Engineering Design as a Foundational Metaphor for Information Science: A Resistive Postmodern Alternative to the "Scientific Model"

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by

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Abstract

There are two linked fundamental crises in Information Science: an urgent need for solutions to the information explosion; and a lack of an operative metaphor upon which to base solutions. Current theoretical debates focus on whether information science is a coherent field of thought or an "assemblage of chunks" drawn from other disciplines. The "assemblage of chunks" phrase is sometimes applied in a pejorative sense to the field of ***engineering***. Moreover, engineering is often neglected or misunderstood as an epistemologically coherent entity, especially in the literature of information science. Vincenti asserts that misconceptions about the nature of engineering have led some researchers to view engineering (incorrectly) as mere applied science. Buckland and others have indicated some areas of information science are so strongly dominated by a "scientific model" of research that they are not able to grasp an the potential value of engineering as a problem solving metaphor.

Examination of engineering as a problem solving framework holds promise of advancing the field of information science. Engineers are just beginning to address design as a coherent, human orientation toward problem solving. Analysis of engineering epistemology and application of a postmodern lens to engineering and information science demonstrate that information science has been "barking up the wrong metaphor." Rorty's theory of pragmatics and Levi-Strauss's concept of "bricolage" provide a strong link between the strengths of engineering and the crises of information science.

Acknowledgments

Humility is perhaps the best word to describe the research process. One is privileged to engage the works of many great minds and to contact a variety of scholars whose ideas bear on one's investigations. When one explores new fields and borrows from other's works, there is a sense of cobbling together many pieces and threads into a whole tapestry. It is my hope that those who assisted me see their works embedded within my tapestry and that they will forgive any flaws I may have introduced into that tapestry.

Of course, any piece of research and especially a doctoral dissertation is a team effort. I want to acknowledge all those on this team. The faculty of the School of Library & Information Management have been most supportive of this research enterprise. My dissertation committee was supportive, rigorous, and always available. On my committee, from the School of Library & Information Management were Herbert Achleitner and Roger Wyatt; from Sociology & Anthropology, Evandro Camara. I most especially thank my chair, Brian O'Connor.

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Chapter One: Introduction

Prolegomenon to Dialectic

Several fundamental crises exist in Information Science. These range from concern about lack of a theoretical framework for the field to the urgent need for solutions to the information explosion.[1] Harris (1986) asserts many of these issues remain unresolved - he attributes this failure to use of inappropriate models for problem solution. In particular, he characterizes the application of a scientific model in Information Science as "nonsense" and as a "ludicrous misapplication" of positivist technique (p. 529). Gutting (1980) further asserts that use of a positivist line of inquiry in Information Science is "misdirected and fruitless" (p. 84). Indeed, Giddens (1976) argues researchers who persist in searching for a "social-scientific Newton as a sure path to science" in this field "are not only waiting for a train that won't arrive, they're in the wrong station altogether" (p. 13).

Engineering design as a problem-solving framework holds promise of resolving the crises. Engineers themselves are beginning to address the nature of engineering design as a coherent, human orientation toward problem solving. However, engineering is often neglected or misunderstood as an epistemological entity, especially in the literature of Information Science. Layton (1976) and Vincenti (1990) assert misconceptions about the nature of engineering have led some researchers to view

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[1] For a litany of "traps, diseases and malaises" associated with the information explosion, see Wurman, R.S. (1990). Information anxiety: What to do when information doesn't tell you what you need to know. New York: Bantam Books, pp. 124-129.

engineering as mere applied science. In a similar vein, Buckland and Liu (1995) have indicated some areas of Information Science are so strongly dominated by a "scientific model" of research they are not able to grasp an appropriate perspective of the potential value of engineering as a problem solving metaphor for the field.[2] The literature of engineering epistemology provides a contextual framework that informs the direction of this study and illuminates ideas for an operative metaphor that is an alternative to the "scientific model" for problem solving in the field. This epistemological framework is given direction by "Kuhnian" indices or frames.

Issues in Information Science: A Dialectic of Defeat

Kuhn (1970) states that theories are at best only approximations of the reality observed in any given study. Theories and the models derived from them "attach to nature only here and there" (p. 21). In the "interstices" between those points of attachment, one may encounter other theories and models that stimulate a direction for inquiry. Yet researchers often fail to recognize the potential value these theories and models have for advancing their respective investigations. Harris (1986, 1993) posits ideas that challenge the fundamental nature of research in Information Science. He states there is something "dramatically wrong" with the field's research orientation (1986, p. 515). The prevailing ideology favors adoption of a positivist epistemology

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[2] A current example of a strong "scientific model" of research to "successfully extract technical and scientific information from all available sources" in the field is advanced by Zimmerman, D.E. & Muraski, M.L. (1995). The elements of information gathering: A guide for technical communicators, scientists, and engineers. Phoenix, AZ: Oryx Press.

for research in Information Science. Harris argues this type of thinking is a "scientistic delusion" - it has produced an "insular trajectory" in research which in turn has led to a "collective act of intellectual impoverishment" in the field (1986, pp. 515-520). O'Keefe (1993) asserts such positivist efforts "to enforce theoretical coherence on the field can only work to our collective disadvantage" (p. 79).

Similarly, Buckland and Liu (1995) state analysis of intellectual frameworks in Information Science has long been neglected and theory in the field cannot be expected to advance unless alternative sets of assumptions are developed and compared. The long domination of "scientific" logical positivism in Information Science is now being questioned, and theoretical and epistemological assumptions are finally receiving critical attention (p. 389).

Whatever the case may be, Harris (1986) feels this "general malaise of research" signals need for a rethinking of the epistemological foundations of research in Information Science (p. 515). He proposes an orientation that is dialectical in nature. An emphasis on the dialectic challenges the "complacently descriptive approach" of positivism; it questions the search for reductionist answers of "relevance" to complex questions and the tendency to present research results as "professionally palatable findings" (Harris, p. 525). The dialectical mode of analysis explores the contradictions inherent in any given research inquiry and it stresses change, conflict, and tension as the foundations of reality rather than stability and consensus.

To exercise the dialectic approach effectively, scholars must dedicate themselves to arguing well - to the "extended argument" (Harris, 1993, p. 145).

A dialectical line of inquiry supported by the art of extended argument will enable "the analyst to be far more sensitive to social potentialities than the more conventional positivist approaches" that have dominated the field for more 50 years (Harris, 1986, p. 525). It will inform researchers in their attempt "to restructure the way they define the 'right' questions and the nature of 'correct' answers" (Harris, 1986, p. 529). And finally, a scholarly commitment to this process will inform the theoretical orientation of Information Science and provide a framework from which potential problem-solving models for the field may emerge (Harris, 1993, p. 145).[3]

Within this field, from about 1960, the phrases "information science" and "information retrieval" were adopted, largely replacing the older term "documentation" (Buckland & Liu, 1995, p. 386). Vakkari (1994) is supportive of this notion and further asserts researchers would be misguided on theoretical grounds to separate the theory of Library Science from that of Information Science.

These statements illuminate two implications for this study. First, one must be aware issues relevant to the field of Library Science - both currently and from an historical standpoint - were inherited by Information Science and Information Retrieval when the latter terms were adopted. Thus the shift from older terms to newer ones embodied more than a superficial change of syntactical descriptors; it involved recasting fundamental issues from a specifically narrower field to a broader, more

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[3] Similarly, Debons, Horne, & Cronenweth (1988) assert critical discourse among information professionals "allows for active exchange of ideas while implicitly verifying the logic of these ideas for their defense" (p. 48). In particular, critical discourse can provide a forum for developing "valid and appropriate" models of engineering design activity.

interdisciplinary one.[4] In the fields of Information Science and Information Retrieval, these issues reflect a more complex nature (Machlup & Mansfield, 1983). Second, Vakkari's statement implies certain unresolved and problematic issues in Library Science and Documentation must be present in Information Science and, by extension, in Information Retrieval. [5]

Blair (1990, 1992) addresses these issues from the perspective of Information Retrieval; his apparently narrow perspective leads to provocative implications for the broader context of Information Science. Representing documents for retrieval is a central problem in the field of Information Retrieval. Blair asserts the most intricate or carefully designed retrieval algorithms cannot compensate for inappropriately represented documents. Most proposed retrieval algorithms presuppose reasonably good representations of documents. Yet the limited research that has been done to test the effectiveness of document representations has indicated indeterminacy in the representation of documents is pervasive and significant and the indexing process as a whole is not well understood. According to Blair, all work in Information Retrieval is

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[4] The nature of these issues is examined in Richardson, J.V., Jr. (1982). The spirit of inquiry: The graduate library school at Chicago, 1921-51. Chicago: American Library Association. Use of an "architectonic theory" of library science based on a scientific model to legitimize research and documentation in the field are examined by Copeland, J.H. (In press). Pierce Butler (1884-1953). In J. Rosenblum (Ed.), Dictionary of literary biography. Detroit, MI: Gale Research. Also see Butler, P. (1933). The nature of science. In An introduction to library science. (pp. 1-30). Chicago: University of Chicago Press.

[5] Shapiro asserts "every discipline has a terminology whose vicissitudes often assume considerable importance [and hence are] a vital component of the discipline's history" (p. 384). For a succinct history of the term "information science," see Shapiro, F.R. (1995). Coinage of the term information science. Journal of the American Society for Information Science, 46 (5), 384-385. For research on the origins of "information science," see Williams, R.V., Whitmire, L., & Bradley, C. (1997). Bibliography of the history of information science in North America, 1900-1995. Journal of the American Society for Information Science, 48 (4), 373-379.

based on the assumption a reasonably good theory or practice of document representation exists in the field, but this is not the case. Blair also believes problems of representation cause large databases of documents to be fundamentally different from small ones for information retrieval. Among other effects, this qualifies the findings of nearly all retrieval tests conducted in the past as unrealistic and misleading.

Blair (1990, 1992) further asserts indeterminacy problems associated with document representation cannot be resolved by training indexers better nor by developing new classification schemes and new retrieval algorithms. Indeterminacy results in large part from the use of document representations in linguistically unorthodox ways - this is primarily a problem of language and meaning. Blair rejects retrieval models that are derived from traditional theories of language and proposes a "genetic algorithm" based on an "ordinary language" or implementational view of meaning as reflected in Wittgenstein's (1953) theory of "Language Games."

According to Wittgenstein (1953) definitions in everyday language do not make sense for a speaker until he/she understands the general application of the words being defined. This general understanding only comes after the speaker experiences the many "perspicuous examples" of how the words in question are used.[6] Blair (1990) argues document representation - and retrieval models - must be based on "perspicuous

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[6] For succinct discussions of Wittgenstein's "language games," refer to Bloor, D. (1983). Wittgenstein: A social theory of knowledge. (pp. 22-49). New York: Columbia University Press; Bartley, W.W., III. (1985). Wittgenstein. 2nd ed. (pp. 119-155). LaSalle, IL: Open Court; and Monk, R. (1990). Ludwig Wittgenstein: The duty of genius. (pp. 336-346). New York: The Free Press.

examples" of ordinary language. The language in question must be grounded in the activities in which Information Retrieval is embedded. These fundamental activities provide the "perspicuous examples" that are necessary feedback for understanding the language. Blair's proposed model reflects the contingent and pragmatic nature of "ordinary" language.

In a broader sense, Blair's (1990) consideration of a genetic algorithm is an "extended argument" for a new language in the field of Information Retrieval. Indeed, Blair seems to reflect a dilemma described by Popper (1970):

> At any moment we are prisoners caught in the framework of our theories; our expectations; our past experiences; our language. But we are prisoners in a Pickwickian sense: if we try, we can break out of our framework at any time. Admittedly, we shall find ourselves again in a framework, but it will be a better and roomier one; and we can at any moment break out of it again. (p. 56).

The central point is that Blair is caught in the framework of the older language. He is attempting to break out of it and propose a new, more appropriate language for his field.[7]

Blair (1990, 1992) elaborates on the issue of theory in Information Retrieval. He asserts there is "no unifying vision of what it means to work on Information Retrieval theory, or to build effective Information Retrieval systems" (1990, p. vii). Lacking a theoretical framework, Information Retrieval has been unable to develop

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[7] Similarly, Devlin posits the intriguing idea of an "algebra of conversation" based on an "algebraic rug" of underlying linguistic patterns that can potentially interconnect different fields of research. See Devlin, K. (1997). Verbal tangos. In Goodbye, Descartes: The end of logic and the search for a new cosmology of the mind. (Pp. 208-239). New York: John Wiley.

appropriate engineering design models to solve problems inherent in document representation and retrieval. Blair does not deny the existence of such models in the field; he simply notes the models that do exist are "not as easily identifiable" or as well understood as the models that one finds in other more established fields (1990, p. 298).[8] Blair pointedly asks: "Why can't we build document retrieval systems based on a better understood retrieval model?" (1992, p. 12).[9]

These issues lead Blair (1990) to question the fundamental nature of the field from a scientific perspective. He asks: "Is the study of Information Retrieval a science?" That is, "Do researchers in the field conduct their inquiries in a scientific manner, and do they look at problems which are scientific in nature?" (p. 277).[10] Blair responds with a "Kuhnian paradigm analysis" (Gutting, 1980, p. 88) of Information Retrieval. He concludes the field has many scientific components and from a "strictly Kuhnian perspective," Information Retrieval must be viewed as a pre-paradigm or revolutionary field. From the standpoint of engineering models, this implies there are several candidate models emerging and no one model has yet gained "ascendancy". Blair asks: "What might some of these models look like?" (1990, pp. 297, 305).

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[8] Spink and Losee identify problems associated with application of various models in Information Retrieval. See Spink, A. & Losee, R.M. (1996). Feedback in information retrieval. In M.E. Williams (Ed.), Annual review of information science and technology (Vol. 31, pp. 33-78). Medford, NJ: Information Today.

[9] To examine these issues from an historical perspective, see Neill, S.D. (1992). The dilemma of the subjective in information organization and retrieval. In Dilemmas in the study of information: Exploring the boundaries of information science (pp. 1-21). Westport, CT: Greenwood Press.

[10] Miller (1996) offers a treatise on "scientific methods" that illuminates the concerns cited by Blair (pp. 71-104).

In his final point, Blair (1990) states there is a "growing undercurrent of urgency" (p. viii) in the study of theory and research in Information Retrieval. Problems of document representation and retrieval are becoming increasingly complex. Moreover, Information Retrieval is no longer just the "library problem" as similar difficulties with representing and selecting information impact retrieval systems in most other areas of Information Science. Adding to this sense of urgency is the fact that extraordinarily high standards of retrieval are required with increasing frequency in any field in which information plays a strategic role.

Entman (1993) states potential research paradigms in information science have "remained fractured with pieces here and there but no comprehensive statement to guide research" (p. 51). Entman proposes the concept of "framing" as a means of bringing together insights and theories that would otherwise remain scattered in other disciplines. Framing is a potential technique for enhancing the theoretical rigor of scholarship in research. According to Entman, framing essentially involves selection and salience. To frame is "to select some aspects of a perceived reality and make them more salient" (meaningful, noticeable) in a research inquiry ... in such a way as "to promote a particular problem definition, causal interpretation, and/or solution recommendation" for the object of study (pp. 51-52).[11] Entman's concepts of framing,

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[11] Entman's description of frames and salience is similar to Marr's definition of "representation" as "a formal system for making explicit certain entities or types of information" (p. 20). See Marr, D. (1982). Vision: A computational investigation into the human representation and processing of visual information. San Francisco: W.H. Freeman.

selection, and salience stimulate theory and model development for engineering design.

Kahneman and Tversky (1984) posit ideas on framing that relate to assumptions underlying a theory and model of engineering design activity. The authors characterize the concept of framing as a "meta-theoretical stance" or technique that selects and illuminates some features of reality while omitting others. In other words, while frames (for theory and model development) may call attention to particular aspects of the reality described, they simultaneously - and logically - direct attention away from other aspects of the phenomenon under investigation. Most frames are defined by what they omit as well as include. The omissions of potential problem definitions, interpretations, and solutions may be as critical as the inclusions in guiding the researcher. In other words, the selection of a particular research frame (design) not only directs but also limits the types of questions that may ask during a given inquiry (O'Keefe, 1993).[12]

Edelman (1993) addresses this issue in stating:

> The character, causes, and consequences of any phenomena become radically different as changes are made in what is prominently displayed, what is repressed and especially in how observations are classified. The social world is ... a kaleidoscope of potential realities, any of which can be readily evoked by altering the ways in which observations are framed and categorized. (p. 232)

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[12] Capra states "the patterns scientists observe in nature are intimately connected with the patterns of their minds, with their concepts, thoughts, and values." He further notes empirical data from their tests are conditioned by their "frame" of mind. "The sharp Cartesian division between mind and matter, between the observer and the observed, can no longer be maintained. We can never speak about nature without, at the same time, speaking about ourselves" (pp. 86-87). Refer to Capra, F. (1982). The turning point: Science, society, and the rising culture. New York: Simon & Schuster.

Thus exclusion of interpretations by frames is as significant to outcomes as inclusion. Sniderman, Brody, and Tetlock (1991) state a potential "counterframing" of the subject is absent in most research inquiries. They assert counterframes can provide researchers with alternative research engagement, with alternate perspectives for viewing problem definition, interpretation, and solution in any given research inquiry. Counterframing can assist researchers in their "initial attempts to elucidate [the] topographical details" of their investigation (Hoyningen-Huene, 1993, p. 175).

In The Study of Information: Interdisciplinary Messages (1983), Machlup and Mansfield identify 40 emerging disciplines and subject areas in which information plays a strategic role using position papers and commentaries from scholars in the field. Machlup and Mansfield focus on the pragmatic and logical relations that exist among the different fields and posit three observations that bear on the study of crises in Information Science. First, they cite the tendency of scientists in these particular disciplines to construct arbitrary boundaries or "fences around their fields" (p. 7) of study. This tendency characterizes the isolationist or parochial attitudes of specialists who are uninterested in cognate or complementary fields of inquiry; it is also a barrier which divides the universe of discourse on any given research topic. In consequence, the physicist, the social scientist, the engineer, and the biologist are "encapsulated in their private universes, and it is difficult to get from one cocoon to another" (Bertalanffy, 1968, p. 30). Each discipline or field is becoming "an assemblage of walled-in hermits, each mumbling to himself words in a private language that only he can understand" (Boulding, 1956, p. 198).

For several years, scholars (Bertalanffy, 1968; Boulding, 1956; Simon, 1979; Wiener, 1961) have argued researchers must promote mutual understanding and collaboration if they are to effectively address some of the complex issues facing the different fields in which information plays a strategic role. In similar fashion, Machlup and Mansfield (1993) implicitly argue for an interdisciplinary approach to problem solving in the respective fields of information science. They assert more can be learned from experience and practice in the interplay of conflicting ideas and from the arguments and counter arguments on issues than from the "best-formulated but monolithic expositions of the fields" (p. xiv).

Boden (1983) asserts what is needed for a successful inquiry in information related disciplines is "an interdisciplinary epistemology ... integrated with philosophical understanding and with psychological and biological knowledge" (p. 235). Both Machlup and Mansfield (1983) agree with Boden's comments and they assert such an approach could be equally valid for all interdisciplinary inquiries in the fields concerned with information. However, any researcher who adopts such an approach must be sensitive to the "interdisciplinary messages" (Machlup & Mansfield, p. 4) that he/she will encounter in such an inquiry.

In another observation, Machlup and Mansfield (1983) address the question of "science or nonscience" in the different disciplines they examine. In particular, they note many researchers in Information Science have guilt feelings about the fact that their discipline has neither discovered new laws nor invented new theories and models and therefore did not deserve recognition as a "legitimate" science. For Machlup and

Mansfield, such an "inferior complex" is the result of "indoctrination with an outmoded philosophy of science, with persuasive (propagandist) definitions of science and scientific method" (p. 13). The restrictive meaning of science qualifies and even excludes potentially effective counterframing methods of inquiry in other academic disciplines. Machlup and Mansfield assert the question of whether or not a particular discipline or subject area is a genuine science is of no real value. Little benefit is derived from attributing this "honorific designation" to a particular discipline. Indeed, such "mischievous" practice precludes creative approaches to problem identification and solution in information related fields.

In their final observation, Machlup and Mansfield (1983) make a striking comment for this study. In effect, it serves as a nodal point or centering frame for this research. The authors identify nine disciplines from which they believe a theoretical basis for the field of information science may emerge. One of the fields cited is information engineering. In their analysis of characteristics peculiar to this specific field, Machlup and Mansfield note the question of design is closely related to engineering. Furthermore, they think a "science of design" for the field of information science is not only possible but is actually emerging at the present time. Machlup and Mansfield believe there is a fundamental reason for the emergence of engineering design; "it comes from concern with the information processes of problem solving and goal-directed decision making, which are at the core of design" (p. 25). Machlup and Mansfield even attempt to clarify the nature of this emerging field in asserting it needs "no single paradigm, no overarching scientific research program, no common fundamental postulates and axioms, no unified conceptual framework" (p. 20)[13]

Wegner (1983) further illuminates Machlup and Mansfield's observations on an "emerging science of design." He asserts information science is a young discipline striving to gain the type of "legitimized" respectability possessed by physics and mathematics. According to Wegner, information engineering will emerge from the field as a central subdiscipline in the 1990s "with paradigms that will emphasize interactive man-machine cooperation in the management, learning, and use of knowledge" (p. 163). Information science currently has several paradigms that coexist with and complement each other. Wegner further asserts the coexistence of multiple paradigms is characteristic of "pre-science" rather than "normal science" in the field. Information science is not a single discipline like physics, but is instead "a collection of disciplines like the physical sciences, and the flourishing of many paradigms is a sign of health and vigor rather than of immaturity" (p. 163).[14] Based on Wegner's assertions, information engineering is perceived as an emerging, pre-science discipline embodying multiple paradigms - it offers potential for developing alternative design (problem-solving) models in the context of information science.

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[13] For a collection of essays that focuses on these issues, see Williams, J. G., & Carbo, T. (Eds.). (1997). Information science: Still an emerging discipline. Pittsburg, PA: Cathedral of Learning.

[14] O'Keefe (1993) asserts efforts to enforce theoretical coherence on a given field's "subdisciplinary paradigms" can only work to a "collective disadvantage." According to the author, there is little justification for the continuing search for a "unifying theoretical consensus." Instead of arguing for a return to "grand theorizing" in the various fields of Information Science, researchers should promote "theoretical and methodological tolerance and disciplinary cohesion" (pp. 79-81).

Dialectical Response to the Issues

This is a dialectical response challenging the "positivist definition of epistemological rectitude" cited in Information Science theory and research (Harris, 1986, p. 526). It is an "extended argument" for alternative approaches to a "scientific model" for problem solution in the field. Engineering may be such an alternative to the scientific model (Machlup & Mansfield, 1983, p. 24). Engineering design can be shown to be a coherent, human orientation to problem solving in Information Science.

Analysis of works on engineering epistemology and application of a postmodern lens to engineering and information science activities will demonstrate Information Science has been "barking up the wrong metaphor."[15] Rorty's (1991) theory of pragmatics and contingency and Levi-Strauss's (1966) concept of "bricolage" provide strong links between the strengths of engineering design and the crises of Information Science. The engineering - bricolage - pragmatics metaphor rescues Information Science from its state of crisis by turning[16] the Kuhnian, "Are we a science?" dilemma on its head.

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[15] The phrase "barking up the wrong metaphor" emerged jointly during conversations with Brian O'Connor.

[16] The concept of "turning a dilemma on its head" is inspired by Burke's notion of "perspective by incongruity" in which association of dissimilar or antithetical ideas may lead to different frames of thinking or reinterpretation of collective metaphors. Citing Burke's ideas, Mills asserts researchers often get the best insights by constructing "polar types" and considering extremes, by deliberately inverting their sense of proportion, or by thinking of the opposite of that with which they are directly concerned. Then one should ask: "What difference does that make?" (pp. 213-215). See Burke, K. (1939). Permanence and change. New York: New Republic Books; and Mills, C.W. (1959). The sociological imagination. London: Oxford University Press. Also note that Handy advances "upside-down thinking" as a method for "stimulating the imagination, of spurring our creativity" by "looking at things upside-down, or back to front, or inside out" (pp. 251-252). Handy, C. (1989). An upside-down society. In The age of unreason. (pp. 237-255). Boston, MA: Harvard Business School Press.

According to Vincenti (1990), there are few works in the field of engineering or technology that treat engineering design as a primary subject of investigation. The design process is often linked to other aspects of engineering - production and operation - within the framework of a broader topic such as technology. Any serious attempt to identify and extract specific elements of the design process from such studies becomes problematic - indeed, the researcher is immediately confronted with the ambiguity of such an endeavor.

Of the few studies that do examine engineering design, most focus on a particular characteristic of the process. Each of the works selected for examination here embodies a different perspective on engineering design. Each work is presented succinctly within the context of each author. Several content analysis iterations of each author's text - identifying and paring down what is and what is not relevant for this study - distill core ideas and concepts concerning engineering design. A list of themes from first examination of each author's work suggests a dynamic, provocative image:

Hapgood - Solution Space
Ferguson - Visual Activity
Petroski - Role of Failure
Florman - Introspection and Existentialism
Bucciarelli - Engineering Design
Vincenti - Anatomy of Design and Selection-Retention Model
Plotkin - Evolutionary Epistemology
Langs - The Emotion-Processing Mind.

These themes provide a rich contextual framework in which to analyze the design process. An inductive approach to content analysis of each author's work will allow an image of engineering design as a human problem solving activity to emerge.

In a landmark study using content analysis techniques (Buckland & Liu, 1995), Jarvelin and Vakkari (1985) provide a structural framework that is useful for analyzing texts on engineering design. Of particular interest is the schema the researchers develop for classifying and categorizing the different data that emerge from their analysis. Krippendorf (1980), Berelson (1971), and Weber (1990) provide critical insight into the fundamental techniques of content analysis for this study. Krippendorf clearly outlines the steps content analysts typically follow - from conceptualization of the research question to interpretation of the findings. Berelson's study challenges the assumptions of "manifest content" in textual analysis. More importantly, he describes how an inferential approach to content analysis can allow themes and categories to emerge inductively from the data that might otherwise be overlooked by researchers who adopt a scientific perspective in their analysis. Weber extends Krippendorff's techniques on content analysis while addressing issues of reliability and validity. And Hicks, Rush, and Strong (1985) clarify how key word lists derived from content analysis of purposefully selected documents can generate rich contextual categories for a model of engineering design.

