Instantiation Constraints: those constraints in which a feature is assigned a value (e.g. side wall width = .060").

Relationship Constraints: those constraints in which one feature, the dependent feature, is related to one or more independent features (e.g. side wall width = isolating wall width).

Constraint Propagation Network: a history of the interaction of the constraints in a design.

Decisions: the operations in which constraints interact resulting in new derived constraints. The input constraints to any decision are some subset of all the given, introduced, and derived constraints extant in the design. The result of a decision is one or more new derived constraints. Using this model, every derived constraint is said to be the result of a decision.

Design history: a record of the process carried out by the designer while designing a mechanical artifact. A medium independent form of a complete design notebook.

Design notebook: a bound notebook in which all of a mechanical engineer's work on a particular design is performed; the pages typically are permanently bound, numbered, and dated.

Protocol: a method of studying behavior whereby a subject is audio and video taped performing some specific task of interest.

Question: interrogation by the subject or discussion initiated by the subject about any uncertain aspect of the design. Either the examiner, the drawings, or the subject's own memory can be probed in a questions for this research.

Verification Question: A question formed such that a simple answer is all that is required by way of response. These are primarily yes or no questions formed when the subject wants to verify a single, conjectured, plausible answer

e.g. "Is this ****?"

Also in this class are disjunctive questions asked when the subject has conjectured two feasible answers.

e.g. "Is this **** or @@@@?"

Note that questions of this form are classified as *verification questions* whether or not they are explicitly verified.

Open Question: A question asked requiring a detailed answer. Formed when the subject has no clear idea of what the answer might be.

e.g. "What is this?"

Index

assembly 13,34,40,47
battery contacts problem 28
component 13,34,40,47
confirmation 37,38,44,45
conjectures 10,11,26,29
    simple 33,40
    taxononomy for 11,33
    with verification 33,40
constraints 4,9,13,14
    as spoken 20-21
    derived 14-18,21,22
    downstream 22
    flexibility of 16,20
    form 43
    function 43
    given 14-16,21
    input 13,16,18,21
    instantiation 14,19
    introduced 14-16,21
    language for 19-20
    motivating 15,21
    output 13
    propagation of 17,22,23
    relationship 14,19
    source of 14-16,21
    superseding 18,23
construction 36,42
decisions 3,7,8,13,16,21,24
design history 2,4,7,9,13,
        17-24,29,41-50,56
design notebook 3,8
design object 13-14,24,35,40
design process model 13
features 13,20,34,40
    atomic 13
    composite 13
    dependent 14,19
    form 14
    function 14
    independent 14,19
flipper dipper 27
gIBIS 6,7
Hyperclass 17,24
interface 35,40
Letovsky, Stanley
        6,10,31,60
location 36,42
nature 36,42
operation 37,42
protocol 17,25
purpose 37,42
questions
    disjunctive 38
    open 33,38,40
    taxnonomy for 11,33
    verification 33,39
taxonomy 32
topic 34,40
    age 35
unconfirmed 37,38,40
validity 38
vmacs 6,8