The themes and categories that emerge from content analysis will be synthesized into a list of attributes of engineering design. Essentially the list of attributes becomes "raw data" for modeling engineering design. Yet to place the data within the context of a model can be problematic. What is the theoretical framework of a model? What are the epistemological assumptions and, indeed, the ambiguities that necessarily underpin the development of a given model? And finally, what would a model of engineering design look like?

To address these issues, one must search for a better understanding of models. Mintzberg's (1995) response to "What is a model?" in engineering and Blair's (1990) provocative comments on the nature of models will be used to frame the development of a model for engineering design. Other thoughts on the nature of models will illuminate the perspective. Nagel's (1961) research identifies the assumptions of scientific models and how they influence model development in other fields. A current description and understanding of models is provided by Wilson (1997) as well as Principia Cybernetica Web (1997). Laudan (1984) raises questions concerning models in engineering: "Are Models of Scientific Change Relevant?"

A theoretical framework suggested by Black (1962) will give a structure to the attributes of engineering design. This schema will link certain themes reflected in the list of attributes to themes that Chia (1995), Jackson and Carter (1992) and Cahoone (1996) have identified in postmodernism. A model derived from a postmodern sensibility captures and illuminates the dynamic attributes of engineering design. In particular, Rorty's (1991) theory of pragmatics and contingency and Levi-Strauss's (1966) concept of "bricolage" stimulate development of a robust metaphor of engineering design. Indeed, Rorty and Levi-Strauss provide a strong link between the strengths of a postmodern model of engineering design and the crises in information science. This is a response to the urgent need for an operative metaphor upon which Information Science might base solutions. Such a metaphor challenges the primacy of a positivist epistemology in the field and invites scholars to think in different ways about problem identification and solution in the context of their own areas of investigation.

Chapter 2: Engineering Design Epistemology

Few studies in the field of engineering and technology focus on engineering design. Most critics who address this apparent gap in the literature tend to simply complain about it - they offer little thought on how to remedy the dilemma. They fail to recognize problematic issues inherent in any investigation of research on the topic. In particular, Addis (1995) "bemoans the lack of intelligent and well-exemplified treatments"(p. 52) of engineering design; he asserts current research on the topic tends to be "non-essential" and to "clutter" the underlying dynamics of design as a problem solving process. Addis further asserts researchers must "link engineering science with real engineering design issues" if they are to avoid the "dangerous" and costly errors resulting from use of scientific models for problem solution (p. 52). How can researchers remedy this dilemma? Is there any literature on the topic that warrants mention? Addis does not address these critical issues in a direct manner. He does not clarify what "engineering design issues" are nor does he explain how researchers might remove the "non-essential clutter" from the field of research.

Similarly, Roland (1992) complains about "deficiencies" in research on engineering design. He responds to this problem by identifying potential sources that treat the topic. He cites research by Eugene Ferguson, Samuel Florman, Henry Petroski, and Walter Vincenti as "standard works" (p. 318) on engineering design epistemology. Roland's suggestions are useful as a starting point for an exploratory study into the theory of design activity. However, his assumption that these sources are "standard works" is not evident in other writers. Each source focuses on a particular characteristic of engineering design and, as such, tends to project a fragmented framing of the topic. Moreover, Roland does not seem to recognize that these sources, if considered together, provide a rich context from which a holistic image of engineering design may emerge.

In a broader sense, the critical perspectives of Addis (1995) and Roland (1992), like those of other scholars in the field (Mark, 1992; Pacey, 1993; Thompson, 1994), miss the mark completely. They overlook theory-oriented research as a potential means to "fill in the gaps" (Rudestam & Newton, 1992, p. 47) and to advance the field of engineering design. They also fail to recognize this type of research approach "must of necessity address certain problematic issues and assumptions that surround the topic itself" (Rudestam & Newton, 1992, pp. 46-48).

Critics who do not understand the nature of engineering design or who neglect the few studies that exist on the topic inhibit attempts to develop a coherent field of research on engineering design. They embrace the "extended argument" to voice their complaints about research in the field but fall short in their ability to offer possible remedies to the dilemma. Yet there is a way out of the critical quandary surrounding research on design activity. An examination of the relationship between design activity and technology can serve as a starting point.

Engineering Design versus Technology

Engineering design as a human problem solving activity receives little attention from scholars in the field of technology and engineering. Many scholars, when they pay heed to engineering at all, tend to think of it in the broader context of technology and this tends to complicate selection of descriptors or terminology used in search techniques. "Technology" reflects a general activity that embraces all aspects of design, production, and operation of an artifice (Vincenti, 1990). "Engineering design" as an activity falls within that of technology and engineering knowledge forms part of the broader domain of technology.[17] Unfortunately, historians and philosophers of technology seldom make such a distinction in their research and this creates an ambiguous perspective for any study that attempts to focus on engineering design. [18]

Vincenti (1990) asserts, although design is essential to engineering, it is curious that a subject heading by that name rarely appears in research journals of technology and engineering. Researchers tend to deal with design in some other context, usually as part of the invention, development, or innovation of some important or dramatic device.

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[17] Adams states the word "technology" is derived from the Greek words "techne," which means art or skill, and "logia," meaning science or study. The word "engineer" is from the Latin word "ingeniator," meaning one who is ingenious at devising. In most languages, this derivation is clear. Unfortunately, in English, confusion results from taking the word "engine" from the same root. Engineers in English-speaking countries therefore "drive trains, run power plants, and help fly airplanes as well as being ingenious in devising." However, Adams asserts "being ingenious at devising is a characteristic of humans, and the engineer is expected to be a specialist at it." See Adams, J.L. (1991). A brief history of technology: The underpinnings. In Flying buttresses, entropy, and o-rings: The world of an engineer (pp. 5-30). Cambridge, MA: Harvard University Press.

[18] Billington (1996) cites the ambiguous relationship between engineering design and technology. He uses the "imperfect but suggestive metaphor of a human body" to illustrate four fundamental "interconnections" that distinguish engineering design activity from technology (pp. 19-20).

They neglect the engineering design process that underpins the development of a given artifact or device.

Similarly, Petroski (1994) indicates the state of the art in engineering as reflected in current research is often only "a superficial manifestation of what is understood about the substance and behavior of the products of engineering" (p. ix). It overlooks the fundamental nature of the design process itself. In particular, there is a "decided gap" in research dealing with engineering design as a human problem solving activity. Petroski states any literature search using the descriptor "engineering design" will reflect the lack of research on this subject. The majority of retrieved documents will be related to the structural behavior of engineering designs themselves or to the potential impact of their use in society.

Laudan (1984), too, cites the lack of useful literature on engineering design and states the design process itself "remains locked inside an impenetrable black box" (p. 1) of technology. She does note historians are finally beginning to identify areas for further research in technological history and are attempting to develop a coherent narrative of the field. Yet, Laudan cautions, any narrative account of the field requires an examination of engineering design as the fundamental process underlying development of any given technology. She urges the development of theoretical generalizations about engineering design to guide model construction.

Technology and Science: A Dialectical Tension

A broader issue emerging from research in this field involves the "dialectical tension" that exists between technology and science. In citing this dilemma, Channel (1991) states that over the years there has been a widespread belief modern engineering is "applied science." It is often perceived as a subdiscipline of science that does nothing more than apply the results and discoveries generated by pure science without making any fundamental contributions to those discoveries. The field of engineering is sometimes viewed in a pejorative sense as "an assemblage of chunks" drawn from the more formal scientific research (Machlup & Mansfield, 1983, p.19).[19]

Whatever the origins of the idea that technology is applied science, Laudan (1984) notes it has had "extraordinary vitality" (p. 9). She asserts "the specter of technology as a subordinate exercise, the tedious and unexciting result of applying the results of science to practical ends is hard to exorcize" (p. 9).[20] One still encounters the claim technology is a form of science since its practitioners attempt to solve problems rationally and hence apply "the scientific method."[21] For Laudan, this trivializes the

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[19] For a historical treatment of these issues, see P.T. Durbin (Ed.). (1980). A guide to the culture of science, technology, and medicine. New York: The Free Press. In particular, note Michalos, A.C. Philosophy of science: Historical, social, and value aspects (pp. 197-281) and Mitcham, C. Philosophy of technology (pp. 282-363).

[20] Boorstin cites typical examples of the persistence of this claim: "Technology, a synonym for experiment, is a name for the applications of science" and "Technology is science plus purpose" (pp. 47; 61). See Boorstin, D. The republic of technology. New York: Harper and Row.

[21] Layton attempted to reintroduce the Aristotelian definition of technology into the field as "systematic knowledge of the useful arts," which in no way suggested this knowledge was generated by science and applied by technology. See Layton, E. (1974). Technology as knowledge. Technology, 15, 31-41.

issue by making the concept of scientific method "so wide as to exclude nothing and explain little" (p. 9).[22]

Researchers must confront the widely held belief technology is applied, and the corollary "once we understand the discovery and justification of scientific knowledge, nothing remains to be added about technological knowledge" (Laudan, 1984, p. 9). Both science and technology are forms of knowledge and at the most general level can be thought of as generated by a some type of problem solving process, but the differences between these processes are very significant. Thus, one might assume technology is distinctively different from science.[23] Exploring "disanalogies as well as analogies between science and technology" (Laudan, 1984, p. 10) is essential if one is to understand the cognitive processes that underlie change in technology.

Ferguson (1977) asserts there can be no question about the greatly increased contribution science has made to technology - and hence engineering - during the nineteenth and twentieth centuries. Borrowing methods as well as information from science, "bodies of engineering doctrine have been built up with the ideal of scientific

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[22] Latour (1987) cites the "harsh realities" of the scientific method. "Each and every scientific action is a move in a game where the objective is to win." It is "a Hobbesian war, a war of everyone against everyone ... if scientists make an alliance, it is an expedient linkage, oriented to 'winning'; and if they accept a knowledge claim, it is accepted out of expedience - [both] will be set aside immediately [if] circumstances require it" (p. 115). For other comments on this issue, see Barnes, B., Bloor, D., & Henry, J. (1996). Scientific knowledge: A sociological analysis. Chicago: University of Chicago Press.

[23] Hindle pursues the same theme, arguing artisans generally think differently from scientists and "design" is much more important to them. See Hindle, B. (1981). Emulation and Invention. New York: New York University Press.

rigor as a guiding principle" (p. 834). Using Layton's (1971) metaphor, the structure of engineering doctrine has become a "mirror image" of the structure of the physical sciences. Wagner-Dobler (1997) extends Layton's metaphor by analyzing "rapprochements between science and technology" (p. 171). In particular, he cites methodological and empirical difficulties that arise from an assumed "coupling of science and technology."[24] According to Vincenti, this problematic relationship is summarized in the "discredited statement" that "engineering is applied science" (1990, p. 50).

An attempt to identify potential attributes of engineering design within the broader framework of the literature of technology - and to select it out from the ambiguous relationship with science - reflects the fundamental complexity of this situation. A current definition of design from a source in the field of science and technology states :

> Design is concerned with the creation of systems, devices, and processes useful to, and sought by, society. The process by which these goals are achieved is engineering design. (Parker, 1994, p. 712)

The definition is supplemented by a one-dimensional graphic of the design process. One might assume this formalized definition adequately characterizes design activity. However, neither the definition nor the graphic identifies precisely what

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[24] Mayr attempts to deal with similar difficulties from an "assumed coupling" of science and technology. He asserts the number of variables in the relationship is so large that "a dynamic model that would do justice to all would be prohibitively complex." This conclusion may be true, but to give up modeling entirely would make epistemological discussion of engineering design itself even more difficult. Refer to Mayr, O. (1976). The science-technology relationship as a historiographic problem. Technology and Culture 17, 663-673 Note Keller (1984) responds to this issue by presenting an assortment of metaphorical models for the science-technology relationship (pp. 175-177).

activities underlie engineering design. To better understand the historical significance and current perceptions of engineering design, one must turn to another source.

As the Oxford English Dictionary attests, the word "engineer" designated "one who contrives, designs, or invents" (Simpson & Weiner, 1989, vol. V, pp. 251-252) more than a century before it came to mean also "one who manages an engine" (Petroski, 1994, p.8). The latter meaning dates from 1839, when the railroad was emerging as the great metaphor of the Industrial Revolution, and "it is not surprising that there came to be a ...confusion of the contriver and the driver of the vehicle" (Petroski, 1994, pp. 8-9).[25]

Around the middle of the nineteenth century, the work of engineers was perceived by society as involving some type of scientific process as it transformed classical thinking into precise mathematical calculations. As engineering began to apply the scientific method to structural problems, it moved away from purely aesthetic considerations and separated itself from architecture. According to Petroski (1994), engineering design separated itself from problem solution as a human activity and came to mean "use of the scientific method to solve problems" (p. 9). [26]

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[25] Billington (1996) further notes modern engineering design "is thought to be defined by industry and machines ... Even the name 'industrial revolution' connotes the identification of modern technology with machine industry" (p. 35). Billington asserts the association between technology and industry obscured the intrinsic nature of engineering design activity.

[26] Based on scientific principles, these "formulaic blueprints" (engineering design theories and models) were applied to all types of human problem solving activities in management and they exhibited the "strong positivist orientation" of early design activity cited by Petroski. See Taylor, F.W. (1911). The principles of scientific management. New York: Harper; Fayol, H. (1916). General and industrial management. Belmont, CA: David S. Lake; and Gulick, L. (1937). Notes on the theory of organization. In Papers on the science of administration. L. Gulick & L. Urwick (Eds.). New York: Institute of Public Administration.

Many scholars, particularly historians of technology, have come to challenge this belief. Layton (1974) credits engineering design with its own "significant component of thought" (p. 32).[27] This form of thought, though different in its specifics, resembles scientific thought in being creative and constructive; it is not simply routine deductive as assumed in the applied-science model. In this newer view, engineering design, though it may apply science, is not the same as applied science. Layton (1976) further argues :

> From the point of view of modern science, design is nothing, but from the point of view of engineering, design is everything. It represents the purposive adaptation of means to reach a preconceived end, the very essence of engineering. (p. 696)

Other scholars argue engineering design generates its own form of knowledge in the form of concepts and methodologies that cannot simply be reduced to scientific knowledge. This shift in perspective is cited by Pinch (1991). He states :

> A quiet revolution has occurred in how we think about the relationship between science and engineering. Engineers were once taken to be the handmaidens of science; science discovered and engineers applied. Engineering was worthy but dull stuff; engineers are at last escaping from the shadow of science. Engineering, within the new view, is better seen as its own form of culture, with its own set of rules and bodies of practice - a culture different from science and certainly not a mere appendage to or an application of science. (p. 205)

This shift in perspective challenges theory-oriented research on this topic. It signals an opportunity for exploring alternative views on engineering design epistemology.

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[27] DeCamp presents an interesting historical perspective on engineering design "thought" in DeCamp, L.S. (1987). The ancient engineers. New York: Ballantine.

A Conceptual Map of Research on Engineering Design

A conceptual map is more than a visual rendering of research on design activity. It focuses the topic of engineering design as a human problem solving activity and it identifies core research frames from which an image of design can inductively emerge. It also illuminates problematic issues surrounding the topic in the broader domain of science and technology research. (See Figure 1)

As indicated earlier, few studies focus on engineering design. Those works that do exist frame the topic in a fragmented manner. Moreover, attempts "to set the narrow topic within the larger, ongoing dialogue in the literature" (Marshall & Rossman, 1989, p. 89) are problematic. In such cases, especially those involving theory-oriented research, Creswell (1994) suggests use of an inverted triangle to describe the phenomenon. It provides a framework for exploring a subject that is often neglected or, indeed, misunderstood by researchers in the field.

At the apex of the triangle is the focus. This point generates questions that guide theory and methodology of the problem. Questions arise: What is the nature of engineering design? What attributes of the design process can be extracted from existing literature? What characterizes engineering design as a human problem-solving activity?

In broadening the search toward the base of the triangle, one discovers a few studies that respond to questions on engineering design. These studies form the core research on the topic, yet they constitute only a fragmented view. Each author treats a singular attribute or characteristic of design activity. Some of these scholars do, indeed,

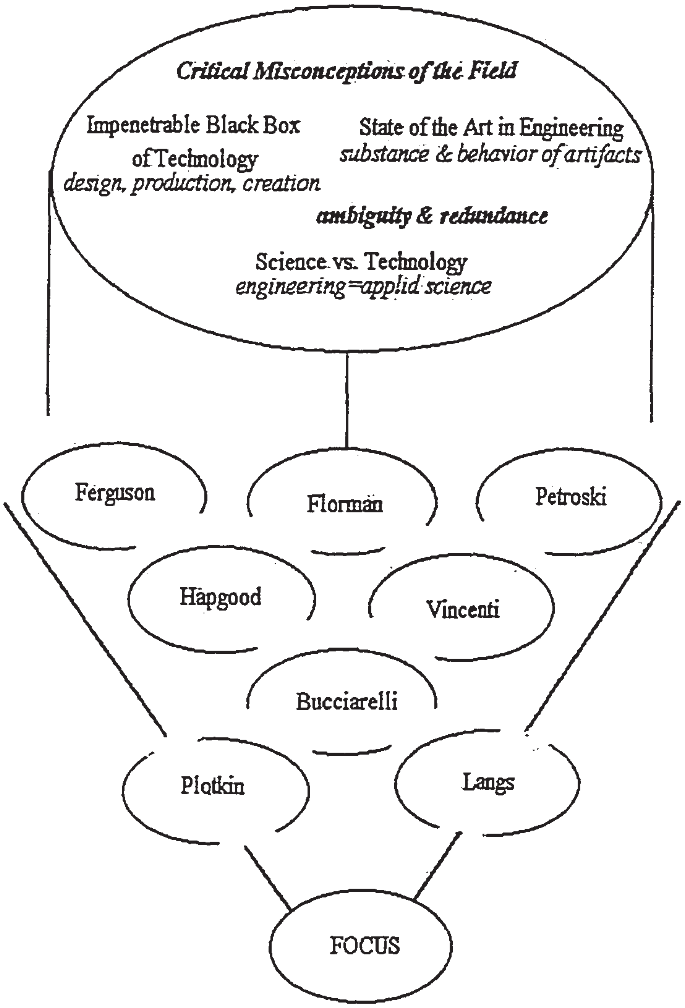

Figure 1. Conceptual Map of the Research Plan

acknowledge other research on design activity, but they neglect to synthesize these core ideas into a more holistic picture of engineering design.

Certain critics (e.g., Mark, 1992; Pacey, 1993; Thompson, 1994) tend to see only the deficiencies in this research, and consequently, they overlook the significant implications of it for engineering design. These implications become quite evident if one synthesizes the various frames of design activity that are presented in the studies cited. Linking the design attributes together as "integrative, theoretical summaries" (Creswell, 1994, p. 24) provides a rich context from which an image of engineering design will emerge. Moreover, these integrative frames provide the "substantial literature orientation" (Creswell, 1994, p. 24) required for exploratory research aimed at theory and model development in engineering design.

Boden (1983) asserts what is essential for theory-oriented research is an "interdisciplinary epistemology ... integrated with philosophical and biological knowledge" (p. 5). However, she notes, some scholars and critics alike tend to rely on "mere intellectual communication" within their own disciplines and "to plug their ears to interdisciplinary messages" (p.5). In response to Boden's comments, a shift in focus from the few studies on design activity to other fields is productive. In particular, in the field of evolutionary epistemology, one discovers ideas by Plotkin (1994) and Langs (1996) that contribute to an image of engineering design as a human problem-solving activity.

Perhaps unknowingly, Petroski (1994) provides a pathway from engineering design to the field of evolutionary epistemology. He asserts there are "timeless constants" of human problem-solving activity that are addressed in the research of ostensibly disparate disciplines. In this case, Petroski has constructed an intellectual bridge by means of which interdisciplinary messages from evolutionary epistemology can contribute to an image of engineering design.

A search for relevant data on engineering design in the broader literature of the field is problematic. Indeed, if a researcher ventures beyond the core research at the base of the inverted triangle, he/she quickly experiences a sense of ambiguity and a loss of focus. It is similar to an encounter with a "jigsaw puzzle in which several pieces have been misshapen by others while some parts are overtly missing" (Krippendorff, personal communication, March 13, 1997).[28] This complex problem is delineated by the conceptual map as a multi-faceted dilemma. The critical misperceptions that abound in this area have already been cited. A review of the state of the art literature on engineering yields little data that is relevant to the design question.

Retrieval of design attributes in the broader domain of scientific research must deal with the traditional misconception of engineering design as applied science. Extracting data on the design process from the field of technology is a complex undertaking. Attributes of design proper are often locked into an "impenetrable black box of technology" (Laudan, 1984, p. 1). That is, relevant data are lost in an inextricable mix of design, production, and operation that make up the broader

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[28] Noel cites a similar dilemma related to research for models of design activity in the field of management: "In retrospect, I felt I had been working on a giant jigsaw puzzle, with many pieces missing" (pp. xii). Refer to Mintzberg, H. (1995). Twenty-five years later ... the illusive strategy. Unpublished manuscript.

definition of technology. The few "gems" of data that one might extract from any of these areas have a high redundancy factor. More often than not, they are already cited in the core research at the base of the triangle.

A return to the apex of the triangle - and to the focus on engineering design - generates thoughts and questions of a different nature. Marshall and Rossman (1989) cite the need to "frame a study within a tradition of inquiry and a context of related studies" (p. 31) in order to relate a specific topic to the broader context of theory and previous research in the field. There is no "tradition of inquiry" or "context of related studies" in engineering design literature. Any attempt to cast engineering design "within the ongoing dialogue in the literature" (Marshall & Rossman, 1989, p. 89) is irrelevant. There is no "ongoing dialogue" in the field! What one discovers is a series of disjunctive dialogues that contribute nothing to development of a coherent narrative on engineering design. Indeed, the field seems to reflect an anti-narrative attitude that inhibits research into any aspect of engineering, not to mention design activity. How does one contribute to a field of inquiry in which an "ongoing dialogue" does not exist? What means can one use to redress the misperceptions about engineering design?

Construction of a prolegomenon to dialogue in the literature is one approach to these issues. It is an attempt to foster development of a coherent narrative in the field of engineering design. It is an exploratory, theory-oriented technique that views core research as the integrated frames from which an image of engineering design will emerge. Such an approach enables this image to emerge inductively from the core data and it stimulates development of a robust model of engineering design.

Chapter 3: Theories and Models

Implications for Engineering Design

According to Miles and Huberman (1984), it is critical to identify assumptions that underlie the development of theory and models for any given research topic. Otherwise, one might overlook or neglect issues that impact the fundamental direction of the research process itself. Miles and Huberman further assert qualitative research design itself is problematic. There is "no universally agreed upon format" (p. 6) for this type of study and the researcher who advances a tentative conceptual framework in an inductive study is likely to confound the nature of theories and models. This perplexed or uncertain state impacts the fundamental nature of theories and models in qualitative research. One discovers such theories and models "come in several shapes and sizes ... they can be rudimentary or elaborate, theory-driven or commonsensical, descriptive or causal" (Miles & Huberman, pp. 6, 28-29).

Creswell (1994) cites similar problems in qualitative research design. He asserts writing a theory into a qualitative study is difficult because there is no standard terminology for theory; the term used for "theory" varies by type of design. In addition, there are no explicit rules about placement of theory in a qualitative study. Creswell recognizes all qualitative designs employ an inductive mode of development, and, therefore, the placement of theory tends to be toward the end of the study. Yet one finds such research designs vary in "emerging shapes and formats" from one field to another (Creswell, pp. 93, 100-101).

Extending the conceptual map of engineering design research is useful for visually charting the "emerging shape and format" of research on the topic and for identifying those issues cited by Miles and Huberman (1984). In particular, the map illuminates points in the research process where theory and model development for engineering design will emerge and it provides a context for analyzing issues relevant to design activity.

Charting a Theory and Model of Engineering Design

At the focal point of the conceptual map presented in Figure 2 is core research on engineering design. This research comprises the few studies identified on the topic. Each study frames a particular aspect of design activity. These frames form the "rich context" (Creswell, 1994, p. 24) or "thick description" (Rudestam & Newton, 1992, p. 39) of design activity and represent the "substantial literature orientation needed at the outset" (Creswell, p. 24) of a theory-oriented exploration of engineering design. Each one is presented as an iterative distillation of the author's ideas on the design process.

A content analysis of core research frames using an inductive or inferential mode of inquiry allows themes and categories of design activity to emerge. The themes in turn stimulate "substantive theories" (Merriam, 1988, p.86) about engineering design.[29] These imply "conjecture and speculation" about the nature of design activity;

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[29] Sanitt cites the use of scientific theories to generate "zetetic" ("proceeding by inductive inquiry") models of the design process and contrasts with "erotetic" logic which applies to questioning in a deductive sense (p. 48). See Sanitt, N. (1996). Science as a questioning process. Bristol, England: Institute of Physics.

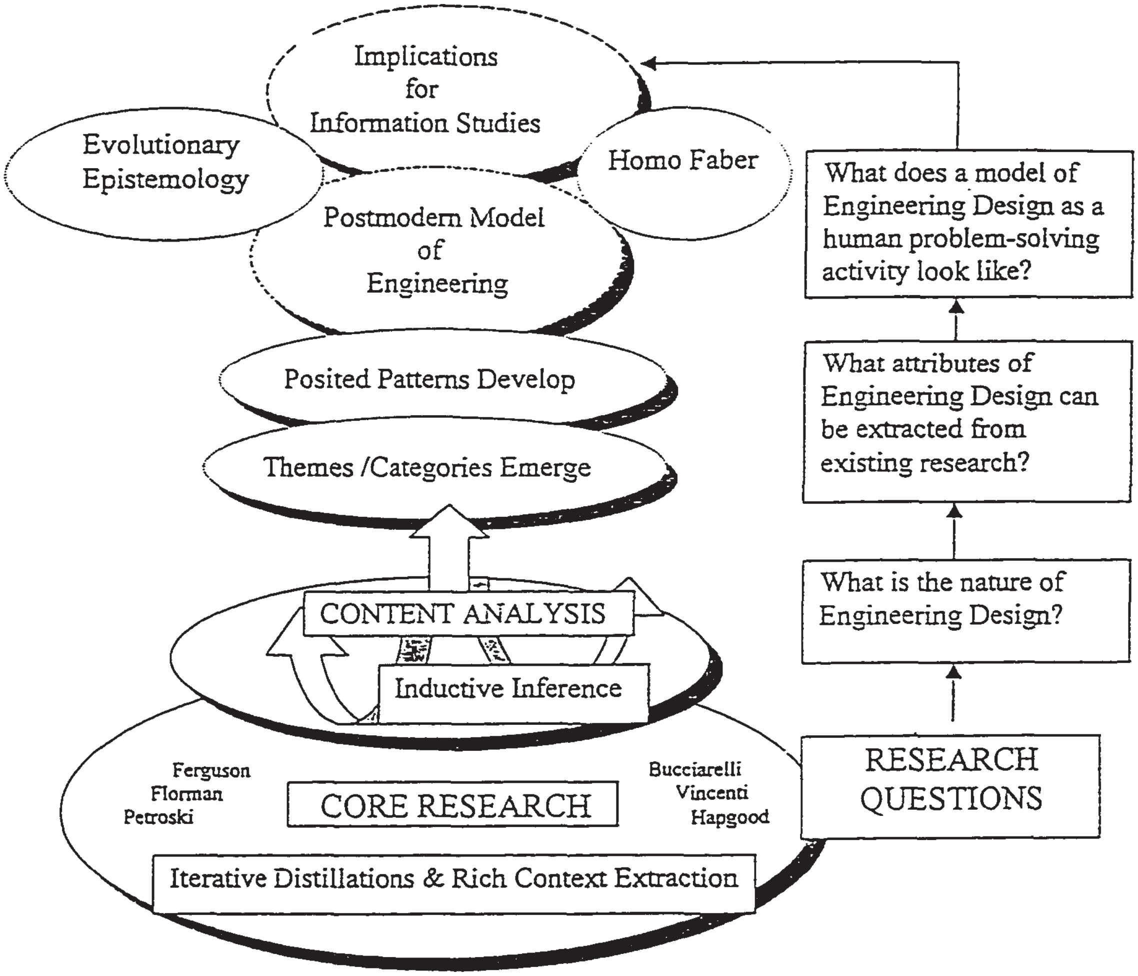

Figure 2. Conceptual Map of Research

they are "an imaginative formulation of underlying principles" (Principia Cybernetica, 1997) of engineering design.

Rosengren (1993) postulates "theory is at best only a dim mirror image" of the "blooming richness" of this type of phenomenon (p. 9). Formal models, with their lack of ambiguity, are critical in the translation of theory and reality by means of data. It is that "indispensable interplay between substantive theory, formal models, and empirical data that produces effective processes of confrontation" (pp. 10-11).

Theories are the "conceptual frameworks to initially describe the phenomenon ... [they are] the language that allows us to move from observation to observation and make sense of similarities and differences" (Rudestam & Newton, 1992, p. 6). Specifically, they are what Guba and Lincoln (1988) and Strauss and Corbin (1990) refer to as "pattern theories," theories that are grounded in the raw data inductively collected from content analysis of core research on design activity. They represent interconnected thoughts linked to an emerging, holistic image of engineering design.

Neuman (1991) posits thoughts on pattern theories useful for engineering design:

> Pattern theory does not emphasize logical deductive reasoning. Like causal theory, it contains an interconnected set of concepts and relationships, but it does not require causal statements. Instead, pattern theory uses metaphor or analogies so that relationship "makes sense." ...They specify a sequence of phases or link parts to a whole. (p. 38)

No preconceived notions, expectations, or a priori frameworks shape the pattern theories of design activity. The intent is "not to be constrained by a deductive theory" (Creswell, 1994, p. 95) but to allow a visual model of pattern theories to emerge.

At this point, two issues warrant attention. First, Creswell (1994) asserts "the methodological use of some larger explanation must fit into the logic of an inductive process of research" (1994, p. 94). As noted on the conceptual map, a postmodern perspective will provide the "larger explanation" or interpretive framework for modeling the pattern theories on engineering design. The second issue centers around the use of a model. Rudestam and Newton (1992) assert any model carries with certain assumptions.

They further assert the term "model" has been used in "many, often confusing ways" in different disciplines and scholars and practitioners alike disagree on what constitutes a model for any given field of research. For the authors, the term "model" designates "a higher order theory," that is, "a representational system at a higher level of abstraction that can inform and be informed by alternative theories" (p. 21). It is close to the framework or world view that helps guide researchers and has been identified as a "paradigm" by Kuhn (1962).

What does this definition imply for a model of engineering design? Rudestam and Newton's (1992) definition may suffice for a general comment on the nature of models, but it does little to clarify the issues cited above by Miles and Huberman (1984). In particular, it lacks a specific context or reference point in order to focus the definition. Without a focus, the definition fails to identify assumptions and problems underlying use of any given model, not to mention a model of engineering design.

Principia Cybernetica Web (1997) defines a model as "a set of propositions or equations describing in simplified form scme aspects of our experience." It also states "every model is based upon a theory, but the theory may not be stated in concise form." The Oxford English Dictionary also advances this perspective of a model as "a representation or simplified conception in three dimensions of some projected or existing structure, showing the proportions and arrangements of its component parts" (Simpson & Weiner, 1989, p. 941).

Wilson (personal communication, January 28, 1997) posits thoughts on the nature of models that extend the above definitions. He asserts :

> the term 'model' is very loosely used, especially by social scientists and it can be applied to any deliberately over-simplified representation of a situation or process, whether given in mathematical terms or verbal description, plus or minus diagrams or other visualizations.

Wilson's description of a model provides a framework for exploring other research that addresses issues surrounding the development of a model of engineering design.[30]

Vincenti and Mintzberg: Point - Counterpoint

What implications underlie development of a model of engineering design? What would a model of design activity look like? One might think Vincenti's (1990) research in engineering epistemology would be an obvious desideratum for a theoretical model of design process. Roland (1992) asserts Vincenti's understanding of "what engineers really do" is "different from anything found in the existing literature" and the author's thoughts have "finally coalesced in a model" that illuminates engineering

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[30] For a succinct discussion of "perspectives" associated with various models in Information Science and Information Retrieval, see Methods in information science (pp. 49-50) and Systems theory and information science (pp. 57-86). In Debons, A., Horne, E., & Cronenweth, S. (1988).

design epistemology (p. 317). Channel (1991) and Pinch (1992) are supportive of this claim and further note Vincenti has contributed a "substantive" model of engineering design to research in the field. Vincenti even asserts his model has "universal applicability" for the field of engineering (p. 200).

What Vincenti (1990) actually presents in his work is a matrix that plots six kinds of design knowledge against seven engineering activities from which new knowledge arises. It is a one-dimensional graphic that utilizes straight lines and the indicator "x" to pinpoint where engineering knowledge and the activities that generate it intersect. The matrix is prefaced by a diagram that distinguishes engineering knowledge-generating activities from those in the scientific field. (See Appendices A and B). Vincenti refers to this matrix as an "anatomical model" of engineering design knowledge and it becomes the basis for his "variation-selection" model for the growth of engineering knowledge (p. 241). Yet Vincenti does not include a graphic or visual representation of this model. Where is the model that the critics cite? Is Vincenti's matrix, supported by textual description, the model of "universal applicability" for the field?[31] And what does Vincenti mean by the term "anatomical model?"

Mintzberg (1994) asserts there are "all kinds of lists and matrices in the formalized literature of engineering," but "a list and a matrix are not models ... even if presented in the form of a circle, meaning the ends have been joined" (p. 11). Attempts

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[31] Wilson's description of a model may clarify this issue. Nagel may "very loosely" employ the term "model" as an over-simplified verbal representation without diagrams or visualizations.

to integrate ideas and theories into a model "get lost in the conventional process of describing them" (p. 11). Without such a model, one cannot effectively address issues in the field of engineering design. An extended search for definitions of "model" in the literature of engineering and technology confirms a dilemma noted by Petroski (1994). Most put "model" in the context of the behavior and substance of artifacts, not in relation to design activity. Yet other literatures yield insights on models useful for engineering design.[32]

Scientific Theory and Models: Vestiges of Positivism

Kerlinger (1977), author of "a highly respected text on research methodology" (Rudestam & Newton, 1992, p. 6), asserts "the basic purpose of scientific research is theory and model development" (p. 8) for confronting the problems of natural phenomena. He cites Nagel's (1961, 1979) work as "the most detailed, cogent and comprehensive defense for use of scientific theory and models in the field of research" (p. 9). Kerlinger encourages scholars in the social sciences to adopt Nagel's ideas as a fundamental starting point for their research.[33] Nagel's notions[34] about theories and

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[32] For an in-depth study of models of "experimental inquiry" that have implications for the "nitty-gritty" details of engineering design, refer to Mayo, D.G. (1996). Models of experimental inquiry. In Errors and the growth of experimental knowledge. (pp. 128-173). Chicago: University of Chicago Press.

[33] Kerlinger (1977) develops formal definitions for scientific research and the "scientific approach" ("problem-obstacle-idea") from a formulaic method quite similar to Nagel's abstract calculus (pp. 2-15).

[34] Barnes, Bloor, and Henry present an analysis of "modeling in scientific theorizing" that clarifies Nagel's perspectives on scientific research. See Barnes, B., Bloor, D., & Henry, J. (1996). Scientific knowledge: A sociological analysis. (pp. 107-109). Chicago: University of Chicago Press.

models in science have implications for model development in engineering design. According to Nagel (1979), scientific theory has a defined tripartite structure that comprises:

> an abstract calculus that is the logical skeleton of the explanatory system, and that "implicitly defines" the basic notions of the system; a set of rules that assigns an empirical content to the abstract calculus by relating it to the concrete materials of observation and experiment; and a model for the abstract calculus, which supplies some flesh for the skeletal structure in terms of familiar conceptual or visualizable materials. (p. 83)

In sum, any given scientific theory embodies an abstract calculus (explanatory theory); a set of operational definitions (for assigning empirical content to the abstract calculus); and a model (for interpretation of the abstract calculus). Nagel claims his "abstract calculus" can be used to "implicitly define" the basic notions of systems in the social sciences and other fields. He further claims the set of rules derived from empirical observation and experiment can lead to effective "model generation" (p. 85) in these fields. What type of model would Nagel's "abstract calculus" generate for engineering design? Would such a model be appropriate for design activity? [35]

Ferguson (1992) argues any model of design activity based on Nagels' scientific "formula" is problematic. It implies design is a formal, sequential process that is deductive in nature. Design is perceived as discrete, linear segments which lead to predictable outcomes. Ferguson cites a "block diagram" as a type of model derived

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[35] A potential "scientific model" of engineering design activity is implied in the research findings of Shuchman, H.L. (1981). Information transfer in engineering. Glastonbury, CT/Washington, DC: The Futures Group.

from these assumptions (Appendix C). He further asserts many engineers believe design should follow this assumed pattern "even if it doesn't" in reality (p. 37).

Billington (1996) supports Ferguson's argument concerning the assumptions underlying Nagel's scientific formula. He states:

> formulas do not solve problems. Formulas suggest designs, stimulate insights, and define limits, but they never provide ways to the best solutions, as so many technologically illiterate writers on engineering [design] suppose. Formulas do not define a "one best way" or an optimum. Formulas represent a discipline, not a design; they can never ensure ... essential elegance. (p. 4)[36]

Dupre (1993) further asserts theories and models derived from the "prestige of science" reflect a kind of assumed unity that has no genuine consequences for engineering design epistemology. The term "scientific" (as in Nagel's application of the term) has become:

> an epistemic honorific quite independent of any general consensus about what makes scientific claims any more deserving of credit than beliefs from any other source. The entitlement to this pseudoepistemic power and the extent of this hegemony are depressingly illustrated and parodied in the absurd or banal claims made by actors in white lab coats in television advertisements. (pp. 221-222)

For both Dupre (1993) and Billington (1996), the "demarcation problem" of what distinguishes a "legitimate" science, in the sense of a body of opinion that deserves epistemic authority, from a pseudo science or something that has only the institutional trappings of a science, is not always clearly evident.

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[36] A "traditional" textbook formula for constructing the types of "idealized" models of design activity cited by Billington are found in Beakley, G.C., & Leach, H.W. (1967). The engineering method of problem solving. In Engineering: An introduction to a creative profession. (pp. 319-340). New York: Macmillan.

As to “art, imagination, and the scientist,” Root-Bernstein (1997) asserts:

> the road to objectivity in science is paved with subjectivity. Einstein, who is often quoted as saying that in creative science, ‘imagination is more important than knowledge,’ also noted that despite the objective nature of scientific results, ‘science in the making, science as an end to be pursued, is as subjective and psychologically conditioned as any other branch of human endeavor.’ (p. 6)

In Nagel’s (1979) scientific theory, the object of experiment, proof and analysis is “to expunge this subjective residue from the final statements of scientific fact.” (Root-Bernstein, 1997, p. 6) However, to ignore the subjective, “even idiosyncratic origins of imaginative ideas in science is to cripple its creative potential” (Root-Bernstein, p. 6).

Shortland (1981) also challenges Nagel's scientific assumptions. He asserts "the trouble with Nagel is not so much with what he examines as in the serious things he has left unexamined" (p. 475). Shortland argues Nagel's "sedulous defense" of scientific theory and models is "ambiguous, confused and lacks precision" (p. 475) for application to any field of study. The notion of "implicit definition" is never defined and this makes any reference to theory or models "arbitrary and incoherent." (p. 476) However, the "greatest danger" (p. 476) lies in Nagel's assumptions about use of scientific theory and models in the social sciences.

Shortland cautions scholars in adopting approaches "that imply a strong, positivist orientation in their line of inquiry" (p. 477). He further asserts "none of the cosmetic readjustments" (p. 480) made in Nagel's revised edition (1979) of his work justifies application of his "abstract calculus" theory to other fields. What does

Shortland's criticism of Nagel's scientific assumptions imply for a model of engineering design?

Peripatetic Thoughts on the Nature of Models

Blair (1990, 1992) has addressed the issue of why engineering is not considered a "legitimate" science. He has raised questions about the influence of the scientific model in engineering and cited problems that result from attempts to adopt this model in the field. Indeed, one might think a list of attributes that define a normal scientific model (such as Nagel's) could be developed and then used to examine the field of engineering. Such an approach implies two alternatives. One is to cite those scientific qualities that engineering lacks and then to propose means to remedy the lack of fit between engineering and the scientific model. In other words, how to upgrade the field of engineering so that it will match the attributes of an objective, rational scientific model. The other approach, and the hypothesis of this dissertation, asserts engineering has been "barking up the wrong metaphor" by attempting to adopt the scientific model. Blair illuminates problematic issues in developing a model of engineering design.

Blair's (1990) thought-provoking ideas on models are a response to Nagel's (1961) straightforward definition of scientific theory. Blair observes theory that is composed of a formal calculus, operational definitions and a model may not count as "scientific" at all. Nagel's three components of scientific theory may indeed serve as "symbolic generalizations or operational definitions" (1990, p. 279) for developing models in a given field; however, according to Blair, the real issue involves the "tacit" assumptions that underlie models derived from scientific theory.

In effect, for Blair (1990), models are one way of ordering and organizing researchers' perceptions. They can be explicit or implicit; that is, researchers may or may not be aware of the perceptual predispositions or assumptions of the models. Implicit models often reflect a tacit nature that may unconsciously frame the way researchers interpret reality. Researchers may even "be deluded into thinking that they can see 'pure facts' in a reality unadulterated by preconceptions" (Blair, p. 281). What researchers refer to as "facts" are not context free; they are "intimately connected to an endless number of other facts" (Blair, p. 281). They achieve "salience" or distinction only within the context of a model that emphasizes some of these empirical phenomena over others.[37]

Blair (1990) further asserts, in some cases, the perceptual frameworks in a given field may be so strong that researchers "simply cannot regularly see things as raw uninterpreted data" (p. 282). In particular, these frameworks "predetermine what researchers think they see" (p. 282).[38] Blair's observations parallel Fleck's (1979) ideas concerning scientific thought collectives and they imply other issues relevant to a model of engineering design. In particular, Kuhn (1970) offers valuable insight in this area.

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[37] Blair's ideas on the power of models to lend salience to facts is similar to Entman's (1993) and Endelman's (1993) concept of framing, counterframing and salience.

[38] Similarly, Mills asserts "since one can be trained only in what is already known, training sometimes incapacitates one from learning new ways" (p. 216). Refer to Mills, C.W. (1959). The sociological imagination. London: Oxford University Press.

Thought Collectives, Intersubjective Models and Counterframes

Fleck (1979) argues cognition is not an individual process but instead involves the individual, the social collectivity to which he/she belongs and the socially legitimated objects of inquiry. Fleck points out:

> individuals are necessarily members of a thought collective with a particular thought style which, often unbeknown to the individual, or indeed the entire collective, exerts a compulsive force upon their thinking. When a particular conception permeates throughout the thought collective and influences everyday life and idiom, any contradiction, therefore, appears unthinkable and unimaginable. (p. 39)

Fleck (1979) characterizes a scientific thought collective as a "pragmatically useful social activity" that functions as the "common carrier" of a given thought style (p. 158).[39] The thought style in turn functions by constraining, inhibiting, and determining the collective's way of thinking. It acts as "a legislative authority" for corroborating and sustaining the a priori nature of the thought structure. What the thought collective supplies its members "is somehow like the Kantian[40] categories,

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[39] For an explication of "memes" as common carriers of a given thought “contagion” or “infection,” see Lynch, A. (1996). Thought contagion: How belief spreads through society. New York: Basic Books; and Brodie, R. (1996). Virus of the mind: The new science of the meme. Seattle, WA: Integral Press. Both Lynch and Brodie characterize memes (memetics) as “autonomous entities in an evolutionary drama, leaping from brain to brain in much the same way that viruses leap form body to body,” spreading and infecting the population of “ hosts” with potent ideas that stimulate replication of dominant thought styles. In its most revolutionary aspect, memetics asks not how people accumulate ideas but how ideas accumulate people. In similar metaphorical fashion, Kerlinger (1977) describes research problems as “inchoate and tentative, a troubled, perplexed, trying situation, where the difficulty spread[s] throughout the entire situation, infecting it as a whole” (pp. 11-12). For a fully articulated theory of memetics and implications for engineering design, refer to Dawkins, R. (1989). 2nd ed. The selfish gene. New York: Oxford University Press. Dawkins coined the term “meme” in the 1979 edition of this text.

[40] For analyses of Kant’s categorical (or formal) imperatives as “prerequisite to thought,” refer to Booth, W.J. (1986). Interpreting the world: Kant’s philosophy of history and politics. Toronto, Canada: University of Toronto Press; and Bigger, C.P. (1996). Kant’s methodology: An essay in philosophical archeology. Athens, Ohio: Ohio University Press.

prerequisite to any thought at all." (Fleck, p. 159) In particular, Fleck cites the difficulties of transmitting ideas between any two thought collectives. These are "closed systems" that restrict participation of any member in more than one "thought community."[41] Very different thought styles "are used for one and the same problem more often than are closely related ones" (Fleck, pp. 159-160).

Kuhn (1979) examines Fleck's (1979) theories within the context of model development. He argues a thought collective functions as "an individual mind writ" largely because "its inducted members are possessed by it"(p. vii). He further asserts "the tenacity of such self-contained systems of opinion" may force its members to participate in "a kind of harmony of illusion" (pp. vii-xi). The last phrase is intended metaphorically and, for Kuhn, it is "a damaging metaphor" (p. x). Under the influence of this particular metaphorical thought style, one cannot think in any other way. It excludes alternative modes of perception by exerting a compulsive force upon the entire collective's thinking.[42] It stimulates development of intersubjective theories and models that reinforce conformity to the dominant thought style.[43] Gaggi (1989) asserts

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[41] Kuhn recognizes the "startling quality" of Fleck's remarks on the incompatibility of different thought collectives. He acknowledges Fleck's influence on his theory of the "incommensurabilty of paradigms." See Foreword to Fleck's (1979) text, pp. vii-xi.

[42] Margolis refers to dominant thought styles as "habits of mind" characterized by "deeply entrenched cognitive propensities" that are disciplinarily endemic in nature. These propensities can operate as paradigm barriers and may constrain alternative modes of thinking while "stubbornly pushing things their way" (p. 6). See Margolis, H. (1993). Habits of mind; Paradigms; and Barriers. In Paradigms and barriers: How habits of mind govern scientific beliefs. (pp. 7-42). Chicago: University of Chicago Press.

[43] For an analysis of subjective models and theories, refer to Sanitt, N. (1996). Subjective nature of science. Science as a questioning process. (pp. 65-80). Bristol, England: Institute of Physics. For a study of assumptions see Goldberg, J. (1989). Anatomy of a scientific discovery. New York: Bantam Books.

“scientific truth” derived from this type of thought style “seems to result more from a kind of social pressure that affects an individual’s beliefs than from any ‘objective’ criteria regarding the proper means for apprehending truth” (p. 176).

According to Trenn and Merton (1976), to the extent that an individual does not conform to the collective metaphor, he/she is considered "deviant." Individuals who possess a strong "personal thought style" form "a unique mono-collective"(cited in Fleck, 1979, p. 160) as they conduct a dialogue with themselves outside the metaphorical limits of the thought collective in question; they can participate in more than one collective at the same time. These "marginal individuals" are not only crucial for the exchange of thoughts between different thought communities, they are a potential source for generating alternative styles of thinking that can extend beyond the "intrinsic constraint of a dominant metaphorical thought style" (cited in Fleck, 1979, p. 160). They detect a "perceptual dissonance" in the models of their field and are stimulated to search for alternative "pathways of thought"[44] (Trenn & Merton, cited in Fleck, 1979, pp. 158-160).

For Trenn and Merton, these alternative modes of thinking are the "counterframes" that challenge a collective's normative assumptions; they offer opportunities for thinking in different ways about engineering design.[45] In particular,

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[44] The idea of "perceptual dissonance" is similar to Festinger's theory involving individuals who are motivated to seek "dissonance-reducing cognition." See Festinger, L. (1957). A theory of cognitive dissonance. Evanston, IL: Row and Peterson, pp. 126-137.

[45] Trenn and Merton's observations on dominant thought styles and potential counterframes closely parallel ideas posited by Kahneman and Tversky (1984) and Snider, Brody, and Tetlock (1991).

this type of thought style can generate a model of design activity that is an alternative to models derived from a scientific perspective (cited in Fleck, pp. 158-160).

Laudan's Critique of Scientific Models: An Apologia for a Model of Engineering Design

Laudan (1984) cites "the sparsity of useful analytic tools" (p. 1) for understanding change and development in the field of technology. Technology and engineering design remain "locked inside an impenetrable black box, a 'deus ex machina' to be invoked when all other explanations of puzzling phenomena fail" (Laudan, p.1). Scholars are beginning to identify areas where further research is most needed but they lack theoretical models for "penetrating" this "black box" (p. 1).[46] As such, model building remains "embryonic." For Laudan, the purpose of constructing a model is "to simplify and throw into relief those tacit elements"(p. 2) of design activity that remain undetected by current research practices. Scientific models make up the "bulk" of the theoretically oriented discussions of this multi-faceted phenomenon. However, these models view engineering design as an exogenous variable and consider its internal dynamic as a given. According to Laudan, they have "too gross a structure

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[46] Latour (1987) asserts "surprisingly few people have penetrated from the outside the inner workings [black box] of science and technology, and then got out of it to explain to the outsider how it all works" (p. 15). Yet, for a "glimpse" of the inner workings in the black box, see Rosenberg, N. (1983). Inside the black box: Technology and economics. Cambridge, England: Cambridge University Press; Gans, H.J. (1993). Reopening the black box: Toward a limited effects theory. Journal of Communication,43 (3), 29-35; and Sanitt, N. (1996). Question reformulation and 'black boxing'. In Science as a questioning process. (Pp. 58-59). Bristol, England and Philadelphia, PA: Institute of Physics.

to capture the internal dynamics" (p. 2)[47] of design activity and contribute little understanding to the problem.

Laudan challenges a "widely-held assumption" that engineering design knowledge is largely inaccessible to scholarly study. She asserts it is based on the following reasoning:

> Since engineering knowledge is rarely articulated, and since when articulated, such knowledge is largely in visual, rather than verbal or mathematical form, it does not lend itself to analysis by a scholarly community trained primarily in the analysis of texts and the explication of logical structures. Engineering knowledge, on this construal, is 'tacit' knowledge. Engineering activities cannot be fully specified, and hence rules for their performance cannot be spelled out. (1984, p. 6).

Since engineering knowledge is "tacit," one often assumes it is a necessarily "opaque" aspect of engineering that escapes description. Scholars may be able to describe the behavior of engineering artifacts and to trace their effects on society, but they are not able to construct a model of the activities by which practitioners arrived at these innovations.[48]

From this perspective, engineering design seems "an unpromising subject for model-building" (Laudan, 1984, p.7). Yet Laudan cites Ferguson's (1992) studies on the

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[47] Similarly, Duysters is skeptical of using "textbook neo-classical theories" as a basis for model development in the field of economics. He proposes "evolutionary economic theory" to generate models that can appropriately express the relational fit between a proposed model and the internal and external dynamics of economics (p. 9). See Duysters, G. (1996). The dynamics of technical innovation. (pp. 9-34). Cheltenham, England: Edward Elgar.

[48] This reflects Petroski's (1994) observation that current research in engineering design is often only "a manifestation of what is understood about the substance and behavior of the products of engineering." (p. 8). It overlooks the fundamental nature of design activity as a human problem solving process.

"unique" nature of engineering design as the type of research that is fundamental for development of a model of design activity. Laudan asserts "the time is ripe to see whether some of the analytical categories derived from such studies could illuminate a potential model" (p. 15) of design activity. She further asserts scholars must "venture well beyond" (p. 2) the limits of their own field of research and look to other disciplines to guide theory and model development in engineering design.[49]

Opening Pandora's Black Box Of Technology:
A Potential Model for Engineering Design

Latour (1987) states "probably the best book on the question of models is still Max Black (1962)" (p. 265). He considers Black's (1962) theoretical framework for models a useful starting point for "opening Pandora's Black Box" of technology (p. 15).[50] Wilson (personal communication, January 28, 1997) agrees with Latour's assessment of Black's work and affirms its practical applications for model development in engineering design.

Black (1962) considers various senses of "model" in a systematic order, proceeding from scale, analogue, and mathematical models to metaphors and

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[49] Laudan supports Boden's (1983) and Machlup and Mansfield's (1983) admonition scholars "be sensitive to interdisciplinary messages."

[50] Why "Pandora's" black box? According to Latour (1987), engineers are sometimes perceived as "Janusian bifrons alternatively endowed with demiurgic powers - for good or bad" (p. 15). For a description of the Demiurge as "the artificer of the world," see Leeming, A. (1994). Encyclopedia of creation myths. Santa Barbara, CA: ABC-CLIO, pp. 103-104.

archetypes until he reaches "the impressive but mysterious use of 'theoretical models'" (p. 239). Black asserts all intellectual pursuits, however different their aims and methods, "rely firmly upon exercises of the imagination ... [they are] an affair of the imagination" (pp. 242-243). Yet scholars too often neglect the imaginative aspects of research. Black responds to this dilemma by emphasizing the use of models as a means to stimulate scholars' imaginative thinking.

Black (1962) initiates his treatise by identifying certain "uncontroversial" points about the nature of models in general. A model is a representation of the real or imaginary thing for which it stands. Its use is for "reading off" properties of the original from the directly presented properties of the model. According to Black, it follows that some features of the model are irrelevant or unimportant, while others are pertinent or essential, to the representation in question.[51] There is no such thing as a "perfectly faithful" model; only by being unfaithful in "some" respect can a model represent its "original" (p. 220). As with all representations, there are underlying conventions of interpretation for "reading" the model and for making accurate inferences from the relevant features of the model.

A dominant principle at this point is "isomorphism," the degree to which the form or appearance of the model accurately reflects the domain in question. In "stretching" the language by which the model is described so that it "fits" the new

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[51] Compare the comments by Entman, Kahneman and Tversky, and Edelman on the subject of frames, counterframes and salience.

domain, one hopes to illuminate the existence of a common structure in both fields . One can determine the validity of a given model by checking the extent of its isomorphism with its intended application, that is, by "the sheerly pragmatic test of the goodness of the fit" (p. 238) between the model and the domain.[52]

Black's (1962) list of attributes is useful for a consideration of models in a general sense and it has implications for engineering design. Yet, in his discussion of the conditions for use of a theoretical model, Black raises issues in which the sense of "model" sharply diverges from that applied to other types of models. In particular, he reveals the outlines of a potential model for design activity.

Black (1962) characterizes theoretical models as "heuristic fictions" that use language appropriate to the model in thinking about the domain of application. These models work not "by" analogy but "through" and by means of an underlying analogy. They are not literally constructed; the "heart of the method consists in 'talking' in a certain way" (pp. 228-229). According to Black, it is plausible to say the use of theoretical models consists in introducing a new language or dialect,[53] suggested by a familiar theory but extended to a new domain of application.

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[52] Implications of isomorphic structure and relational fit in a model of engineering design are found in Sanitt, N. (1996). Science as a questioning process. (p. 35). Bristol, England and Philadelphia, PA: Institute of Physics.

[53] For issues related to reduction of "creeping ambiguity, vagueness and loose concepts" in language and their implications for models of engineering design, see Black, M. (1968) The labyrinth of language. (pp. 128-138). New York: Frederick A. Praeger.

There are five conditions for use of a theoretical model that Black summarizes:

> - A researcher has an original field of investigation in which "some" facts have been established, ranging from disconnected items and crude generalizations to relatively well articulated theory.
>
> - A need is felt, either for extending the original corpus of knowledge and conjecture, or for connecting it with disparate bodies of knowledge.
>
> - One describes salient entities belonging to a relatively unproblematic or more familiar secondary domain; the postulated salience of these entities is described in whatever detail seems likely to prove profitable.
>
> - Explicit or implicit rules of correlation are derived for translating statements about the secondary field into corresponding statements about the original field.
>
> - Inferences from the assumptions made in the secondary field are translated by means of the rules of correlation into a model of the domain in question.
>   (1962, p. 230).

The key to understanding the entire transaction is the "identity of structure" in the model; in favorable cases, it permits assertions made about the secondary domain to yield insight into the original field of interest. Black (1962) asserts the virtue of a theoretical model is that it replaces abstractions and mathematical formulas with pictures or any form of representation that is readily visualized. Toulmin (1970) further asserts :

> It is in fact a virtue of a good model that it does suggest further questions, taking us beyond the phenomena from which we began, and tempts us to formulate hypotheses which turn out to be experimentally fertile. (pp. 44-47).

It is a "speculative instrument" with implications "rich enough" to suggest new perspectives in the primary field of investigation. To make good use of such a model, one usually needs an intuitive grasp ("Gestalt knowledge") of its capacities in order to draw inferences from its "identity of structure" (Black, 1962, p. 231-233).

Black (1962) argues theoretical models "are not epiphenomena of research or disreputable understudies for mathematical formulas" (p. 236). They play a distinctive part in investigation and strongly resemble metaphors. Black asserts :

> We are forced to employ models when, for one reason or another, we cannot give a direct and complete description in the language we normally use. Ordinarily, when words fail us, we have recourse to analogy and metaphor. The theoretical model functions as a more general kind of "metaphor." (p. 236)

In a metaphorical sense, a theoretical model is a distinctive mode of insight that employs a new language or dialect; it is a lens that enables one to see subject matter in a new light.[54] It brings about a "wedding of disparate subjects" whose outcomes are unpredictable. A theoretical model also helps one to notice what otherwise might be overlooked, to shift the relative emphasis attached to details, in short, to "see new connections" (Black, p. 237).

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[54] Miller's (1996) theoretical framework for exploring the "pervasiveness" of metaphors, models, and language extends the notion of "new insights and connections"cited by Black (pp. 217-262).

Implications for a Model of Engineering Design

Chia's (1995) ideas on the "different styles of thinking" in research analysis can illuminate salient points about the nature of models. In particular, his thoughts on modernist and postmodernist thought styles are useful as an interpretive framework for examining issues surrounding a model of engineering design. Figure 3 identifies and contrasts the characteristics of this postmodern model with one derived from modernist assumptions.[55] According to Chia (1995), a model based on Nagel's (1979) notion of a scientific theory being based on an abstract calculus and operational definitions represents a modernist thought style. It relies on a strong ontology of "being," a distal state that privileges thinking in terms of discrete phenomenal states, static attributes and sequential events.[56] It models a linear style of thinking in which things and entities rather than relations are privileged, and it implies one can control, predict, and generalize the research outcomes of any given phenomena (Chia, pp. 579-581).

Whitehead (1985) asserts this thought style accentuates a view of social reality as comprising discrete, static and hence describable phenomena; it is a deductive mode of thinking that "turns verbs into nouns, process into structure and relationships into things"(p. 69). The modernist style sees physical objects and things as the natural units

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[55] Rorty (1991) asserts modern and postmodern modes of thought can be distinguished by their "epistemological priorities." These are best understood as differences in styles of thinking, each with their own set of ontological commitments, intellectual priorities, and theoretical preoccupations.

[56] Law characterizes a thought style based on strong modernist ontology as "a fait accompli" attitude. See Law, J. (1992) Notes on the theory of the actor-network: Ordering, strategy and heterogeneity. Systems Practice. 5: 379-393.

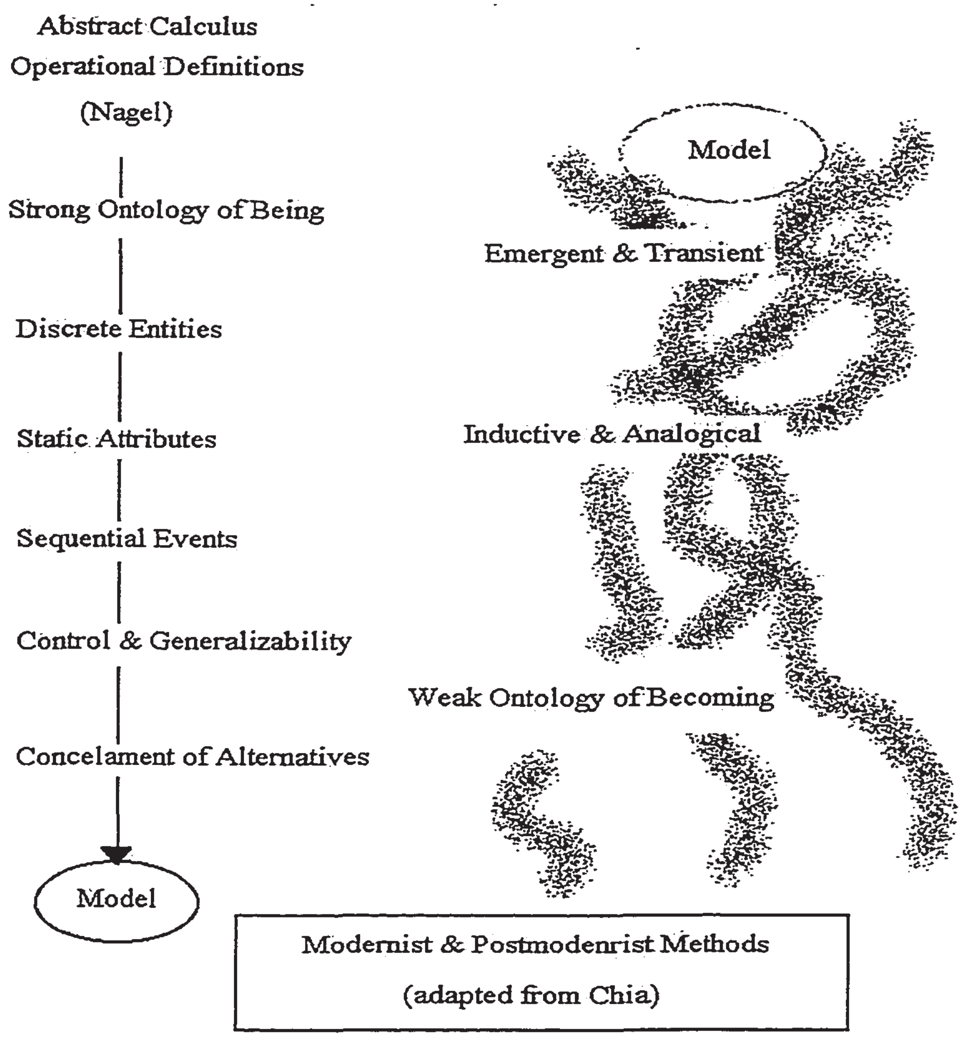

Figure 3. A Comparison of Modernist and Postmodernist Assumptions

of analysis ("givens") rather than, more properly the relationships between them. Whitehead calls this tendency the "Fallacy of Misplaced Concreteness"(p. 69). The "paradox only arises because we have mistaken our abstractions for concrete realities" (Whitehead, p. 69). Models based on a strong ontology of being tend to conceal alternative models or styles of thinking.[57] An engineering design model based on postmodern thinking privileges a weak ontology of "becoming" which emphasizes dissonance, disparity, plurality, change, and even ambiguity, paradox, and the "not-yet-known." It views the phenomenon of design activity as "a processual, heterogeneous and emergent configuration" (Chia, 1995, p. 579). The postmodern sensibility is a proximal style of thought in which design activities are deemed to be continuously in flux and transformation and hence unrepresentable in any static sense. It is an inductive and analogical mode of thinking that uses a verbal approach to describe "the emergent relational interactions and patternings" (Chia, pp. 581-582) that underlie the dynamics of design.

In a broader sense, a postmodern thought style is an attempt to "de-center" modernist thinking about the nature of engineering design. It enables one to think about ignorance and uncertainty in the "respectable" terms cited by Smithson (1993). As such, it becomes an exploration of the negative spaces of engineering in a human context,[58]

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[57] Compare Fleck's theory of how a particular thought style exerts a compulsive force upon the thinking of individuals in a given thought collective.

[58] Smithson offers a model of ignorance and uncertainty and discusses "configurations of negative space", shape scientific thought, and knowledge creation. See Smithson, M. (1993). Ignorance and science: Dilemmas, perspectives, and prospects. Knowledge: Creation, Diffusion, Utilization, 15,(2), 133-156.

and an attempt to think, as Davidson (1978) notes, in terms of metaphorical "visions, thoughts, and feelings" rather than in "concrete articulations" of modernist literalism (p. 41).[59] The "gap to be bridged here is not one of slight attitudinal differences, but of differing perceptions" about engineering design, of alternative ways of thinking about "the processual actions and movements" (Schwartz & Ogilvy, 1979, p. 24) of design activity.

Chia (1995) asserts adopting a postmodern mode of thinking in research implies radical consequences for theory and model development in any given field. A model of engineering design based on a postmodern thought style is a response to Chia's assertion. It is a postmodern "counterframing" of design activity. In particular, it is a response to Blair's (1990) argument for an alternative way of thinking about the nature of one's engagement with research and to Laudan's (1984) "apologia" for an alternative model of engineering design. Further, it is an opportunity for stimulating a dialectic approach in research on design activity, and it is a dynamic framework for engaging Harris' (1986) "extended argument" in the field.

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[59] For an analysis of the distinctive levels of meaning in Davidson's "theory of metaphor," with implications for engineering design, refer to Woo, J. (1995). What metaphors tell us about pictures. Unpublished manuscript. University of California, Berkeley.

Chapter 4: Methods

The Methods chapter of a qualitative study on engineering design prepares the reader for what is to follow and provides a framework within which to incorporate essential components of the design process. This approach allows one to address certain assumptions underlying a particular design technique and it shapes the organization of the chapter itself (Rudestam & Newton, 1992).

Rudestam and Newton (1992) assert qualitative studies must meet the same criteria for completeness that quantitative studies do; that is, they must be able to describe in sufficient detail the methods and procedures to permit replication of the study. Yet the authors note it may not be possible to predict some components of the procedures in a qualitative study with same degree of precision as in a quantitative study. Creswell (1994) indicates "few writers agree on a precise procedure for data collection, analysis, and reporting of qualitative research" (p. 143). Thus, researchers must be especially specific in their description of methods used in a qualitative design. This is important because of the growing awareness among qualitative researchers about alternative designs and their distinctive characteristics. In particular, Smith (1987) states qualitative designs are "interpretive, artistic, systematic, and theory-driven" in nature and, as such, they must specify the assumptions and methods underlying the given design (p. 66).[60]

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[60] For an in-depth analysis of issues surrounding qualitative research design, see Denzin, N.K. & Lincoln, Y.S. (1996). Introduction: Entering the field of qualitative research. (pp. 1-17).

Characteristics of a Qualitative Research Problem

A qualitative approach often adopts a view of research design - sampling, instrumentation, procedures, and data analysis - that is contrary to the views held by those conducting more traditional "rationalistic" inquiry (Marshall & Rossman, 1989, p. 49). Rudestam and Newton (1992) assert inductive qualitative designs challenge the epistemological and philosophical foundations of traditional social science research. This type of design begins with specific observations and moves toward the development of general patterns and themes that emerge from the phenomenon under study. The researcher does not impose an a priori organizing structure or make assumptions about interrelationships among data prior to making the observations.[61]

Rudestam and Newton (1992) further assert this technique is quite different from the "hypothetico-deductive" approach to experimental designs that prescribe specification of variables and hypotheses prior to data collection. It is a "countervailing trend" that "calls for sidestepping the artificiality and narrowness of experimental studies" by promoting inductive techniques which allow researchers to be "more spontaneous and flexible" in exploring a given phenomenon (pp. 29, 32).[62]

Lincoln and Guba (1985) refer to this countervailing trend as the "paradox" of

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[61] Similarly, Churchland asserts “once we are freed from the grip of the orthodox philosophical approach, we can pursue the question of theory evaluation with a fresh eye” (p. 276). See Churchland , P.M. (1995). The engine of reason, the seat of the soul: A philosophical journey into the brain. Cambridge, MA: MIT Press.

[62] Mills suggests researchers be receptive to "unforeseen and unplanned linkages" by exercising "a release of the imagination" and by adopting an attitude of "playfulness." The essence of this process is "the combination of ideas that no one expected were combinable" (pp. 211-21, 215). See Mills, C.W. (1959). The sociological imagination. London: Oxford University Press.

designing a qualitative inquiry, and they argue "the design specifications of the conventional paradigm form a Procrustean bed of such a nature as to make it impossible for the naturalist to lie in it - not only uncomfortably, 'but at all'" (p. 225).

They outline a broad series of design considerations that focus on the ontological and axiological assumptions that underlie a qualitative study, and the "fit" of these assumptions to the methods being used. In particular, the authors attempt to distinguish "the fit between the purpose of the study, the basic guiding principles underlying the approach, and the substantive theoretical framework" (pp. 225-226).[63] The lack of fit between purpose, approach, and theory in research may become apparent when findings and implications seem to make no apparent sense in light of the original questions.

Morse (1991) notes qualitative research is exploratory and researchers use it to explore a topic when the variables and theory are unknown. She states:

> Characteristics of a qualitative research problem are: (a) the concept is "immature" due to a conspicuous lack of theory and previous research; (b) a notion that the available theory may be inaccurate, incorrect, or biased; (c) a need exists to explore and describe the phenomena and to develop theory; or (d) the nature of the phenomenon may not be suited to quantitative measures. (p. 120)

Creswell (1994) also cites specific methodological assumptions that apply in a qualitative study of engineering design. These assumptions include:

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[63] Guba and Lincoln (1985) assert it is critical in inductive, qualitative designs to clearly determine (1) a focus for the inquiry; (2) the fit of paradigm to focus; and (3) the "fit" of the inquiry paradigm to the substantive theory selected to guide the inquiry (p. 225).

- inductive, exploratory process
- mutual simultaneous shaping of factors
- emerging design
- categories identified during research process
- data are context bound
- patterns, theories, and models are developed for understanding
- the area of inquiry may lack a theory base

(Creswell, 1994, pp. 145-146).

Merriam (1988) further notes qualitative design is concerned primarily with process rather than outcomes or products. It is descriptive in that the researcher is interested in process, meaning, and understanding gained through words or pictures. Qualitative research is inductive in that the researcher builds abstractions, concepts, theories, and models from details.[64]

Merriam (1988) states these particular theories vary in terms of their breadth and scope, and he groups them into three types. "Grand" theories attempt to explain large categories of phenomena and are most common in the natural sciences. "Middle-range" theories fall between minor working hypotheses of everyday life and the all-inclusive grand theories. "Substantive" theories are restricted to a particular setting, group, or problem. Merriam asserts research in a given field may show theories at all

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[64] Kuhn (1970) characterizes research design as a "puzzle-solving" process. It is "an individual's best guesses about the proper way to connect" his/her own research problem with the assumptions of a given paradigm (p. 4).

three levels. For engineering design, the initial focus is on development of "substantive" theory with inductive movement toward an interpretive "grand" theory for model development.

Rudestam and Newton (1992) and Creswell (1994) both state the method for a qualitative study needs to evolve out of the research question and be determined by it. In particular, Creswell indicates research questions, not objectives or hypotheses, are typically written into qualitative design. These questions may take the form of a "grand tour" question; it is consistent with the emerging methodology of qualitative designs and is posed as a general issue so as not to limit the inquiry. The grand tour question is followed by relevant subquestions that narrow the focus of the study but that do not constrain the qualitative researcher. These questions, in turn, can become the topics specifically explored in documents. The researcher can expect the questions to evolve and change during the study, "a thought consistent with the assumption of an emerging design" (Creswell, 1994, pp. 71-72).

According to Creswell (1994), the "only universal" in design, whether qualitative or quantitative, is "a general commitment to using logical argument and evidence to arrive at conclusions that are recognized as tentative and subject to further amendment" (p. 23). Finally, a qualitative method implies the data are in the form of words as opposed to numbers. Whereas quantitative data are generally evaluated using descriptive and inferential statistics, qualitative data are usually reduced to themes or categories and evaluated subjectively. There is more emphasis on description and discovery and less emphasis on hypothesis testing and verification. Polkinghorne

(1991) asserts qualitative methods are especially useful in the "generation of categories for understanding human phenomena and the investigation of the interpretation and meaning that people give to events they experience" (p. 112).

What is the researcher's role in an exploratory study of engineering design? Qualitative research is interpretative research. Thus, the axiological assumptions - the biases, values and judgment - of the researcher should be explicitly stated.[65] Locke, Spirduso, and Silverman (1987) assert such openness can be useful and positive.

Personal Communications on the Design Process

A variety of experiences impacted the researcher's thinking on engineering design activity. Doctoral seminars on information engineering and design with Brian O'Connor provided the substantive content and theoretical framework that influenced the direction of research on the topic. A series of focused discussions with O'Connor and Patrick Wilson (personal communication from July 28, 1995 to April 2, 1997) helped in identifying salient aspects of design activity as a human problem-solving process. These efforts were supported by personal communications with several scholars whose research activities bear on various aspects of the design process. In particular, certain contacts provided "interdisciplinary messages" (Machlup & Mansfield, 1983, p. 4) which revealed provocative aspects of engineering design.

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[65] Wilson (personal communication, September 12, 1995) asserts in a dissertation using a qualitative approach, it is "absolutely required that the researcher be explicit about his/her theoretical commitments, research methodologies, and paradigms."

A list of these scholars with a brief description of contributory thoughts or "salient frames" on the design activity follows:

Fred Hapgood (personal communication from September 22, 1994 to February 27, 1997) - Design activity is a traversal through solution space in which pattern generation and matching often lead to a "satisficing" or less than optimal solution.

Henry Petroski (personal communication, January 9, 1997) - A model of engineering design must of necessity incorporate a theme of failure. Failure and human error reflect the fundamentally contingent and pragmatic nature of design activity itself. It is an activity that is "in our bones."

David Blair (personal communication, February 3, 1997) - The central problem of information retrieval is how to represent documents for retrieval - a problem of language and meaning. There is an urgent need for new models or modes of symbolic expression based on "perspicuous examples" (demonstrative knowledge) of the field.

Paul Churchland (personal communication, March 8, 1996) - Models may be viewed as a "family of heuristic prototypes" that enable one to recognize and understand "slices" of a problem or question state. These adaptive models seek a relational fit between the idiosyncratic, inferential context of the individual and the evolving patterns of change in the external world.

Edward Pai (personal communication, January 5, 1996) - "Flavors of relevance" in models of information retrieval suggest an inductive approach to generating and linking categories of design activity based on degrees of relevance among various "thematic flavors" of engineering design.

Doug Macbeth (personal communication, February 23, 1996) - Visual inquiry may be characterized as a method which "enables us to find our tongue" in the presence of "description-resistant" phenomena, and as "a search for coherence" in which failures are often more interesting, and certainly more visible, than successes.

David Carr (personal communication, November 16, 1993) - Critical thinking is "typically a solo act and often improvisatory." Like the musician, playing with the possibilities inherent in structures, "we can move into unknowns simply by making unanticipated turns of the mind: look at this, see that, look more closely at these." A "tension of consciousness comes from having to risk our old certainties in order to build newer and more tentative structures." Beyond the edge, certainty disappears and "we have to search for new edges."

Paul Thagard (personal communication, March 11, 1996) - Divergent concepts can fit together into an evolving, conceptual system, "creating a web of relationships" which provide "explanatory coherence" of a given human phenomenon from a multiplicity of perspectives.

Henry Mintzberg (personal communication, March 1, 1996) - An integrated model of a given human activity can be built "from the inside out," that is, by moving from internal core themes through concentric layers of related activities to the external context that surrounds the model itself.

Stanley Deetz (personal communication, December 4, 1996) - Research realms have developed ways of answering the types of questions they pose and "do not work terribly well" in answering others. Theories, and models are "contests for meaning."

Everett Rogers (personal communication, August 15, 1996) - There should be more emphasis on divergent models of communication; they are an "intriguing" alternative to traditional models of convergence and suggest alternative paths to problem solution in a given field of inquiry.

Michael Harris (personal communication, April 13, 1994 & January 3, 1996) - Emphasis on extended argument and dialectic in research in library and information science as a means to challenge the "prevailing" positivist epistemology in the field.

Klaus Krippendorff (personal communication from March 13, 1997 to April 28, 1997) - Engineering design activity is "an area of exploration that badly needs attention." A conceptual model of this activity can be achieved through inductive content analysis of engineering design "distillations".

Robert P. Weber (personal communication, April 15, 1997) - Key-word-in-context and word-frequency techniques in content analysis applied to an inferential schema of engineering design can reveal "rich contextual" categories and themes of design activity.

Lawrence Cahoone (personal communication, May 1, 1997) - Themes of pragmatics, contingency, and bricolage are "conceptually promising clues" to an emerging postmodern model of engineering design.

Richard Rorty (personal communication, January 6, 1997) - A model of engineering design interpreted through a postmodern lens of pragmatics and contingency is an "interesting" concept.

These frames illuminate the researcher's assumptions about design activity for the reader. In particular, they can be seen to have influenced the researcher's impressions of engineering design as a human problem-solving process. In addition, the frames guided the selection and order of techniques used in exploring engineering design. Seeking to discover, explain, and describe the nature of design activity is an evolving research technique guided by three "purposefully" selected modalities: Document Sampling; Instrumentation; and Procedures.

Document Sampling

What is the nature of engineering design? Specifically, what are the attributes of design activity as a human problem-solving process? These "grand tour" questions suggest the parameters for data collection and "determined where and from whom data would be collected" (Creswell, 1994, p. 74). As indicated above, a search of existing literature on engineering design revealed few studies on the topic. The studies that do exist treat only certain "salient" aspects of design activity and frame the topic in a fragmented manner. Extended search on the topic yielded results with a high redundancy factor. These are the "inferential signposts" which guided "purposefully selecting" documents that best respond to the research questions (Creswell, 1994, pp. 78, 148). No attempt was made to randomly select documents or informants.

Thus, the researcher "eschews random or representative sampling in favor of purposive or theoretical sampling" in an attempt to "uncover the full array of multiple realities" (Guba & Lincoln, 1985, p. 40) that exist in the few studies on engineering design. Krippendorff (personal communication, March 13, 1997) describes this sampling technique as an "idiographic" perspective in which there is no attempt to generalize the findings to a larger context; emphasis is on exploring and describing a unique view of a given human activity or phenomenon (Guba & Lincoln, p. 30).[66]

In a similar vein, Rudestam and Newton (1992) assert determining the appropriate number of documents or subjects for a given design is "one of the most difficult sampling problems" (p. 63) in qualitative research. In fact, the authors state the best method to approximate the appropriate number of documents is to conduct a "power analysis."[67] However, the use of power analysis in engineering design research is unrealistic. This is due to the fact that there are not enough documents on the topic "to meet the requirements of a purely mathematical procedure" (pp. 64-65). Thus, the use of a purposive sampling design is appropriate for retrieving and selecting documents that respond to the research questions.

A purposive sampling of documents on engineering design, informed by the research questions, yielded the following sources:

Eugene Ferguson

"The Mind's Eye: Nonverbal Thought in Technology" (1977);

Engineering and the Mind's Eye (1992);

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[66] Turkle (1995) characterizes this type of inductive design as a "soft style" or "bottom-up rather than top-down" approach (p. 51).

[67] A power analysis lets the researcher know how many subjects are necessary in order to detect any effects due to the independent variables, given (a) the size of the effect of these variables; (b) the type of statistical tests to be utilized; and © the level of significance (or alpha level) of the study (Rudestam & Newton, p. 64).

Henry Petroski

To Engineer is Human: The Role of Failure in Successful Design (1985);

"Failure as a Unifying Theme in Design" (1989);

The Evolution of Useful Things (1992);

Design Paradigms: Case Histories of Error and Judgment in Engineering (1994);

Fred Hapgood

Up the Infinite Corridor: MIT and the Technical Imagination (1993);

Samuel Florman

The Existential Pleasures of Engineering (1994);

The Introspective Engineer (1996);

Louis Bucciarelli

Designing Engineers (1994);

Walter Vincenti

What Engineers Know and How They Know It: Analytical Studies From Aeronautical History (1990).

The researcher examined each document sample in order to identify the human, problem solving aspects of engineering design. In this iterative process, textual elements that were not patently applicable to the research question were deleted. The salient aspects of the topic were united or "sutured" together to provide a readable, "thick description" of design activity. To examine a document sample in this iterative fashion produces a distillation of each author's ideas on engineering design; specifically, it is an exploratory process that reveals "the articulation itself" (Simpson &

Weiner, 1989, p. 332). Krippendorff (personal communication, March 21, 1997) and Weber (personal communication, April 15, 1997) support the use of document distillations in qualitative design. The authors indicate distillations can be an "inferential framework" for illuminating salient data on engineering design. In particular, Weber (1990) feels succinct iterations derived from purposefully selected documents on design activity can be useful in formulating a prolegomenon or preliminary discussion on the given topic.

Instrumentation

What type of design instrumentation is appropriate for analyzing documents on engineering design? Does a particular instrument "fit" the assumptions that underlie an inductive, qualitative inquiry into the topic? Berelson (1971) cites qualitative content analysis as an effective technique for analyzing "small or incomplete samples" of a given topic. He further notes this technique employs "less formalized categories and more complex themes than quantitative analysis (p. 121). In particular, it is relatively less concerned with the content of documents as such than with content as a "reflection of deeper phenomena" (pp. 121-123).

Weber (1990) posits a definition of content analysis which extends Berelson's (1971) thoughts on the technique and which illuminate assumptions underlying an inductive inquiry into design activity. He asserts :

> A central idea in content analysis is that the many words of the text are classified into much fewer content categories. Each category may consist of one, several, or many words. Words, phrases, or other units of text

> classified in the same category are presumed to have similar meanings. Depending on the purposes of the investigator, this similarity may be based on ... words implying a concern with a concept. [This method] produces highly reliable and valid indicators of symbolic content. (p. 12)

The rules of this inferential process vary with the theoretical and substantive interests of the investigator.

Krippendorff (1980) indicates content analysis is a fundamentally exploratory, unobtrusive technique which "seeks to understand data not as a collection of physical events but as symbolic phenomena" (p. 7). He further states:

> As is true for most research, content analyses are also rarely ever finished. Although a good content analysis will answer some questions, it is also expected to pose new ones, leading to revisions of the procedures for future applications, stimulating new research into the bases for drawing inferences, not to mention suggesting new hypotheses about the phenomena of interest. The beginning and end of a content analysis mark but an arbitrary segment in time. (p. 169)

As such, the data can always be interpreted from numerous perspectives.

Krippendorff (1980) further asserts any content analysis must be performed relative to and justified in terms of the context of the data. Indeed, the context is the "environment of the data" (p. 23) and the researcher's experiences and knowledge determine the construction of the context within which inferences are realized. For Krippendorff, inference is the "raison d'etre" for any content analysis; it "consumes all knowledge a content analyst may have about the way data are related to their context" and "this knowledge will be strengthened with inferential successes" (pp. 26-28).

Guba and Lincoln (1983) argue content analysis is an appropriate technique in an inductive, qualitative design, especially if the researcher "wants some or all of his categories to emerge from the data ... rather than be imposed 'a priori' by a theoretical construct" (pp. 240, 244). From this perspective, the categories are "grounded in the data, and hence, in the context" of the phenomenon under investigation (p. 240).

Such observations indicate content analysis is an appropriate instrument for a qualitative inquiry into engineering design as a human problem-solving process. In particular, the technique "reflects the conceptualization of the phenomenon in a manner that is consistent" (Creswell, 1994, pp. 66-67) with that of the researcher. Yet Weber (1990) emphasizes "there is no simple 'right way' to do content analysis"; (p. 13) researchers "must tailor their methods to the requirements" of the research design (p. 13, 41).[68] In particular, they must judge what specific techniques within content analysis are most appropriate for the substantive problems. Frost and Stablein (1992) further stress "traditional" methods of content analysis are not sensitive to qualitative designs that are "reflexive" in nature.[69] A problematic issue most often arises when the researcher has purposefully selected documents in the domain of inquiry and structured them according to an emerging pattern or theme (pp. 19, 21).

Weber (personal communication, April 15, 1997) responds to these issues within the context of an inquiry into design activity. He states a qualitative design using content analysis as the primary method of data collection can be enhanced in certain

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[68] Krippendorff (1980) asserts "content analysts are known to invent ingenious devices to obtain apparently valid inferences" about a given phenomenon (p. 180).

[69] For an in-depth discussion of this issue, see Schon, D.A. (1987). Educating the reflective practitioner. San Francisco: Jossey-Bass.

ways, especially if little research exists on the topic. An inductive approach to content analysis using a key word extraction program and word frequency techniques allows categories or themes to emerge from the documents or "secondary data."[70]

Weber (1990) states summaries of the documents on design activity can be useful in framing the emerging categories as "contextual themes." These summaries may be succinct presentations or "distillations" of an author's essential ideas on the given topic arrived at through an iterative process by the researcher. These distillations inform the data from content analysis, and relate emerging categories on design activity to the "contextual environment" from which they were extracted (Krippendorff, 1980, p. 30). Integration of categories or themes becomes an interpretative or "translation" process (Weber, 1990, p. 78) stimulating theory and model development.

Procedures

Content analysis of engineering design documents is an evolving, exploratory procedure conducted simultaneously with data collection and data interpretation. In this respect, the analysis procedures for design activities clearly differ from a quantitative approach to the topic. A visual display (See figure 4) helps identify emerging characteristics of the content analysis for engineering design.

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[70] Wilson cites specific assumptions of secondary data or "second-hand knowledge" underlying cognitive authority; Russell characterizes this type of data as "knowledge by description" (learning in a passive mode) in contrast to "knowledge by acquaintance" (learning by doing). See Wilson, P. (1983) Second-hand knowledge: An inquiry into cognitive authority. Westport, CT: Greenwood Press; and Russell, B. (1949) Human knowledge: Its scope and limits. 3rd ed. New York: Simon and Schuster.

Procedures

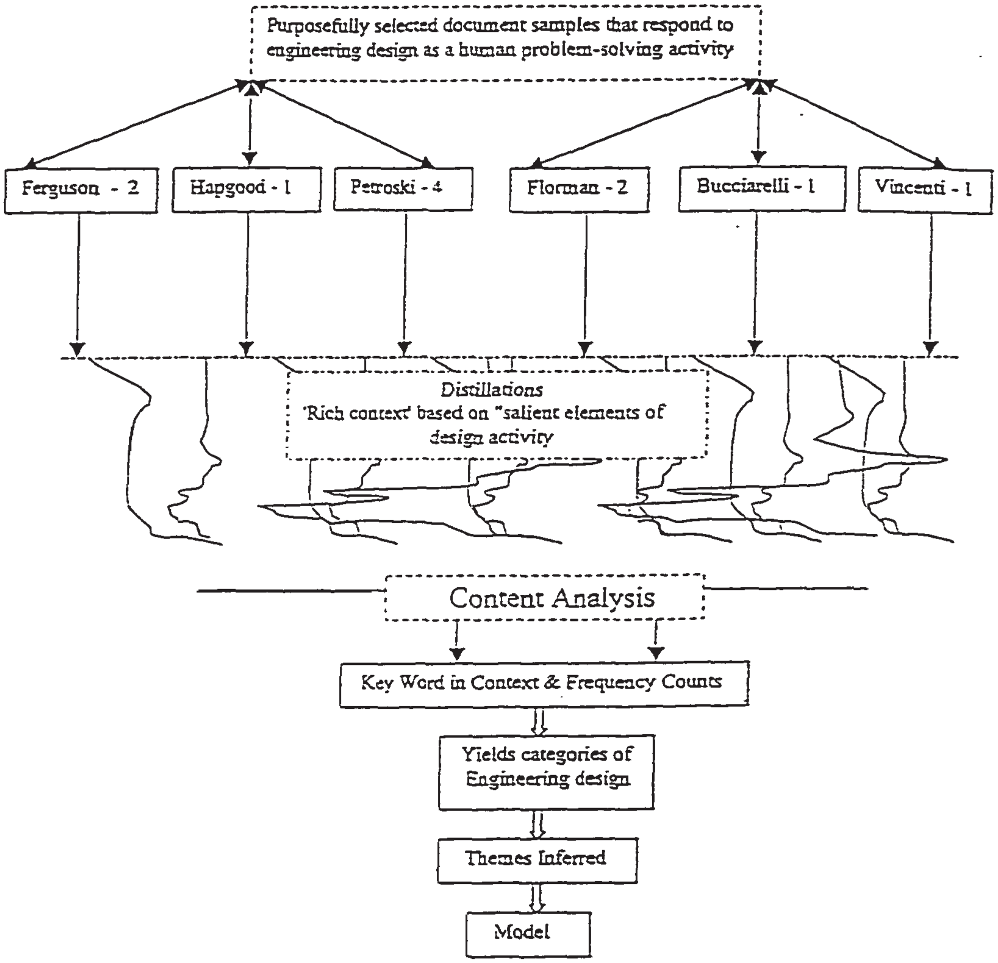

Figure 4. Visual Display of Methods

Problematic issues related to content analysis procedures require consideration. According to Tesch (1990), the process of qualitative data analysis is "eclectic"; there is "no right way ... metaphors and analogies are as appropriate as open-ended questions" (p. 97). Data analysis requires that the researcher be "comfortable" (Creswell, 1994, p. 153) with developing categories and making inferences, comparisons and contrasts. Similarly, Patton (1980) notes there is a tendency for researchers to collect much more information than they can manage or reduce to meaningful analysis (Patton, 1980).

With respect to qualitative content analysis, Guba and Lincoln (1983) assert there are no standard norms for classification, and the construction of categories is often "a trial-and-error process" forcing the researcher to move between the data and the "emerging" grounded theory (p. 245). According to the authors, it is "far better [to have] an approximate answer to the 'right' question, which is often vague, than an 'exact' answer to the wrong question, which can always be made precise" (p. 242). Thus, data analysis "must progress by approximate answers, at best, since its knowledge of what the problem really is will at best be approximate" (p. 242).[71]

In this type of analysis, Berelson (1971) notes "categories are, so to speak, picked up where they come to hand, are not systematized or defined clearly enough to

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[71] Wilson (personal communication, August 18, 1995) says it is not surprising that researchers "find themselves with more questions than answers." He states researchers should not worry about getting the question "just right." The way one finds out "what's the right question is often by asking what turns out to be the (very or slightly) wrong question." Researchers have to take risks asking questions; this is a "horrifically difficult area in research and nobody gets it just right." Similarly, Sanitt asserts "it is often more difficult to ask the right questions than to find the right answers" (p. 125). See Sanittt, N. (1996). Science as a questioning process. (pp. 31-49, 125-128). Bristol, England & Philadelphia, PA: Institute of Physics.

facilitate or, in some cases, even permit checks" (p. 126). Berelson implies qualitative categories may be viewed as an "emergent bricolage." Turkle (1995) further suggests this type of data analysis is a "tinkering" process in which the researcher, as "bricoleur," approaches problem-solving "by entering into a relationship with [his/her] work materials that has more the flavor of a conversation than a monologue" (p. 51). It is a process "marked by a desire to play .. to move [around and develop] ... elements of a collage" (p. 52).[72] Entman's (1983) ideas on "framing" relate to content analysis procedures for design activity. He states the major task of determining textual meaning should be to identify and describe frames. Content analysis informed by a theory of framing would avoid treating all negative or positive terms as equally salient and influential. Often, researchers code or "simply tote up" (p. 57) all the messages they judge as positive and negative and draw conclusions about the dominant meanings. They neglect to measure the salience of elements in the text, and fail to “gauge” the emerging relationships of the most salient clusters of messages (the frames) to the broader context from which they are derived. Unguided by a framing paradigm, content analysis may often yield data that misrepresent the messages that are embodied in the texts themselves.

A computer-based content analysis was performed on the distillations of the purposefully selected documents from engineering design. In the case of Hapgood,

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[72] Similarly, Mills states “you should try to think in terms of a variety of viewpoints and in this way to let your mind become a moving prism catching light from as many angles as possible” (p. 214). Refer to Mills, C.W. (1959). The sociological imagination. London: Oxford University Press.

Bucciarelli, and Vincenti, the distillations involved one sample document from each author. The distillations for Ferguson, Petroski, and Florman involved more than one document from each author. For each of these authors, the salient elements of engineering design were extracted from each of the documents of a given author and then sutured together as one document sample from that author.

The central focus here is on computer-based content analysis "as a means of text manipulation, data reduction, and data analysis in which the word or phrase becomes the basic unit" (Weber, p. 41). Weber (personal communication, April 15, 1997) indicates key-word-in-context (KWIC) listings and word-frequency counts are appropriate means for manipulating document sampling on engineering design. In particular, the researcher wanted to discover which "design activity words" appear in the distillations. The KWIC lists show the context in which each word appears and identifies the larger context of word usage. In addition, it makes syntactical and semantic differences more apparent. A KWIC list provides essential information concerning "symbol usage and facilitates translation of substantive theories [of design activity] into concern with specific symbols" (Weber, 1990, p. 49). In addition, this list "can be thought of as a concordance, a rich data base for detailed studies of word usage in the larger textual context" (Weber, 1990, p. 49). Hicks, Rush, and Strong (1985) assert key word lists can function as "discriminators" for generating rich contextual categories are "conceptually closely related" (p. 83).

Another technique in content analysis "counts words" that have been classified into categories. This process yields word-frequency lists that "reveal aspects of the text that would not be apparent otherwise" (Weber, 1990, p. 56). Specifically, the lists allow the researcher to view the distillations from another perspective by examining the highest-frequency words in each emerging category of design activity, except those on the stop list.[73] Because each list accounts for a relatively large proportion of the document, many content analysts focus their efforts primarily on the most frequently occurring words.

Potential problems of content analysis originated mainly in the data-reduction process by which the numerous words from the distillations were classified into fewer categories. Marshall and Rossman (1989) refer to this problem as data “reduction” and data “interpretation” (p. 114). In this instance, the researcher takes a voluminous amount of information and reduces it to certain patterns, categories, or themes and then interprets this information by using some schema. Tesch (1990) calls this process "de-contextualization" and "re-contextualization" and asserts it results in a "higher level" analysis. While much effort in the analysis process consists of "taking apart ... the final goal is the emergence of a larger, consolidated picture" (p. 97).

The key-word-in-context lists on design activity were reduced to fewer categories using the" grand tour" question as a guiding schema. In other words, an inferential coding procedure was based on the researcher's perspective of engineering

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[73] The most frequently occurring words in most any text are those generally classified as function words. This class of words includes the prepositions, conjunctions, articles, and similar words that serve a syntactic function in the text but which do not serve directly to express substantive content. Hicks, Rush, and Strong also includes words which are "deemed meaningless." One eliminates these words from consideration in a text through the use of a table of these words or a stop list (Hicks, Rush, and Strong, p. 64). See Appendix D.

design as a human problem-solving activity. Words that related to this inferential context were graphically charted. Words that did not fit the assumptions of design activity, as well as a stop list (Appendix D), were excluded. The distillations themselves were shaped by a perspective of engineering design as a human problem-solving process. Thus, key word extractions were already embedded in an inferential schema "for making explicit certain entities" (Marr, 1982, p. 20) of design activity "a latent, connotative" framework for inductively stimulating ...themes on a given human activity (Berelson, 1971, pp. 19-20).[74]

Certain assumptions underlie word-frequency counting as a mode of analysis. Weber (1990) asserts word-frequency lists must be used with caution because these lists "do not reveal very much about the associations among words" (p. 52). Similar to the key-word-in-context lists for design activity, the "associations" for the frequency-word lists were inferred by the context of the data from which they were retrieved. In particular, the frequency lists were helpful in identifying the most salient elements of engineering design. Some words with less frequency[75] revealed provocative subthemes of engineering design, instead of being .(Weber, 1990, p. 52).

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[74] Pai posits an exploratory model of information retrieval in which links between categories of information are highlighted through "flavors of relevance." Pai, E. (1991) "Flavors" of relevance: A review of different notions on the concept of relevance. Unpublished manuscript.

[75] Weber (1990) further notes "advocates of inferred categories " often fail to recognize category generation requires an underlying theory to explain the range of possible categories and the empirically observed variation in category schemes. Without such a theory, research using inferred categories "is unlikely to lead to the cumulation of comparable results" for model development (p. 38).

The inferential coding procedures reduced the key-word-in-context and word-frequency lists to categories of design activity. The categories derived from this procedure satisfy five qualitative design criteria cited by Guba and Lincoln (1983). First, they "reflect the 'purpose' of the research;" that is, they respond to the "grand tour" question (Creswell, 1994, p. 74), what is the nature of engineering design as a human problem-solving activity? Second, the categories are "exhaustive" in that it is possible "to eventually place each datum in one category or another." The key-word-in-context and word-frequency lists identify salient design activity words, and, in turn, these words illuminate emerging, exhaustive categories. Third, the categories are "mutually exclusive" in that no single piece of content datum fits into more than one category. Mutual exclusivity is revealed by the word-frequency countsby the degree of salience to engineering design as a human problem-solving activity.

Fourth, the categories are "independent;" the assignment of a particular piece of data does not in any way affect the classification of other pieces of data. The categories of design activity may be viewed as "affectively" (Creswell, 1994, p. 71) interdependent from an inferential perspective. The assignment of a particular piece of data from content analysis to a given category contributes to "fleshing out the skeleton" of design activity. In turn, the emerging categories inform the researcher about the nature of design activity and generate an emerging, holistic image of the design process. Fifth, the categories are derived from a "single classification principle." Specifically, the categories of design activity are derived from an inductive classification principle based on purposefully selected documents that highlight design activity.

Even with this "set of rules," Guba and Lincoln (1985) assert "it is still not clear how one goes about the creation of categories for unitizing and taxonomizing the symbols identified" (p. 244). There are no simple answers to this question, although there are several "tacks". The qualitative researcher would want some or all of the categories of engineering design to emerge from the data, so the derived classification system would be "well-grounded" (p. 244) in the inferential data of engineering design. Guba and Lincoln further assert qualitative researchers seldom adopt the classification scheme of a predecessor; the emphasis on "new" or "unique" problemssuggests new classifications and coding systems are needed. Creswell (1994) suggests the classification and coding systems derived from an inferential schema, the distillations, "fit" the assumptions of an inductive, qualitative approach (Creswell, p. 53).

Graphic displays provide a useful format for the results of content analysis, highlighting salient categories of engineering design activity by each author.[76] They illuminate categories as "thick descriptions" or "topical areas" (Creswell, 1994, p. 155) for generating themes and patterns that point [77] to a model. They "form the basis for the emerging story to be told by the qualitative researcher" (Creswell, 1994, p. 154).

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[76] The basic schema for presenting results (categories) of content analysis of engineering design distillations was suggested by Jarvelin and Vakkari's analysis of journal articles in library and information science. See Jarvelin, K., & Vakkari, P. (1992). The evolution of library and information science 1965-1985: A content analysis of journal articles. In P. Vakkari, & B. Cronin (Eds.), Conceptions of library and information science: Historical, empirical and theoretical perspectives. (pp. 109-123). Los Angeles: Taylor Graham.

[77] Similarly, Van Maanen cites how stories or "impressionist tales typically highlight the episodic, complex, and ambivalent realities that are frozen and perhaps made too pat and ordered by realist or confessional tales" (p. 119).Refer to Van Maanen, J. (1988). Impressionist tales. In Tales of the field. (pp. 101-124). Chicago: University of Chicago Press.

Chapter 5: Theoretical Frameworks for An Emerging Image of Engineering Design

Few authors examine design activity as a human problem solving process. In an inductive theory-oriented study of such a topic, Creswell (1994) states "substantial literature orientation at the outset" may be required to "frame" and “counterframe” the topic under investigation (p. 24). In this sense, a distillation of each author's work on design activity can provide this type of framing orientation. In addition, this technique will allow a conceptual framework or “map of the territory being investigated” (Miles & Huberman, 1984, p. 33) to evolve inductively from this study. From a holistic perspective, the distillations represent the “rich context" (Creswell, 1994, p. 21) from which an image of engineering design will emerge. In addition, Krippendorff (personal communication, April 7, 1997) states the distillations can serve as an inferential framework that informs the data about engineering design as a human problem solving activity. They are the "thick description" (Rudestam & Newton, 1992, p. 39) for generating inferences about the data (key words) and categories of design activity that emerge from content analysis.

The Mind's Eye: Visualization in Engineering Design

According to Ferguson (1977, 1992), there is much human experience that cannot be wholly captured by verbal expression - these particular experiences emerge in individuals' minds through "visual thinking" and the "mind's eye." Much of what one learns by observation or through practical experience is not even remembered in terms of verbal cues, but it returns to the individual when needed through the nonverbal route known as "intuition."[78] Yet scientific thinking tends to assume fundamentally creative insights are expressed in words or in mathematical equations, and the nonverbal, visual mode of thinking is scarcely recognized.[79]

In the context of engineering, Ferguson (1977, 1992) argues the neglect of visual thinking can be dangerous. Since the 1950s, the education of engineers has focused more than ever on science and mathematical analysis, with practical and visual disciplines increasingly ignored. But many problems in engineering cannot be solved optimally by analysis; they require an ability to visualize artifacts and the environment in which they operate. Engineers make poor judgments when this ability has not been nurtured and this can lead to design failures. Ferguson asserts :

> This scientific age too readily assumes that whatever knowledge may be incorporated in the artifacts of technology must be derived from science. This assumption is a bit of modern folklore that ignores ...nonscientific decisions ... Many objects of daily use have ...been influenced by science, but their form, dimensions, and appearance were determined by technologists ...using nonscientific modes of thought. (1992, p. xi)

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[78] Laudan (1984) characterizes this nonverbal route in engineering design as "intuitively paradigmatic" (p. 5). Mintzberg (1995) calls it a "turning point." He asserts "we don't get to choose critically very often, and we can, in fact hedge and stall and do all kinds of dumb things day in and day out, but every once in a while we had better get it right. And getting it right at those times usually seems to mean listening to that inner voice, which goes by the name of 'intuition,' not to the babble of the social world or the logic of formal analysis" (p. 353).

[79] Here Laudan (1984) emphasizes the "unique" nature of engineering design knowledge. She asserts , when compared with science, engineering design is a highly visual activity, yet "we are relatively ill-equipped for the analysis of knowledge expressed in visual form" (p. 7). For an analysis of the "disinclination" of engineers to verbalize, see DeSolla Price, D.J. (1965). Is technology independent of science? A study in statistical historiography. Technology and culture 6, 553-568.

The dominant trend in engineering has been away from knowledge that cannot be expressed as mathematical relationships. Engineering schools, accepting a hierarchy of intellectually respectable disciplines, have integrated each new analytical technique without considering what will be lost when the less numerically rigorous, and therefore less respectable, subjects are dropped from the curriculum. Even in these schools, "visual thinking" course is seen as an "aberration rather than as a discipline that should be incorporated into an engineer's repertoire of skills" (Ferguson, 1977, p. 832).[80]

In response to this dilemma, Ferguson (1977) posits several theories that clarify the nature and significance of nonverbal thought in engineering. In further articulating the ideas of Arnheim (1969) on visual thinking, Ferguson identifies nonverbal thinking as the central mechanism in engineering design. This style of thinking involves perceptions that are the stock-in-trade of the artist and not the scientist. Because perceptive processes are not assumed to entail "hard thinking," it has been customary to consider nonverbal thought among the more primitive stages in the development of cognitive processes and inferior to verbal or mathematical thought. This particular component of engineering design, which is nonliterary and nonscientific,[81] has been generally unnoticed because its origins lie in art and not in science.

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[80] For representative engineering treatises that address these issues, refer to Krick, E.V. (1969). An introduction to engineering and engineering design. 2nd ed. New York: John Wiley; Gasson, P. (1973). Theory of design. London: Batsford; and Roylance, T.F. (1966). (Ed.). Engineering design. New York: Pergamon Press.

[81] On this point, Miller argues nonverbal "thinking in images is an essential ingredient of scientific research of the highest creativity" (p. 222). See Miller, A.I. (1986). Imagery in scientific thought: Creating 20th century physics. Cambridge, MA: Harvard University Press.

Ferguson (1992) asserts modern engineering - that is, the engineering of the last 500 years - has depended heavily and continuously on nonverbal learning and nonverbal understanding. Most of an engineer's deep understanding is by nature nonverbal, the kind of intuitive knowledge that experts accumulate. Many features and qualities of the objects that an engineer thinks about cannot be reduced to unambiguous verbal descriptions; therefore they are dealt with in the mind by a visual, nonverbal process. The engineering designer, who brings elements together in new combinations, is able to "assemble and manipulate in his or her mind devices that as yet do not exist" (1992, p. xi). If researchers and practitioners are to understand the nature of engineering, and thus advance the process of design itself, they must appreciate this fundamental yet often overlooked mode of thought. It has been nonverbal thinking, by and large, that has fixed the outlines and filled in the details of society's material surroundings. In their innumerable choices and decisions, engineers have determined in a physical sense the kind of world humans will inhabit.

In order to produce a new device, structure or other technological artifact, engineers must convert the visions in their minds into drawings and specifications. In doing this, they attempt to solve an ill-defined problem that has no single right answer but that has many better or worse solutions. Engineers learn a great deal during the design process as they strive to articulate the visions in their minds and seek ways to bring indistinct elements into focus. When the engineers think they understand the problem, they make tentative layouts and drawings, analyze their tentative designs for adequacy of performance, and then complete a set of drawings and specifications. The individuals who will make the new object or structure can then learn from the drawings and specifications exactly what they are expected to produce. Ferguson (1977) characterizes this design activity as a "translation" process. The engineer "translates a picture held in his mind into a drawing that will produce a similar picture in another mind" that "will eventually become a three-dimensional artifact" (Ferguson, p. 828).[82]

Engineering drawings are expressed in a graphic language, the grammar and syntax of which are learned through use. This language has idioms and concepts that only those who work in engineering will recognize and understand. Although the drawings may appear to be exact and unequivocal, their assumed precision "conceals many informal choices, inarticulate judgments, acts of intuition, and assumptions about the way the world works" (Ferguson, 1992, p. 3). Ferguson asserts the conversion of an idea to an artifact is a complex and subtle process that will always be closer to art than to science.

The design of the artifact will inevitably be modified as the engineers "wrestle" with unanticipated difficulties that appear only when the "paper parts" are converted to actual material constructs. Myriad design choices may be necessary to orchestrate the

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[82] According to Ferguson (1992), Albert Einstein rarely thought in words at all. His "visual" and "muscular" images had to be translated "laboriously" into conventional verbal and mathematical terms (p. 45). For an extended essay on the significance of Einstein's nonverbal thinking, refer to Holton, G. (1988). Thematic origins of scientific thought. Rev. ed. Cambridge, MA: Harvard University Press. On Einstein's difficulty in translating thoughts into words, see Pines, M. (1973). The brain changers. Upland, PA: Diane Publishing. Richard Feynman (inventor of "Feynman diagrams," a visual alternative to scientific equations) suggests Einstein failed to develop his unified theory of physics because he "stopped thinking in concrete physical images and became a manipulator of equations" (p. 62). See Dyson, F. (1981). Disturbing the universe. (pp. 53-76). New York: Basic Books; and Miller, A.I. (1996). Insights of genius: Imagery and creativity in science and art. (pp. 397-410). New York: Copernicus.

operation of the various components of the object. Some of the choices may indeed be wrong. Yet, for Ferguson (1992), making wrong choices is the same kind of game as making right choices; there is often no a priori reason to do one thing rather than another, particularly when neither has been done before. Furthermore, "no bell rings when the optimum design appears" (Ferguson, p. 9). It would be extraordinarily difficult to fully articulate the principles and techniques of engineering design, no matter how much those espousing a "design science" may believe an engineer's palette could be incorporated into a general-purpose design algorithm.

Ferguson (1992) notes the formal knowledge that engineers use is not science, although a substantial part of it is derived from science. It also includes knowledge based on experimental evidence and on empirical observations derived from direct testing of artifacts and structures, both past and present. Ferguson, like Vincenti (1990), argues engineering knowledge has been developed and formalized primarily to meet the needs of engineers in problem design. As such, this particular knowledge base reflects a "collective practical judgment (based largely on subjective opinion) of a sort that cannot be avoided in engineering ... an instance 'par excellence' of engineering, as opposed to scientific, knowledge" (1992, p.10). Eventually a consensus on the knowledge base is codified in reasonably unambiguous terms and made routine in the design process.

It is noteworthy that Ferguson (1992) cites Layton's (1971) critical insight into what engineers call "the engineering sciences" - mechanics, thermodynamics, and materials science - which have taken their patterns from science. They are mathematical and exact within prescribed limits, and their similarities to the "hard sciences" are so striking that Layton calls science and the engineering sciences "mirror-image twins" (Layton, p. 562). The purpose of the engineering sciences, however, is not to record "laws of nature" but to state relations among measurable properties such as length, weight, and velocity in order to permit a technological object to be analyzed mathematically. And these relations, even though expressed in precise mathematical terms, are often only approximations at best.

The engineering sciences further distinguish themselves from "pure" science in that they have an array of abstract concepts, independent of science, that serve as a framework within which design problems can be analyzed. These concepts embody the pragmatic elements of engineering knowledge that Ferguson notes above. Yet it is often the very use of engineering sciences that obscures the fundamental importance of practical judgment and intuition in the problem solving process.

Ferguson (1992) states most engineers do not mind being called scientists but they resist being called artists. Art, as it is understood in engineering schools, is effete, marginal, and perhaps useless. It is a "soft" subject that lacks the rigor of the hard sciences and the supposed objectivity of engineering. Yet engineers' drawings, whether made with pencils and pens on a drawing board or with an electronic cursor on a computer screen, share important characteristics with the drawings and paintings of artists.[83] Both the engineer and the artist start with a blank page. Each will transfer to it

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[83] Mark analyzes the "interactive links" between the art or aesthetic qualities of engineering design and the structure of Gothic cathedrals. Refer to Mark, R. (1990). Light, wind, and structure. Cambridge, MA: MIT Press.

the vision in his/her mind's eye. The choices made by artists as they construct their pictures may appear to be quite arbitrary, but those choices are guided by the goal of transmitting their visions, complete with insights and meaning to other minds.

Pickover (1995) advances ideas that clarify Ferguson's observations on art, science, and engineering design. He notes "the line between science and art [as practiced in engineering design] is a fuzzy one" (p. v). He asserts:

> Art and science will eventually be seen to be as closely connected as arms to the body. Both are vital elements of order and its discovery. The word 'art' derives from the Indo-European base 'ar', meaning to join or fit together. In this sense, science, in the attempt to learn how and why things fit, becomes art. And when art is seen as the ability to do, make, apply, or portray in a way that withstands the test of time, its connection with science becomes more clear. (p. v)

In addition, an artist generally follows rules implicit in a particular period and a specific style or school. The engineer's goal of producing a drawing of a device or artifact may seem to rule out most if not all arbitrary choices. Yet engineering design is surprisingly open-ended. A goal may be reached by many different paths, some of which are better than others but none of which is in all respects the one best way. Engineers have recourse to analytical calculations to assist them in making decisions, but the number of decisions that are based on intuition, a sense of fitness, and personal preference made in the course of working out a particular design is probably equal to the number of artists' decisions that engineers call "arbitrary, whimsical, and undisciplined" (Ferguson, 1992, p. 23).

Miller (1996) posits ideas that illuminate Ferguson's observations on the relationship between art and science. Both work according to distinct theoretical procedures or rule-based systems that often generate “strikingly similar results”:

> In art, the formal system can be articulated in a descriptive manner, or in a visual language. In science, the rule-based system is comprised of mathematics and certain physical principles assumed to be inviolate. Yet [similar] thought experiments spring from both procedural processes. (pp. 430-431)

For Miller’s (1996), the formal processes of art and in science may indicate distinctly different approaches in design, yet the results or “solutions” are often quite similar.

Ferguson (1992) cites other points about engineering design that bear mention here. First, the design process is not a totally formal affair; drawings and specifications emerge as the result of a social process. The various members of a given design group or team can be expected to have divergent views of the most appropriate or desirable ways to accomplish the design they are working on. Indeed, "informal negotiations, discussions, laughter, gossip, and banter" among members of the group will often have "a leavening effect on the outcome" (1992, p. 32). Second, engineering design is a contingent process, subject to unpredictable complications and influences as the design emerges. The precise outcome of the process cannot be deduced from its initial goal.

Design is not, as some engineering textbooks would have one believe, a formal, sequential process that can be summarized in neatly prescribed classroom diagrams. “Block diagrams” (Appendix C) imply division of design into discrete linear segments, each of which can be processed and completed before one moves to the next step. Although some engineers may believe design should work this way, even if it does not, it is clear that any such patterns of assumed order and predictability are quite unlike the usual chaotic growth of an actual design.

Ferguson (1977) notes any new design incorporates both formal knowledge and experience, and he agrees there may well be only one acceptable arrangement or configuration for a particular technological device. However, the arrangement or configuration that emerges from the design process is not necessarily self-evident or scientifically predictable. According to Ferguson, this is due to two specific characteristics of the design process itself. First, the "non-scientific component of design always remains primary - it rests largely on the nonverbal thought and nonverbal reasoning of the engineer, who thinks with pictures" (Ferguson, p. 28). Second, the design process contains more judgment than certainty. Judgment emerges as the engineer responds to the design in progress by repeatedly modifying means to reach desired ends.

Design is thus a contingent process, subject to changes brought about by conditions that arise during the process itself. It is also a creative process in which the engineer's imagination is required whenever a contingency occurs; as such, the creative process is virtually unpredictable. Mann (1989) comments on this aspect of design:

> The sequence of steps is never known at the beginning. If it were, the whole process could be accomplished by the computer since the information prerequisite to the computer program would be available. Indeed, the creative process is the process of learning how to accomplish the desired result. (p. 359)

The vision at the heart of a design is often in an engineer's mind long before a need has been articulated. And once a design process begins, second thoughts may emerge and impact the direction and even the goal of the design in question. It is not unusual for the different steps or processes to interact out of sequence and even blur as the design emerges. Ferguson (1992) states, despite its complexity and refusal to fit into neat diagrams, engineering design follows a natural and contingent path that cannot be changed by computer-assisted design (CAD) or by "a wished-for science of design."

Indeed, such "computerized illusions of certainty do not reduce the quantity or the quality of human judgment" (Ferguson, p. 37) required in successful design. Assumptions and matters of judgment will always be present in engineering design, no matter what the format of the design may be. Because not all assumptions can be made explicit - "there is too much tacit knowledge and too many inarticulate (and inarticulatable) judgments to make that possible" (Ferguson, p. 40) - it is important to put the assumptions, judgments, and decisions in the hands of engineers who have studied design from a pragmatic standpoint as well as from that of engineering sciences.

Visual thinking or "thinking in pictures" is an intrinsic and inseparable part of engineering design. It is the "true alphabet of the engineer" (Ferguson, 1992, p. 41). A major portion of engineering information is recorded and transmitted in a visual world that is in effect the "lingua franca" of modern engineers. It is the language that enables readers of technologically explicit and detailed illustrations to visualize the forms, the proportions, and the interrelationships of the elements that make up the object depicted. It is the language in which engineers explain to others exactly what they want them to construct.

The mind's eye, the locus of images of "remembered reality and imagined contrivance" (Ferguson, 1992, p. 42), is an organ of incredible capacity and subtlety. Collecting and interpreting much more than the information that enters through the optical eyes, the mind's eye is the organ in which a lifetime of sensory information - visual, tactile, muscular, visceral, aural, olfactory, and gustatory - is stored, interconnected, and interrelated. Engineers get to know the world around them through a series of sensual interactions: bumping, smashing, touching, smelling, dropping, and lifting. The arbiter of all these experiences is the mind's eye (Ferguson, 1992). Through it, engineers make sense of the lived physical world.. Visual thinking is successful to the extent the thinker possesses an array of sensual experience, converted by the mind's eye to usable visual and visceral information.

In his repeated admonitions, Ferguson (1992) models the dynamics of design as "messy nonscientific decisions, subtle judgments, and human error" (p. 170). This model also assumes a genuine curiosity that engineers have about the physical meaning of the artifacts and structural solutions they design. A scientific mode of thinking causes the "working knowledge of the world" to disappear; the nonverbal, tacit, and intuitive understanding essential to engineer design atrophies.[84] No matter how rigorously the laws of science are applied to the solution of a design problem, the engineer must still picture the desired outcome. "Scientific laws are not found in nature ... they are constructs of the human mind; they are models which are valid as long as events do not prove them wrong" (Ferguson, p.172). Most engineering designs, Ferguson notes, meet requirements that are logically inconsistent. Engineering design is simply that kind of process; "it always has been; it always will be" (Ferguson, p. 194).

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[84] Miller (1996) analyzes problematic issues relative to visual imagery in scientific thought and implications it has for engineering design activity (pp. 263-324).

Petroski and the Role of Failure in Engineering Design

Henry Petroski (1985, 1989, 1994) states the essence of what engineering is and what engineers do is not common knowledge in the general field of engineering itself. The state of the art is often only a superficial manifestation of what is understood about the substance and behavior of the products of engineering. Research neglects the process of engineering design that underpins the development of any given technology. There appears to be a "de-emphasis on engineering experience and judgment" (1994, p. 8) due to the use of increasingly sophisticated analytical techniques in design.

Yet the fundamental nature of engineering design itself transcends the state of the art. Although one may freely use the term "engineering design," its precise definition is curiously elusive and is yet to be articulated in a universally agreed-upon form. But for all its fuzziness, the engineering method is no less practiced than is tying one's shoes in the absence of directions on a package of laces. Lessons that are seemingly obsolete and as simple and self-evident as tying a bow can provide insight into some of the most fundamental aspects of engineering design and its method.

Petroski (1994) states an inquiry into the design process represents one of the most potentially effective means of improving reliability in engineering. In particular, historical case studies can illuminate aspects of conceptualization, judgment, and error that are "timeless constants" (p. ix) of the design process. An awareness of the timeless elements of engineering design and their commonality across ostensibly disparate specialities can give a theoretical foundation to the engineering curriculum, a lingua franca among the various fields.

Petroski (1994) also articulates a model for explaining how errors are introduced into the design process. The model is intended to inform engineers how to avoid making similar errors.[85] Petroski feels a carefully selected group of case histories illustrating different aspects of the design process can serve as paradigms for both theory and practice. To be effective as a paradigm of error, a particular case study must be capable of evoking a host of related case studies in a wide variety of engineering contexts and disciplines, thus demonstrating how, over time, the same or similar mistakes have led to repeated failures of design. If a paradigmatic case study can do this, then it is likely to embody a general principle of design error that can also arise in new design situations.[86] Thus the paradigm will provide two linked tools: a guide understanding of the design process and a means of improving it by alerting the engineer to common pitfalls in design logic.

When engineers understand both the negative and positive aspects of the role of failure in the design process, the process itself can be made more understandable, reliable, and productive. Petroski (1994) clearly states this collection of failure-based

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[85] Petroski's idea on failure are similar to Michael's concept of "error embracing," a mode of learning which stimulates a multiplicity of interpretations and theories about a given phenomenon to emerge. See Michael, D. (1996). On learning to plan and planning to learn. 2nd ed. Alexandria, VA: Miles River. Mayo asserts engineers learn about the world by being "shrewd inquisitors of error", by actively probing, manipulating, and simulating patterns of error, and by deliberately introducing "known patterns" of error into analysis of the design process. Refer to Mayo, D.G. (1996). Error and the growth of experimental knowledge. Chicago: University of Chicago Press.

[86] Similarly, Gibbons and Johnson affirm "detailed case histories" can provide appropriate insights into the precise interaction between theory and practice in engineering design. See Gibbons, M. & Johnson, C. (1982). Science, technology and the development of the transistor. In B. Barnes & D. Edge (Eds.), Science in context: Readings in the sociology of science (pp. 177-185). Cambridge, MA: The MIT Press.

paradigms is not intended to constitute an exhaustive or definitive classification of design errors, but rather to show the efficacy of the approach; in effect, failure-based paradigms can become as important a part of the engineer's intellectual tool kit as are laws of mechanics, rules of thumb, and computer models.

For Petroski (1994), engineering has as its principal object not the given world but the world that engineers themselves create, one that involves constant and rapid evolution. And it means there are many more ways in which something can go wrong. The idea of design - of making something that has not existed before - is fundamental to the nature of engineering. Petroski takes design and engineering to be virtually synonymous. Although Petroski bases his theories on examples from structural designs commonly associated with mechanical and civil engineering, he asserts the underlying principles of these theories are applicable to all branches of engineering.[87]

Engineering is a human endeavor and, thus, is subject to error. Failure considerations and proactive failure analysis are essential for achieving success. Understanding how errors are made can illuminate the very process of design. Indeed, engineering students experience self-doubts about success and fear of failure much the same way a medical student worries about losing a patient or a lawyer is concerned about losing a crucial case. Petroski (1984) believes this concept of failure is central to an understanding of engineering - it is the "one unifying principle of the whole design

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[87] For an analysis of the underlying principles of design activity that interconnect different branches of engineering, see Petroski, H. (1994). Failed promises. American Scientist, 82, 6-9; and Petroski, H. (1997). The fixed link. American Scientist, 85, 10-14.

process" (p. 214). Virtually all of the process can be seen as "the identification, anticipation, analysis, and obviation of failure modes" (Petroski, p. 214).[88]

The author recognizes most engineers do not want to learn by mistakes, yet they cannot learn enough from successes to go beyond the state of the art. Petroski (1994) asserts the history of engineering in general may be viewed in terms of "failures"; they contain more unambiguous information than successes. Thus Petroski's work is a direct response to the questions "What is engineering?" and "What do engineers do?" (Petroski, 1985, p. xi).

Engineering design is a process in which diverse parts of the "given-world" of the scientist and the "made world" of the engineer are "reformed and assembled into something the likes of which Nature had not dreamed" and this process "divorces engineering from science and marries it to art" (Petroski, 1985, p. 8). Petroski even compares the process and products of engineering design to the artistic processes involved in poetry, painting, and music. Petroski further asserts "we are all engineers of sorts, for we all have the principles of machines and structures in our bones" (p. 15).[89]

The ideas of engineering are part of human nature and experience. Humans have

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[88] Bussolari asserts any valid understanding of engineering design must incorporate the fundamental notion that "there is always a real chance of failure." He further asserts the design process is "a trade-off, a compromise... one arrives at a compromise in all engineering design - it's always a compromise." Stephen R. Bussolari. (1988). The light stuff. In Nova - Celebrating 20 years on PBS [Film].

[89] Adams supports Petroski's idea that humans "are all engineers of sorts" and he advances a succinct view of engineering design activity as a human problem solving process. Refer to Adams, J.L. (1991). Engineering. In Flying buttresses, entropy, and o-rings: The world of an engineer. (pp. 44-47). Cambridge, MA: Harvard University Press.

learned to continually adapt their brains and bodies to a changing environment, and human behavior often reflects the fundamental limitations of engineering structures. Even language itself is ambiguous about the daily trials to which humans beings, as engineering structures, are subjected. Both human beings and machines are said to be under stress and strain - this can lead to a breakdown or failure to function in either case. Humans respond by adapting in makeshift ways to failures and breakdowns that occur in a changing environment - they learn "a lot from failing and screwing up" (Petroski, 1994, p. 84). For Petroski (1994), the anthropomorphic language of engineering is no accident since man is not only the archetype machine but also the Ur-structure. Thus structural failure is viewed as an integral part of the human condition.

Petroski (1994) develops an image of the artist that reflects figuratively if not literally the creative process in engineering design.[90] There is the familiar image of the writer staring at a blank sheet of paper in his typewriter beside a wastebasket overflowing with crumpled false starts at his story. The archetypal writer may be viewed as trying to put together a new arrangement of words to achieve a certain end. The writer wants the words to take the reader from here to there in a way that is both original and familiar so that the reader may be able to picture in his own mind the scenes and the action of the story or the examples and arguments of the essay. The crumpled pages in the wastebasket represent attempts that did not work - sometimes the discards represent single sentences, sometimes whole chapters or even whole books.

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[90] Similarly, Ferguson (1992) presents an image of the "working artisan" that closely parallels the creative modeling processes in engineering design activity (pp. 4-5).

Why the writer discards this and keeps that can often be attributed to his explicit or implicit judgment of what works and what does not. Judging what works is always trickier than what does not, and very often the writer fools himself into thinking this or that is brilliant because he does not subject it to objective criticism. Flawed manuscripts are usually caught by the editor and sent back to the author with reasons why they do not succeed. Some writers save every scrap of paper - their false starts and failed drafts - as if they recognize they will never reach perfection and will eventually have to choose the least imperfect from among all their attempted endeavors. These documents of the creative iteration process are invaluable when they represent the successive drafts of a successful book or any work of a successful writer.

What other authors tend to learn from the manuscripts and drafts of such writers cannot be learned from the final published version of a work. For creating a book can be seen as a succession of choices and real or imagined improvements in a particular work. Moreover, writers often express the thought that they "abandon" a work rather than complete it. What they mean is that they come to realize for all their drafts and revisions, a manuscript will never be perfect, and they must simply decide when they have caught all the major flaws and when it is as close to perfect as they can make it without working beyond reasonable limits.

The emergence of an original engineering design may involve as great a leap of the imagination as the first draft of a novel. The engineer may already have rejected many alternatives, perhaps because he could see immediately upon their conception they would not work for this or that reason. Thus he could see immediately his work would fail. What the engineer eventually puts down on paper may even have some obvious flaws but none that he believes could not be worked out in time. But sometimes even in the act of sketching a design on paper the engineer will see that the approach will not work, and he crumples up the failed design much as the writer will crumple up his abortive character sketch.

Some designs survive longer than others on paper. Eventually one evolves as "the" design, and it will be checked part by part for soundness, much as the writer checks his manuscript word by word. Like the writer, the engineer is seldom satisfied with his creation; he notices, even if no one else does, the word or concept that is not quite "le mot juste" (Petroski, 1985, p. 83) in a given design. When a part is discovered that fails to perform the intended function, it is replaced with another candidate part from the "mind's catalog," much as the writer searches the thesaurus in his own mind to locate a word that will not fail as he imagines the former choice has.

At some point the engineer, like the writer, will reach a version of his design that he believes will work, and the design is submitted to other engineers who serve much as editors in assessing the success or failure of the design. Petroski (1985) maintains the process of successive revision is as common to both writing and engineering as it is to music composition and science, and it is a fair representation of the creative process to see the evolution of a book or a design as involving the successive elimination of faults and errors. It is this aspect of the analogy that is most helpful in understanding how writers and engineers alike learn more from the errors of their predecessors and contemporaries than they do from all the successes in the world.

It is noteworthy that Petroski (1985) compares engineers with artists on the one hand and with scientists on the other. Engineering does share characteristics with both art and science, for engineering is a human endeavor that is both creative and analytical. The innovative designs of engineering test the vocabulary of the critics and it is not always clear-cut whether a new structure will stand or fall, even in the make-believe world of hypothesis testing. The problem with any new structure lies in the very humanness of its origins and of the environment in which it will function.

It is impossible for an engineer to imagine and check every conceivable situation that might arise with a new design, and the engineer must make judgments as to which situations are the most critical and which are insignificant - the former are analyzed while the latter are ignored. Yet, just as the literary critic can discover meanings and symbols an author denies having been aware of in a piece of creative writing, so can the analytical critic of a new engineering design find interactions among the parts of a structure that surprise the designer. Just as a literary re-evaluation may appear years after a book has achieved critical acclaim, so too, an engineering insight may occur when failure of a long standing (perhaps precariously, or in a differnt environment) structure or design happens.

While engineers can learn from design mistakes what not to do, they do not necessarily learn from successes how to do anything but repeat the success without change. And even that is problematical because each new engineering design, no matter how similar it might be to a past one, can be a potential failure. When failure does occur, it becomes critical that engineers perform a "postmortem expose" (Petroski, 1994, p. 81) of the failure in question and that their findings be as openly discussed as possible.[91] If the cause of failure is understood, then any other similar designs should come under close scrutiny and the "incontrovertible lesson of a single failed structure is what 'not' to do in future designs" (Petroski, p. 97).[92] Observations derived from such lessons can contribute to the stored-up knowledge in the field. Engineers should not see the reports of failures as "the airing of dirty laundry" (Petroski, p. 223) but as an admission of the humanness of engineering design itself. [93] Similarly, Dennett (1995) states “making mistakes is the ‘key’ to making progress.” In particular, he indicates:

> What I have in mind is not just the familiar wisdom of nothing ventured, nothing gained. While that maxim encourages a healthy attitude toward risk, it doesn’t point to the positive benefits of not just risking mistakes, but actually of making them. Instead of shunning mistakes, I claim, you should cultivate the habit of making them, turning them over in your mind as if they were works of art ... You should seek out opportunities to make grand mistakes, just so you can then recover from them. First, the theory, and then, the practice. Mistakes are not just golden opportunities for learning; they are, in an important sense, the only opportunity for learning something truly new. (pp. 137-138)

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[91] Petroski’s idea of a “postmortem expose” in design activity is supported by Hapgood’s (1993) assertion that each design failure “contains encrypted somewhere on its body directions to the next step in the process.” In this context, good engineering is not so much a matter of creativity but of having skill and ability in “decoding the clever, even witty messages solution space carves on the corpses of the ideas which you begin with, and then building the road to the next messages” (p. 8).

[92] Constant also suggests there is a distinct kind of “presumptive anomaly of failure,” peculiar to engineering design, that contributes to the engineer’s “store of knowledge” in this area. He defines this anomaly as an occasion where there is no direct evidence of the failure of technology, but when scientific theory suggests that in certain circumstances the technology or design process will fail. Refer to Constant, E. (1980). The origins of the turbojet revolution. Baltimore: Johns Hopkins University Press.

[93] Adams examines “attitudes” toward failure and success in engineering design and how they impact the role of engineers as “risk-takers ” in the design process. See Adams, J.L. (1991). Regulation: The painful inevitability. In Flying buttresses, entropy, and o-rings: The world of an engineer (pp. 221-238). Cambridge, MA: Harvard University Press.

Petroski (1985) affirms engineering design shares certain characteristics with the positing of scientific theories, but instead of hypothesizing about the behavior of a given universe, engineers hypothesize about structural assemblages that they arrange into a world of their own making. Thus each new device may be considered to be a hypothesis in its own right. The process of engineering design may be considered a succession of hypotheses that such an arrangement of parts will perform a desired function without fail. Each hypothetical arrangement of parts or candidate structure is tested; if any of the parts fail, then the design itself may be said to be a failure. The design process continues in iterative fashion until the engineer discovers a way, either by design, by luck, or by a leap of the imagination, a solution to the problem in question. The fundamental feature of all engineering hypotheses is that they state, implicitly if not explicitly, that a designed structure will not fail if it is used as intended. As such, engineering failures may be viewed as disproved hypotheses.

Petroski (1995) states the solution reached in any given engineering design is not necessarily an optimal one. It emerges from arbitrary choices and decisions made by the engineer. In fact, Petroski asserts all engineering designs reflect an arbitrary nature; essentially the engineer has to choose in what degree and where there should be failure. Thus the shape of all designed things is the product of arbitrary choice. One might ask if this iterative process of design by failure ever ends. Will there be a time when engineers will be able to say, without hubris or arrogance, they have produced a flawless design?

In one sense, the process can converge on a design as reliable as is reasonable, but it can never be certain to produce a perfectly flawless design. Design involves assumptions about the future of the object designed and such objects themselves change the future in which they will function. Thus absolute certainty about the fail-proofness of any design can never be attained for one can never predict how the design will function long term in a changing environment. Indeed, the very notion of a truly fail-proof design in engineering is "chimerical" (Petroski, 1985, p. 217).

The human activity of engineering design is not a perfect "science" capable of producing perfect products. Engineering is part art, and it is this aspect of design that is difficult if not impossible to quantify and model completely. There is no finite checklist of rules or questions that an engineer can apply and answer in order to declare a design is perfect, for such finality is incompatible with the whole process, practice, and achievement of engineering. Not only must engineers preface any state of the art analysis with what has been variously termed engineering thinking and engineering judgment, they must also supplement the results of their analysis with thoughtful and considered interpretations of the results. Successful design may be replicated but it can extrapolated only by a proper application of the engineering method embodied in a proper perspective on failure. Engineering advances by proactive and reactive failure analysis, and "at the core of the engineering method is an understanding of failure in all its real and imagined manifestations" (Petroski, 1994, pp. 183-84).

The various manifestations of failure provide the conceptual underpinning for understanding the evolving form of artifacts and the fabric of technology into which they are inextricably woven. It is clearly the perception of failure in existing technology that drives engineers to modify what others may find perfectly adequate or at least usable. What constitutes failure and what constitutes improvement is not totally objective, for in the final analysis a considerable list of criteria, ranging from the functional to the aesthetic, from the economic to the moral, can come into play. Nevertheless, each criterion must be judged in a context of failure, which, though perhaps much easier than success to quantify, will always retain an aspect of subjectivity. The spectrum of subjectivity may appear to narrow to a band of objectivity within the confines of disciplinary discussion, but when a diverse collection of individuals and groups come together to discuss criteria of success and failure, consensus can be "an elusive state" (Petroski, 1992, p 244).

Petroski's (1992) examples of engineering design are mostly the "honest-mistake kind and not the sloppy design and testing" (Markow, 1985, p.25) that often occurs in the field. The breadth of engineering knowledge - encompassing science, mathematics, economics, and analysis - is not fully shown by Petroski. Nor does one get a complete sense of the challenges and constraints that engineers face in the design process, the roles of research, development and testing in advancing knowledge less painfully than through failure, or what characterizes engineering creativity and genius as “a traversal through the corridors of solution space” (Hapgood, 1993, p.10). This dynamic image of engineering design is more fully explored by Hapgood and it complements Petroski’s fundamental ideas on the role of failure in design activity.

Florman: Existentialism and the Introspective Engineer

Florman (1994; 1996) cites the growing intellectual movement of "antitechnology" as a principal force contributing to a negative view of engineering. This movement directs its hostility against the engineer as the "archetypical technologist," and it holds technology to be "the root of all evil" (Florman,1994, p. 44). Proponents of this view are not satisfied in asserting technologists (and engineers) are "careless, foolish, or immoral"; they see the source of society's problems as lying in the concept of technology itself (Florman, 1994, p. 45).[94] The antitechnologists also assert:

> Engineers are half-men whose analysis and manipulation of the world deprives them of the emotional experiences that are the essence of the good life and [whose] scientific way of thinking represents a neurotic inability to face life as a whole. The technologist [engineer] is alienated from his true self and his true needs. He is uptight, lonely, inauthentic, unable to receive or give out sensual vibrations. He is not a real man. He is 'a smoothed-down man,' guilty of 'single vision,' and 'seeing with a dead man's eyes. (Florman, 1994, pp. 154-155).

Florman (1996) identifies Ellul, Mumford, Dubos, Reich, and Roszak as the "pivotal" proponents of the contemporary antitechnological movement, and he lists specific themes from each of these authors that contribute to a negative view of engineering.[95]

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[94] Taylor cites this "harsh criticism" as the reason for which engineering has become "permeated with self-doubt." Moreover, it has caused engineers to be "schizophrenic" about technology in that "a Luddite mentality competes with amazed admiration for what sophisticated machines can do." See Taylor, G. (1996). The existential engineer [Review of the book The existential pleasures of engineering]. Booklist, 92, 1113.

[95] The five texts that Florman considers as "pivotal" in projecting a negative view of engineering are: Dubos, R. (1968). So human an animal. New York: Scribner; Ellul, J. (1967). The technological society. New York: Alfred A. Knopf; Mumford, L. (1970). The myth of the machine. New York: Harcourt, Brace and World; Reich, C.A. (1971). The greening of America. New York: Random House; and Roszak, T. (1972). Where the wasteland ends. New York: Doubleday.

In sum, these themes assert :

- technology is a "thing" or a force that has escaped from human control and it is ruining society;
- technology forces man to do work that is tedious and degrading;
- technology forces man to consume things that he does not really want or desire;
- technology creates an elite class of technocrats which disenfranchises the masses;
- technology cripples man by cutting him off from the natural world in which he evolved; and
- technology provides man with technical diversions which destroy his existential sense of his own being (Florman, 1994, pp. 53-54).

Florman (1994) takes issue with the "antitechnology poets who write of 'dark Satanic mills'" (p. 55). In particular, he finds them "guilty of sloppy and dogmatic thinking - those modish jeremiads about the 'anonymity' of technology are a suspiciously convenient rhetorical technique for making the broadest accusations with the fewest possible specifics" (p.55) Further, he finds in the antitechnologists a "distressing elitism and arrogant pseudo-objectifying of subjective values, leading to their unthinking claim the perfectly legitimate preferences and goals of the great unwashed consumer are nothing but a pitiable symptom of technocratic manipulation" (Florman, pp. 55-56).

Florman (1994) argues "it's time for technologists - especially engineers - to stop letting themselves be pigeon-holed as soulless dullards and [to] joyously proclaim their identity as 'craftsmen': builders and makers, heirs to all human ambition and curiosity" (pp. 112-113).[96] If anything positive is derived from the "contemptuous judgments" of the antitechnologists, it is that "at least they have brought us down to the hard substratum upon which must be founded any new conception of the profession" (Florman, p. 56). It is from this "hard substratum" that Florman develops his ideas on the nature of engineering design. He is not interested in describing "in any detail what engineers 'do.'" He is interested in "how engineers think and feel about what they do, and in the more general aspects of what it 'means' to be an engineer" (Florman, p. x).[97]

According to Florman (1994), typical perspectives on engineering activity are too static and "misconceived;" they tend to overlook traits that embody what it means to be an engineer. Engineering is often taken as "the art or science of ... practical application of the knowledge of pure sciences" (Florman, p. x). In other words, although engineers are not scientists, they study the sciences and use them to solve problems of practical interest through creative design. Engineers are not mechanics, nor are they technicians. Florman asserts engineers are members of a profession with roots in the earliest development of the human species, and he advances two concepts that more appropriately "capture" how engineers think and feel about what they do.

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[96] Florman calls for a return to the "mission" of engineering professions of the 1920s in the United States. They attempted to do "social good," yet these efforts declined during the depression and engineering became synonymous with the "social ills" attributed to technology (1996; p. 175). For an historical analysis of the engineering professions of this period, see Layton, E.T. (1971). <u>The revolt of the engineers.</u> Cleveland, OH: Case Western Reserve Press.

[97] Florman acknowledges "engineering" and "technology" are terms that are being constantly defined and redefined. Although "technology" is a broader and more comprehensive term than "engineering," he does not hesitate to use the two words interchangeably when he thinks it is appropriate (1994; p. x).

Florman (1996) argues society has "no idea how professional engineers spend their time and no understanding of what they do" (p. 4). The "archetypical image" of the engineer is of one "who creates, discovers, and produces" (Florman, p. 123). For Florman, this simplistic description of engineering activity is problematic.[98] It fails to capture the dynamic processes that underlie the design process. Indeed, even in the field itself, many of these processes are "practically invisible." Moreover, the profession contains a wide variety of human types, engineering being "an elemental expression of the human spirit" (Florman, p. 125). Clearly there is no archetypical engineer about whom one can make "sweeping" generalizations. Yet Florman cites three scholars who advance ideas on an emerging image of engineering design as a human problem solving process; these scholars provide a framework for Florman's concepts on engineering design activity.

Adams (1986; 1991) asserts engineering design can be classified by "field of study" and "type of activity." Most engineering activity, whatever the specialty, is done in a process that has a series of sequential stages. According to Adams, "engineering [design] begins with a desire. This is reduced to a problem." (Adams, 1991, p. 44) Definition of the problem is usually followed by "preliminary design" of a product, and

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[98] Florman asserts science has had its own "image" problems, and engineering's difficulties stem in part from"ambiguous links that confuse engineering with science, or worse, [view] it as subservient to its esteemed relative" (1996; pp. 6-7). Similarly, Cromer argues the formal thinking needed for problem solution in science is not physiologically normal in humans. Scientific thinking, which is analytical and objective, "goes against the grain of traditional human thinking, which is associative and subjective" (p. 189). See Cromer, A. (1993). Uncommon sense: The heretical nature of science. New York: Oxford University Press. For a controversial analysis of this type of scientific thinking, see Watson, J. (1980). The double helix. G. Stent (Ed.). New York: Norton.

then by "detailed design." The next step in the sequence involves "development," including testing, to bring a prototype to a functional and economic level that is deemed satisfactory or "workable" (Adams, 1991, pp. 45). [99] Adams' concept of design activity may seem too predictable and sequential; yet he states engineers often "suffer from intellectual myopia" in the initial stages of the process.[100]

Ferguson (1992) argues the ability to do engineering design derives initially from "inner vision," from a sense of how things "fit" and how things "work." In particular, design activity stresses the need for "sound judgment and an intuitive sense of fitness and adequacy" (p. 193). Ferguson recognizes good sense and conceptual facility constitute only a small part of engineering design. Indeed, researchers who approach engineering design as a human problem solving process will be frustrated in their "fruitless search for a comprehensive definition of ...'engineer'" (Florman, p. 194).

Vincenti (1990) attempts to define the character of engineering knowledge as an "epistemological species." He demonstrates many of the ways in which engineering progress occurs and he reveals a "rich mix of theory and experimentation, intuition and craftsmanship, mathematics, drawing, modeling, and luck" (Florman, 1996, p. 121) in the design process. Specifically, Vincenti identifies seven "knowledge-generating

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[99] Similar to Petroski (1985), Adams recognizes failure as an "essential component" of engineering design epistemology. He asserts an understanding of failure in design activity is necessary to advance the field. Refer to Development, test, and failure: The proof of the pudding. In Flying buttresses, entropy, and o-rings: The world of an engineer. (pp. 150-176). Cambridge, MA: Harvard University Press.

[100] Adams' assertion that engineers often "suffer from intellectual myopia" is comparable to Hapgood's (1993) idea of engineers "searching solution space"(p. 7) and Pirsig's (1974) notion of "stuckness" or "being stumped" (p. 311) in the design process.

activities" in which engineers engage during the design process. He then suggests these activities yield six categories of "engineering design knowledge." Finally, Vincenti explores the concept of growth in engineering knowledge through a blind variation-selective retention model based on Darwinian theories. According Vincenti, many possibilities "pop into an engineer's mind through blind chance, and then are screened" (Vincenti, 1990, p.246). Only the fittest ideas survive (Vincenti, pp. 245-248). Vincenti adds engineering is "flesh and blood, real people overcoming uncertainties and frustrations" and concedes his "model for knowledge growth" is "relatively conjectural and subject to controversy" (p. 96).

Florman (1996) affirms Adams, Ferguson, and Vincenti reveal essential insights into engineering design and a "heightened awareness of what engineering is all about" (p. 121). Yet, even after examination of these attempts to describe what engineers do - "with or without attempts at comprehensive exegesis," (p. 122) there still remains "untouched" an important realm of what, or who, engineers are:

> Being an engineer entails looking at the world in a distinctive manner, and experiencing the world in singular ways. [It embodies] a willingness to forgo perfection ... a willingness to accept responsibility and risk failure ... a passion for creativity, a compulsion to tinker, and a zest for change. Engineering is an occupation that responds to humanity's deepest impulses, and is rich in spiritual and sensual rewards. (Florman, 1996, pp. 122-123).[101]

The engineering view or "cast of mind" is a particular way of approaching

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[101] Florman posits the main elements of the "engineering view" or "general outlook" that are shared by members of the engineering profession in his 1987 text, The civilized engineer. New York: St. Martin's Press.

problems. Engineers are trained to solve problems while "taking human nature into account" (Florman, 1996, p. 123). They do not expect to find perfect or optimum solutions because in their work there usually are none. In addition to being problem-solvers, engineers are "imaginative creators, inventors, discoverers of new paths" (Florman, p. 123). Florman (1996) asserts if engineers are to confront the challenges of the future effectively, this particular view "must percolate into the perspective" of the profession and society (pp. 7).

Florman (1996) advances two fundamental points in his philosophical approach to engineering design as a human problem solving process. He asserts most scholars in the field have failed to address these points in their descriptions of this dynamic process. The first point involves introspection in this sense:

> Engineering design begins with introspection, with the implicit conviction that thought will lead to action. Introspection is the act of looking inward, examining one's personal thoughts and feelings, or, more generally, 'looking into or under the surface of things.' Engineers - long said to be obsessed with materials and machines - are increasingly thinking in this mode. They are, however tentatively, seeking better understanding of themselves, their profession, and the role of technology in a rapidly changing world. (Florman, 1996, p. xi)

Engineers are trained to be observant and to learn from experiences with failure. According to Florman, trial and error have always been a key element of the introspective method in engineering design.

The second concept in Florman's (1994) philosophy of engineering design is existentialism. At first, one may think engineering and existentialism are contradictory in nature. The existential search for inner truth suggests a "sloppy emotionalism" that appears in direct conflict with the engineer's reliance upon logic and the scientific method. Specifically, the engineer uses the logic of science to achieve practical results, and the existentialist most typically sees the engineer as an antagonist whose analytical methods and pragmatic approach to life are "desensitizing and soul-deadening - in a word, antiexistential" (Florman, 1994; pp. xi, 101). Yet Florman restricts the use of this term to its most essential meaning: (1) the rejection of dogma, particularly scientific dogma; and (2) reliance on the "passions, impulses, urges, and intuitions that are the basic ground of human existence"(p. xi). These characteristics enable Florman to develop a viable link between existentialism and engineering design activity. The essence of the existentialist view, like that of the engineer, is a "disenchantment with conventional creeds, a resolve to dispense with comfortable delusions and shibboleths, and an insistence on looking inward for new truths" (Florman, 1994, p. xi).

For the existential engineer, "subjectivity must be the starting point, it is what each of us feels in his heart, in his bones, in his gut" (Florman, 1994, p. 100). Analysis, rationality, materialism, and practical creativity do not preclude emotional fulfillment in engineering design. They do not "reduce" experience, as is so often claimed; they expand it. Engineering is superficial only to those who view it from a superficial stance, for "at the heart of engineering lies existential joy and emotional fulfillment" (Florman, p. 101). Indeed, the main goal in engineering has always been "to understand the stuff of the universe, to consider the problems based on human needs, to propose solutions, to test and select the best solution [and] existential delight has been the reward every step of the way" (Florman, p. 113).

Florman (1994) further asserts engineering is a basic instinct in man that "emerges naturally from our genetic constitution" (p. 114). Man's ability "to mold, to carve, to build and also to devise"(p. 114) are evolutionary developments. Essentially, they are "adaptations in problem solution derived from the Darwinian theory of natural selection" (Florman, p. 114). Thus it is not an exaggeration to assert men are driven to technological creativity because of instincts, and these creative functions have evolved because of the workings of natural selection. The activities of the existential engineer can be traced back to homo faber:

> Who does not merely putter around, nor is he interested only in survival and comfort. He shares the values and ideals of the human race - mercy, justice, reverence, beauty, and the like. But he feels these abstract concepts become meaningful only in a world where people lead authentic lives - struggling, questing, and creating. (Florman, 1994; p. 118) [102]

The existential engineer does not underestimate the importance of his contributions to society, but he has abandoned all "messianic illusions." He acknowledges he has made mistakes, but he totally rejects the image of himself as "villain, false prophet, or sorcerer's apprentice"(Florman, p.118).[103] He is a human

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[102] Bernard posits an image of homo faber as "the maker, the ingenious worker with his hands, discoverer of the relation of matter, the father of us all." Homo faber interacted with the material world "not only by the simple, rational use of his hands but also by a deep knowledge of the material in itself, the discovery of its structure, the understanding of its nature - in short, by the power of his mind." From the beginning, homo faber has been at the same time a user of his hands and his brain. "Hand and mind developed simultaneously without hindering each other. The hand is not the mere instrument of the mind, but its close associate... and there we find the deep root of a true equilibrium" (p. 15). Refer to Bernard, J. (1985). The hand and the mind. Parabola: The magazine of myth and tradition, 10 (3), 14-17.

[103] Note Florman's allusion to Latour's (1987) comment engineers are sometimes perceived as "Janusian bifrons alternatively endowed with demiurgic powers - for good or bad" (p. 15). For a provocative study of Janusian thinking that illuminates aspects of antithetical or "self-contradictory thinking" in engineering design, refer to Rothenberg, A. (1979). Creative contradictions. Psychology Today 12, 54 -62.

being doing what human beings are created to do - fulfilling his human destiny both biologically and spiritually, and discovering his reward in "existential pleasure" (Florman, 1994, p. 118). The most obvious existential gratification experienced by the engineer stems from his desire to change the world he sees before him:

> The Constructor [Engineer] ... finds before him as his chaos and as primitive matter, precisely that world-order which the Demiurge wrung from the disorder of the beginning. Nature is formed and the elements are separated; but something enjoins him to consider this work as unfinished, and as requiring to be rehandled and set in motion again for the more special satisfaction of man. He takes as the starting point of his act the very point where the god left off. (Florman, 1994, p. 120)

The existential impulse to change the world "stirs deeply" within the engineer. Indeed, it is from this "impulse" that civil engineering has sprung and, in turn, civil engineering is the "main trunk from which all branches of the profession have sprung" (Florman, 1994, p. 121).[104] To the engineer - whether civil, mechanical, electrical, or chemical - "doing" is something more than mere manufacturing. According to Florman, creative design is the central mission of the professional engineer. The existential response to a successful design, creation, discovery, or invention in engineering can range from "calm satisfaction to absolute rapture" (Florman, p. 143)[105] For the engineer,

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[104] According to Florman, the word "civil" was first used around 1750 by the British engineer, John Smeaton, who wished to distinguish his works from those associated with military purposes. In this context, the civil engineer, "with his hands literally in the soil, is existentially wedded to the earth, more so than any other man except perhaps the farmer" (1994; pp. 121-122).

[105] Ferguson (1992) states design and invention in engineering lie along a continuum that ranges "from the obvious to the inspired, from design routines that involve a minimum of intellectual engagement to original, fundamental inventions that change forever our way of tackling certain problems" (p. 13). Mitcham places design and invention in proper context in the scheme of things by observing "invention causes things to come into existence from ideas, makes world conform to thought; whereas science, by deriving ideas from observation, makes thought conform to existence" (p. 244). Refer to Mitcham, C. (1978). Types of technology. Research in Philosophy and Technology, 1, 229-294.

as opposed to the scientist, "the fullest gratification is reserved for that creative solution which achieves a desired practical result" (Florman, p. 143).

Engineering design is a manifestation of mankind's primordial, existential spirit. It offers the creative engineer more than an "intellectualized brick-and-mortar existence" (Florman, p.150); it is an opportunity for existential fulfillment. This existential pleasure comes "gratuitously, seeping into him unawares" (p. 151) even to the engineer who does not seek it directly . The engineer who will not open up to these opportunities, "who will not feel them, may very well end up as the inauthentic, smoothed-down man that the antitechnologists accuse him of being" (p.152).

Finally, in consonance with Petroski's views on failure in engineering design, Florman (1994) states the "authentic" [existential] engineer should be thinking "soberly" [introspectively] about failures in the design process and about the lessons to be learned from them" (p. 31). In this context, open discussions of human error, lack of imagination, and blind ignorance become potential means of advancing engineering design epistemology. Florman further suggests this mode or "cast" of thinking will enable the introspective, existential engineer to generate the "tentative technological fixes" or "satisficing solutions" that society requires at this point in history.[106]

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[106] Florman (1996) notes the term, "technological fix", has a pejorative connotation when applied to "short-term solutions that result in long-term problems." Yet he suggests at this moment in world history, "a few technological fixes are just what we need" (p. 2).

Bucciarelli and Designing Engineers

The artifacts of engineering design are everywhere, but who or what determines their form and function? In particular, what are specific attributes of engineering design characterize it as a human problem solving process? Bucciarelli (1994) advances these questions as the focus of his study. Data derived from his anthropological analysis of three teams of working engineers in three different "science-based" design settings reveal clues about the nature of this phenomenon. Bucciarelli discovers significant discrepancies about society's ideal image of design as an instrumental process and the reality of design as a historically situated social process that is full of uncertainty and ambiguity.[107] Bucciarelli (1994) cites the challenges one faces in attempting to describe the underlying nature of design activity in more than the usual instrumental terms. Using metaphorical expression, he states :

> When designing is in process, that process is alive. The object is alive and laden with uncertainty and ambiguity. That is what makes designing the challenge it is. When the design is complete ... and most significantly when the team disbands, then the process is over. The object as artifact is dead ... it no longer serves as the occasion for surprise. All is in order; all functions deterministically. No wonder documentation, in its description of what was once alive as a design project, reads like an obituary: Writing about the object as a fully defined artifact for outsiders is often a painful task, a reflection of the inadequacy of 'object-world voice' and the written text to capture the object as social process ... in its design. Only a few take to this finalizing design task. (1994, p. 195)

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[107] In addition to analysis of data from three engineering design settings for his theory, Bucciarelli uses ideas drawn from earlier essays on design activity: a 1988 piece entitled "An ethnographic perspective on engineering design" (Design Studies, July 1988, pp. 159-168); a conference paper on "Engineering design thinking" (Proceedings of the 1987 ASEE Annual Conference, Reno Nevada); and a chapter form F. Dubinskas (Ed.). (1988). Making time: Culture, time, and organization in high technology. Temple University Press.

Bucciarelli (1994) presents his description of engineering design as a "storybook" about three design projects. "Like an ethnographer invited not just to dinner but to help out with the shopping, chopping, and peeling, I was able to participate in the design process" (p. 1).[108] Bucciarelli's central theoretical concept is what he calls engineers' "object-worlds," virtually a subset of their real "life-worlds." As a result of differing disciplinary backgrounds, unique professional experiences, and individual idiosyncrasies, each engineer "sees" a given artifact or technological problem or process - "the object" - differently (pp. 62).

Design, "consensus about the thing that becomes," is the product of social negotiation among engineers inhabiting these different object worlds. The "incommensurable" becomes ""incompatible" in socially made consensus. Technology then is "under determined" either by scientific principle (previously socially produced surrogate for the "world as it is") or by the "market." Technology "as it is" is irreducibly historically and socially contingent, the product of "muddling through and hassling about" (Bucciarelli, 1994, pp. 47).

All engineers engaged in a team "problem solving venture" can and do influence the design, and all must come to agreement in order to realize the design. The process is thus social; it the business of a subculture. Not surprisingly, participants' visions of the social process of designing are strongly influenced by their understanding of the way

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[108] Bucciarelli's characterization of design activity as "shopping, chopping, and peeling" process is strikingly similar to Blanco's reaction to design (of a no-hands music pager) as "simply a matter of press, lift, turn, peel" (Hapgood, 1993, p. 6).

the things they are designing work. To participants in a design setting, the object serves as a kind of icon that embodies a set of attitudes and ways of thinking that are peculiar to engineering. According to Bucciarelli:

> It is the fixation on the physics of a device that promotes the object as an icon in the design process. For while different participants in design have different interests, different responsibilities, and different technical specialities, it is the object as they see and work with it that patterns their thought and practice, not just when they must engage the physics of the device but throughout the entire design process, permeating all exchange and discourse within the subculture [of the group] ... This way of thinking is so prevalent within contemporary design that I have given it a label - "object world" thinking. (1994, pp. 2, 4-5)[109]

Rogers (1995) would assert effective exchange or discourse in engineering design occurs when two or more individuals are homophilous, that is, when they share common meanings, a mutual subcultural language, and are alike in personal and social characteristics. Yet, one of the most distinctive problems in discourse involves the aspect of heterophily. This is the degree to which two or more individuals who interact with each other in a given design context are different in certain attributes such as belief systems, values, education, and social status. Rogers strongly suggests some degree of heterophily among individuals in a design setting is essential in order for innovative ideas to occur.[110] Thus, it is the presence and degree of heterophilous elements (that is,

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[109] Pirsig would call the physics or principles of operation of an object its "underlying form." This is the "physics of the device" knowledge that is often taken as the hallmark of technological literacy. See Pirsig, R. (1974). Zen and the art of motorcycle maintenance. New York: William Morrow.

[110] Rogers' ideas on heterophilous elements in discourse and the degree to which they may stimulate creative problem solution are similar to Festinger's theory of cognitive dissonance in which individuals are motivated to seek "dissonance-reducing cognition." Refer to Festinger, L. (1957). A theory of cognitive dissonance. (pp. 126-137). Evanston, IL: Row and Peterson.

Bucciarelli's degree of "differences" among individuals) in a given engineering design subculture that stimulates creative "object-world" thinking and "promotes the object as an icon in the design process" (Bucciarelli, 1994, p. 4).

Science provides the underlying form of designs. Bucciarelli (1994) speaks of "a founding science or paradigm" as a source of innovation and creative problem solving:

> Science, in a more general sense, is the mode of thinking within object worlds. It also structures the way in which participants frame their work process and interactions. The strongest claim that one might make is that science, in this socializing sense, controls the design process. But this is not the science of those who hold that science determines the form of technology. The scenario about science determining form, as ordinarily understood, misses the complexities of alternative forms and paths to a design. It ignores the diverse interests of participants in the design process, each making claims based upon scientific rationality, and it fails to acknowledge the indeterminacy of technical constraints and specifications and ignores their negotiation in process.[111] (Bucciarelli, 1994, p. 185)

According to Bucciarelli (1994), engineering design is not an autonomous process. There is more to it than "the dressing up of a scientific principle, more than the hidden-handed evolution of optimum technique to meet human needs, and more than the playing out of the bureaucratic 'interests' of participants seeking power security, or prestige" (p. 20). Designing is a social process. In the simplest terms, design is the intersection of different object worlds. No single participant dictates the form of the artifact. Hence design is best seen as a social process of negotiation and consensus, "a consensus somewhat awkwardly expressed in the final product" (Bucciarelli, p. 21).

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[111] Bucciarelli further notes the work of scientists themselves has been depicted as "the rational evolution of ever more comprehensive theory buttressed or denied by experiment." While alternative paths and paradigms are admitted, "the decision-making process classically has been historicized as uncontaminated by social constructs." If one opens up the "black box" of technology, one begins to see "a social process of negotiated order" (p. 214).

There are always significantly different design alternatives given the same initial conditions, and "optimization and satisficing are not determinate" (Bucciarelli, 1994, p. 196). The participants' pragmatic and contingent vision determines the form and function of a given artifact or technology. Using an evolutionary metaphor, Bucciarelli (1994) asserts all elements of the design process are in a "constant state of change," yet they are in "dynamic equilibrium." (Bucciarelli, 1994, p. 16) In particular, the author envisions "varieties of the elements struggling for survival" in the design process. This allows participants an opportunity to assert a more active role in designing, perhaps by fostering mutations in the elements in random anticipation of human psychological and physical needs. Engineers working under the "inescapable pressure" of these natural relationships attempt "to do more with less" and "to anticipate every eventuality" (Bucciarelli, p. 16) in the design process.

This way of thinking strongly influences the process of design, pervading the day-to-day efforts of the participants. Instrumental reasoning does not define the product of design nor does it frame all that transpires in the design as a human problem solving process. The ideal instrumental process results in static, sequential "block diagrams"[112]. Bucciarelli (1994) asserts designing is done in contexts, "in settings for the playing out of different individual and collective interests" (p. 190). The social process in design activity is full of ambiguity, uncertainty, and the "unknown."

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[112] Bucciarelli's criticism of "block diagrams" of engineering design activity as "the fantasy that depicts technique as the sterile embodiment of nature's laws, devoid of human intent and interests" (p. 201) is reflected in similar observations by Ferguson (1992, p. 35).

Ambiguity and uncertainty are especially evident at the interfaces where participants from different object worlds must meet, agree, and harmonize their design proposals and concerns. Ambiguity "allows room to maneuver, to reshape, to relearn and come together again" (Bucciarelli, 1994, p. 188). It serves as "an ephemeral connection" between bricolage and "do-it-yourself" (p. 11) in engineering design. Uncertainty and the unknown make the design process the challenge it is.

Bucciarelli (1994) contrasts his hypothesis of engineering design activity with a "typical block diagram" of the process. (Appendix E). The block diagram is an assumptive representation of the static, sequential steps cited by Ferguson (p. 35). Bucciarelli further notes that this type of diagram is an embodiment of a traditional, positivist epistemology that neglects the human aspect of design activity. The "stuff within the boxes and their linear display simply overwhelm the thin lines indicating the possibility of feedback." (Bucciarelli, p. 122) There is a "Tayloristic" quality to these linear visions of process, "though Frederick Taylor himself, I suspect, would have found them seriously deficient ... these diagrams shed little light"(p. 122) on the disorder, uncertainty, and fuzziness of design acts. In contrast, the author's model illuminates the human aspect of concept formation in the design process through the image of a human heart. This image embodies the pragmatic and contingent nature of engineering design while allowing for elements of ambiguity, paradox, and uncertainty.

Contemporary design is an intersection of multiple object worlds. In Bucciarelli's (1994) model this complex process cannot be divided into a collection of separate tasks that are independently pursued. It requires instead the continual engagement of, and discursive exchange among, participants trained in a range of disciplines. The "object" is not one thing to all participants. Each individual's perspective and interests are rooted in his/her special expertise and responsibilities. Designing is a process of bringing coherence to these perspectives and interests, "fixing" them in the artifact. Participants work to bring their efforts into harmony through negotiation. This harmony, or lack of it, will be reflected in the artifact or in the "built form." The quality of the final design and artifact, as evidenced by the harmony of the different underlying forms of different object worlds, will then depend upon the social process engaged in by participants, that is, the competence of participants working within object world.

If a participant or observer asks, "What is the design?" at any point in the process, Bucciarelli responds that it exists only in a collective sense. In process, the design is not contained in the totality of formal documentation, nor is it in the possession of any one individual to describe or completely define, although every participant will tell his/her "story" if asked. This is the strong sense of "design is a social process":

> Design is not a matter of trade-offs, of instrumental, rational weighing of interests against each other, a process of measuring alternatives and options against some given performance conditions. Nothing is sacred, not even performance specifications, for these, too, are negotiated, changed, or even thrown out altogether, while those that matter are embellished and made rigid with time as design proceeds. They themselves are artifacts of design. (Bucciarelli, 1994, p. 187)

Bucciarelli (1994) asserts the above "theory of operation" may not capture the full nature of the design process. He proposes an alternative image of design as a "puzzle solving" activity. Engineering design "vignettes" are about individuals "figuring out why things don't fit, trying alternative explanations, musing and searching for the piece that will lock in an ensemble of features."(Bucciarelli, p. 87) Yet, puzzle solving is usually a solitary and intense activity - "the joy of finding a missing piece is akin to the engineer's delight in finding the bit of evidence that supports his or her latest model or verifies the functioning of a prototype" (Bucciarelli, p. 87).

Hapgood and the Traversal of Solution Space

Fred Hapgood (1993) posits ideas on "solution space" and engineering as a human activity that complement those of Ferguson and Petroski. Hapgood examines the fundamentals of engineering at MIT, the "flow of the enterprise, the character of its imagination, the nature of its relation to the world" (p. ix). This is particularly evident in two examples the author provides. The first describes the way in which Ernesto Blanco approached a specific engineering design problem. One day, Blanco's niece asked the engineer to figure out a way to design a no hands music pager; she wanted to turn the sheets on a music stand without taking her hands off her instrument. Blanco immediately responded he would design such a device and he began to develop several potential devices for direct trial. After a number of attempts, Blanco failed. Each trial only left some essential features of design "lying on the ground" (Hapgood, p. 4).

Eventually Blanco gave up; he had reached the end of the road. Frustrated and at the end of his rope, he decided to dump the whole thing - he was stuck. He wondered why he was unable to design a solution to the problem. Obviously, he thought, there was a way; he must be an idiot. In fact, Blanco felt he had no right to call himself an engineer. He began to experience a sense of the idiographic or emic nature of engineering as a human activity. At this point in being stuck, Blanco took a length of Scotch tape and wrapped it around his finger, sticky-side out, and began picking up the pages with it. It was easy, his finger could do it, why could he not do it? Then, like a lens suddenly twisting into focus, Blanco noticed what his finger was doing: it was not ripping free from a turned page; it was peeling free by rotating against the page. It was simply a matter of press, lift, turn, peel. Blanco was struck by this revelation; "the answer had been there all the time, literally under his nose, waving, calling out" (Hapgood, 1993, p. 6). Blanco had glimpsed the real world for a bare second and been forced to remember what he should never have forgotten: the difference between peeling and ripping.

Pirsig (1974) insists stuckness (such as that experienced by Blanco) is the key, the heart of the solution process. He informs engineers what to do when they are "stumped," when they have diagnosed "the trouble and then found they were wrong":

> ... Just 'stare' at the machine. There is nothing wrong with that. Just live with it for a while. Watch it the way you watch a line when fishing and before long, as sure as you live, you'll get a little nibble, a little fact asking in a timid, humble way if you're interested in it. That's the way the world keeps on happening. Be interested in it. (p. 311).

Any attempt at solution design, even supposed trivial design attempts like Blanco's no-hands music pager, can bring engineers here. It forces them to feel "left out on the tundra without the least idea which direction to take, empty and void of any confidence in their own notions, world view, or indeed, metaphysics" (Hapgood, 1993,

p. 4). When this happens, when a person is exhausted, demoralized and under enormous pressure and not only has no idea what to do next but has given up all hope of even having a new idea, the ego will sometimes relax and allow its prisoner a few seconds of direct observation of what is sitting right in front of his/her face. For most people, the ego reasserts its claims over their perception, over their stare at "unvarnished reality" (Hapgood, 1993, p. 5) in minutes or even seconds.

This was not a new experience for Blanco. As a professional engineer, he was aware that a temporary release from the ego happens with every engineering design of any interest, however the trauma of the experience can be just as painful with each new design problem that an engineer may encounter. Blanco's exhaustion had released him from his over-attachment to his prior experience with other problems and forced him to refocus his attention on his experience with the pager problem. He had gone into the problem expecting the solution to fall out of his previous experience simply and directly. When that did not happen, he threw out all his attachment to other contexts and started going through only the most directly relevant experiences. He approached those without expecting a solution to pop out at him. He just took the experiences up, one at a time, and let them fall into their own order. When that happened, the solution was lying there on the table. The preconditions were that he had to have accumulated lots of firsthand experience with the problem, then found himself in a state of mind that allowed him to focus on those experiences without integrating them prematurely. The device of "I know I won't be the one to solve this problem, but someone will someday and I wonder how" (Hapgood, 1993, p. 5) was critical.

Hapgood (1993) states engineers solve problems by interactively generating some candidate solutions. They fine-tune the potential solutions using their own experience and then generate some more candidate solutions.[113] The process is an iterative one that embodies pattern generation and recognition. Decision and systems theorists sometimes refer to these volumes of plausible answers as "solution spaces" (p.7) and problem-solving, defining paths through these volumes, as "searching" solution space. Engineering can also be seen as a family of paths crossing a solution space - in this case a space defined by all the possible arrangements and combinations of complex variables that might satisfy the particular specifications of a design. Filtering a good design out of these possibilities by simple, direct calculation is impossible both because of the enormous number of variables and because there are always elements in the specifications that cannot be reduced to a number or folded into a common denominator.

What humans do in these cases is what Blanco did: "think up a completely wrong but sincerely intended approach to the problem, jump in, fail, and then do an autopsy" (Hapgood, 1993, p. 8). Each failure contains encrypted somewhere on its body directions to the next step in the process. For Hapgood, good engineering is less a matter of creativity, centering, grounding, inspiration or lateral thinking, than of

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[113] Tufte states "design is choice ... [it] consists of principles that generate design options and that guide choices among options. The principles should not be applied rigidly or in a peevish spirit; they are not logically or mathematically certain; and it is better to violate any principle than to place graceless or inelegant marks on paper. What is to be sought in designs ... is the clear portrayal of complexity - that is, the revelation of the complex" (Epilogue). Refer to Tufte, E.R. (1983). The visual display of quantitative information. Cheshire, CT: Graphics Press.

"decoding the clever, even witty, messages solution space carves on the corpses of the ideas which you began with, and then building the road to the next message" (Hapgood, 1993, p. 8).

Hapgood's (1993) second example of engineering design involved a challenge to develop an airplane that could take off under human power and fly for a mile. This idea is not entirely new but the performance of such devices had never amounted to much because humans produce very little power per pound of body weight. In theory wing area can compensate for power but humans are too weak to lift a wing design with anything close to even a glider's weight per square foot. Therefore the engineering challenge was to design a structure that had lots of wing area and a total weight half of that of the pilot and that was strong enough to survive the stresses of real flight. Several "heavy theory shops" (Hapgood, p. 9), that included MIT, Cal Tech, and the University of Tokyo, attempted to design a solution to the problem. The team that won was none of these but a group of hobbyists who compensated for their supposed deficiencies in theory by evolving a design that tolerated continual repair and restructuring.

The Gossamer Albatross [114] could be stressed to failure and pushed until it crashed, and it could be repaired cheaply and quickly. The process was repeated over and over. Each of these experiments became a "highly context-sensitive tutorial in the trade-offs possible" (Hapgood, 1993, p. 9) between strength and weight. The failure of

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[114] Youngren characterizes the Gossamer Albatross design experience as "changing ideas about where the limits lie in engineering design ... it involves bringing myth into reality." Harold Youngren. (1988). Daedalus 88 Project. In Nova: Celebrating 20 years on PBS [Film].

any particular part did more than indicate an inadequacy in the original design; it underlined a particular issue needing attention next and pointed in the direction of a possible solution. The winning team crashed the Gossamer Albatross 500 times.

According to Hapgood (1993), this is the fundamental cycle, the "atom of the process" (p. 9), the unit of movement in solution space. In formal contexts, the process is known as "generate-and-test or design-through-debugging or guided iteration" (Hapgood, p. 9).[115] Among themselves engineers call it tinkering or trial-and-error. The development of any given experimental or theoretical tool is a result of thousands of these cycles. From a metaphorical stance, engineering design is a traversal through the corridors of solution space that resonates with "narratives about inching uphill and sliding back down, of being on the wave, of being stuck" (Hapgood, p. 10). The more time an engineer spends in the corridors, the more intuitive an idea solution space becomes; "the subjective and the objective, what is and what should be, the given and the created" (Hapgood, p. 10) begin to blur. The differences that exist between the material and imaginary begin to fade away. Sometimes ideas will arise from within and reflect a mirror image; sometimes the process seems to start with a natural configuration that leaps into one's imagination from the outside.

Hapgood's (1993) metaphor presents a view of the engineer as an operative, a meta-engineer whose design processes imply a demanding and sometimes

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[115] A central proposition of Lang's (1996) theorem on evolutionary epistemology involves the "g-t-r (generation-test-regeneration) heuristic" (p. 70) which defines the means by which an organism adapts to its environment in general and to uncertain futures in particular.

unpredictable art. Terms of motion - freedom of direction, unpredictability of association, and a richness of interchangeableness - characterize an engineer's traversal through the matrix. One is struck by the absence of any intellectual landmarks as he/she moves from "casual jargon to an apt metaphor to an alternate metaphysics to the obviously right way of thinking about the universe" (Hapgood, p. 10).

For Hapgood (1993), the perspectives of engineering and science are simple reciprocals; any statement one might make about the intellectual or spiritual content of one applies, if in inverted form, to the other.[116] Engineering could be seen as a special case of science (or applied science) whereas science could equally well be described as a special case of engineering (or abstract engineering). Scientists are given a phenomenon and asked to find its logical and physical relations to the rest of the universe; engineers are given the relations and asked to define the phenomenon. Scientists derive the specifications from the object; engineers, the object from the specifications. Studying an artifact in order to figure out its logic is known as "reverse engineering" (Hapgood, 1993, p. 50); in that usage science is the reverse engineering of nature, and engineering the science of solution space. A design is an experimental

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[116] Damasio's observations on the role of "emotion" in human reasoning indicate a reciprocal relationship between engineering design and science. While he acknowledges allowing emotions to interfere with one's reasoning can lead to irrational behavior, Damasio argues a complete absence of emotion can likewise lead to irrational behavior. Damasio's research indicates , when taken to extremes, the Cartesian idea of a "coolly rational person," who reasons in a manner unaffected by emotions, is an "oxymoron." "Truly emotionless thought leads to behavior that by anyone else's standards is quite clearly irrational" (p. 278). See Damasio, A. (1994). Descartes' error: Emotion, reason, and the human brain. New York: Grosset/Putnam; and Devlin, K. (1997). Goodbye, Descartes: The end of logic and the search for a new cosmology of the mind. New York: John Wiley.

hypothesis; science is understanding where one is; engineering is getting there.[117]

One might argue only through engineering is it possible to have more than the most cursory relationship with the great fundamental harmonies of nature; scientists observe nature from outside, while "engineers and nature get married and have progeny" (Hapgood, 1993, p. 50). They build, day-in and day-out, working relationships out of common interests and shared goals. Hapgood asserts the fitness of things, the power of connectedness that runs through the universe of mind and matter alike, merits consideration as a fundamental and sanctified harmony.

Vincenti's Theoretical Framework for Engineering

According to Walter Vincenti (1990), engineering knowledge receives little attention from scholars in other disciplines, and when it is noted, engineering is usually thought of as applied science.[118] Vincenti further asserts :

> Modern engineers are seen as taking over their knowledge from scientists and, by some occasionally dramatic but probably intellectually uninteresting process, using this knowledge to fashion material artifacts. From this point of view, studying the epistemology of science should automatically subsume the knowledge content of engineering. Engineers know from experience that this view is untrue.... (p. 3)

Vincenti's (1990) ideas reflect narrative and analytical evidence of historians of

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[117] For a study that bears on the concept of "reverse engineering" and how it applies "to the way things work," see Bloomfield, L.A. (1997). How things work: The physics of everyday life. New York: John Wiley.

[118] Issues surrounding the "engineering as applied science" debate are addressed in Donovan, A. (1986). Thinking about engineering. Technology and Culture, 27, 674-679.

technology who have only recently begun to examine the character of engineering knowledge as an epistemological species. In this view, technology[119] - and hence engineering - appears not as a derivative of science but as an autonomous body of knowledge identifiably different from the scientific knowledge with which it interacts.

Perspectives are quite different if the knowledge content of technology is seen as coming entirely from science. This view immediately defines the science-technology relation. Technology is hierarchically subordinate to science and serves only to deduce the implications of scientific discoveries and to give them practical application. This relation is summarized in the discredited statement "technology is applied science" (Vincenti, 1990, p.50). For Vincenti (1990), such a hierarchial model leaves no basic issues for discussion about the nature of the relationship. Moreover, such a rigid model obscures the complex historical record. Focusing on technology and engineering design as knowledge, Vincenti is able to go beyond the "science-technology question"[120] and explore what Rosenberg (1982), Laudan (1984), and Latour (1987) term "the black box" of technology (Vincenti, 1990, p. 3).

Vincenti's (1990) basic thesis is engineers have their own methods, procedures,

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[119] Pinch (1992) states historians of technology, such as Vincenti, Layton, and Hughes, have been instrumental in advancing this new perspective and "engineers are at last escaping from the shadow of science." Engineering, within this perspective, is "better seen as its own form of culture, with its own set of rules and bodies of practice - ...certainly not a mere appendage to or an application of science" (p. 205).

[120] For in-depth studies of the science-technology question, refer to Keller, A. (1984). Has science created technoiogy? Minerva,22, 160-182; Layton, E. (1987). Through the looking glass, or news from lake mirror image. Technology and Culture, 28, 594-607; Staudenmaier, S.J. (1985). Technology's storytellers: Reweaving the human fabric. Cambridge, MA: Harvard University Press; and Barnes, B. (1982). The science-technology relationship: A model and a query. Social Studies of Science, 12, 166-171.

and bodies of skills whereby they create and construct knowledge. He asserts every technology is a completely human construct. Embedded in its design are the values and limitations of specific engineers and planners.[121] He focuses on engineering design while ignoring production and operation, the other branches of modern engineering, although he believes his conclusions are applicable to those activities as well. Through five case studies in aeronautical engineering, Vincenti examines how problems arising from normal design requirements have complex epistemological consequences that distinguish engineering knowledge from applied science. He asks: How do engineers think? How do they interact with one another? What motivates them? Why do engineers frequently act and think differently than do basic scientists? Vincenti responds to these questions with two theoretical frameworks: an anatomy of engineering knowledge and a new variation-selection model for the growth of engineering knowledge.

Vincenti (1990) focuses his inquiry on the concept of engineering design. For engineers, in contrast to scientists, knowledge is not an end in itself or the central objective of their profession. Rather it is a means to a utilitarian end; this idea is similarly reflected in a statement by G.F.C. Rogers (1983) :

> Engineering refers to the practice of organizing the design and construction of any artifice which transforms the physical world around us to meet some recognized need. (p. 51)

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[121] Staudenmaier (1991) asserts Vincenti's theory of engineering design activity "offers us a believably human image of engineers [who] turn out to be ordinary human beings, subject to the play of uncertainty, surprise, achievement, and failure as the rest of us" (p. 67).

A key term for Vincenti (1990) here is "organizing" for which he also uses "devising" or "planning" (p. 14). The term selects engineering out from the more general "technology," which embraces all aspects of design, production, and operation of an artifice. Draftspersons, shop workers, and pilots, for example, though all technologists, do not organize in the engineering sense and are, therefore, not engineers. All engineers count as technologists, but not all technologists count as engineers. Engineering falls within technology, and engineering knowledge forms part of the broader domain of technological knowledge. Most historians of technology seldom make this distinction; Vincenti is acutely aware of the distinction.[122]

For Vincenti (1990), "organizing the design" (p. 6) is the core process by which engineering knowledge is generated. It is used in the sense of "bring into being" or "get together" or "arrange" (p. 6). It typically involves tentative layouts of the arrangement and dimensions of the artifice, testing a candidate device or solution to see if it does the required job, and modification of the candidate solution when it does not. The design procedure is complex and often iterative. Difficult trade-offs may be required and decisions may be made on the basis of incomplete or uncertain information. At times engineering design[123] activities may seem more like creative art than science.

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[122] The troublesome definition of "technology," is discussed in McGinn, R.E. (1991). Science, technology, and society. Englewood Cliffs, NJ: Prentice Hall.

[123] Rogers (1983) explores the engineering design, creative art, and science. See The nature of engineering: A philosophy of technology. Ch. 3. London: Macmillan. For issues involving the "demarcation" of art, science, and technology, refer to Topper, D. (1996). Toward an epistemology of scientific illustration. In B.S. Baigrie (Ed.). Picturing knowledge: Historical and philosophical problems concerning the use of art in science. (pp. 229-241). Toronto, Canada: University of Toronto Press.

It is noteworthy that Vincenti (1990) restricts his focus to what he terms "normal" design. The engineer engaged in such design knows at the outset how the device in question works, what its customary features are, and that, if properly designed along such lines, it has a good chance of accomplishing the desired task. Normal design is quite different from "radical" design. In the latter process, the dimensions of the device or even how it works is largely unknown. The engineering designer has never seen such a device before and has no presumption of success. The problem is to design a candidate device or solution that will function well enough to warrant further development. Vincenti states normal design more appropriately reflects the day-to-day engineering enterprise. Here Vincenti interprets the term "knowledge" broadly. It includes both "knowing how" and "knowing that" (p. 13); that is, knowledge of how to perform tasks as well as knowledge of facts. Knowing how is reflected as both knowledge of how to do design and knowledge of how to generate the new knowledge - the ideas and information - that such doing requires.

In normal design, this knowledge is more circumscribed and while it does entail novelty and invention in considerable degree, it is not crucially identified with originality in the same way as knowledge for radical design.[124] Vincenti (1990) is careful to note normal and radical design knowledge cannot be sharply separated. Moreover, normal design is not characterized as being a routine, deductive and

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[124] For an historical treatment of normal and radical design in engineering and the role of invention in both design processes, see Staudenmaier, S.J. (1985). Technology's storytellers: Reweaving the human fabric. (pp. 40-61). Cambridge, MA: Harvard University Press.

essentially static process; rather it is a creative and constructive process that changes over time. The changes however are incremental instead of essential; normal design is evolutionary rather than revolutionary. Finally, design, apart from being normal or radical, is also multilevel and hierarchial. Interacting levels of design exist, depending on the nature of the immediate design task, the identity of some component of the device, or the engineering discipline required. Vincenti (1990) recasts Rogers' concept of engineering as a human activity:

> Engineering knowledge reflects the fact that design does not take place for its own sake and in isolation. Artifactual design is a social activity directed at a practical set of goals intended to serve human beings in some direct way. (p. 11)

Engineering is intimately bound up with social and environmental needs and constraints. Staudenmaier (1985) refers to these as "contextual factors that constitute the artifact's ambience" and he sees technological activity as characterized or even defined by a "tension between technical design and its ambience." In addition, the “design-ambient tension” factor is often a result of the cultural functions implicit in the engineering design process itself (pp. 6, 103).

Vincenti (1990) focuses mainly on the internal knowledge required by the design side of this tension. He notes contextual factors have a determining influence that one must consider; however, in normal design, this ambience exercises its greatest direct effect at the upper levels of hierarchy where projects are defined and laid out.[125]

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[125] For an assortment of readings on how the different levels of social context shape the emergence of engineering design, refer to MacKenzie, D. & Wajcman, J. (1985). (Eds.). The social shaping of technology. Philadelphia, PA: Open University Press.

At the lower levels, the contextual influence tends to be less direct. Indeed, it is at these lower levels that knowledge derives predominantly from the internal needs of design itself. This is the knowledge that is used in the central activity of engineering design and it reflects "how engineers think and how their thinking relates to their doing" (Vincenti, p. 11).

Based on his theories of engineering design, Vincenti (1990) presents a categorization of engineering design knowledge and the activities that generate it. This anatomy of design knowledge is intended to apply to all branches of modern engineering. Thus Vincenti is attempting to develop realistic concepts that have universal application to the whole field of engineering. He begins by stating:

> We can start with the obvious statement that engineering is a problem-solving activity. Engineers spend all their time dealing mostly with practical problems, and engineering knowledge both serves and grows out of this occupation. (pp. 200-201)

Design is the central activity in the problem-solving process. At the working level in engineering, problem-solving and design are synonymous. Whatever the source of design problems, their solution depends on knowledge generated at the working or design level. The knowledge generated may not be new; developments and iterations continue, and solutions in individual cases may call for considerable ingenuity.

Vincenti (1990) identifies these six categories of engineering design knowledge:

1. Fundamental design concepts
2. Criteria and specifications
3. Theoretical tools
4. Quantitative data
5. Practical considerations
6. Design instrumentalities.

He asserts the divisions are neither entirely exclusive nor exhaustive; in some cases, the items of knowledge are not clearly distinguishable.

The first category of engineering design knowledge deals with two fundamental design concepts. Engineers who begin any normal design activity bring with them fundamental concepts about the device in question. Polanyi (1962) calls this fundamental concept the operational principle of the device and it means "how its characteristic parts ... fulfill their special function in combination to an overall operation which achieves the purpose" (p. 328) of the device - in other words, how the device works. It is the operational principle that provides the criterion by which success or failure is judged in the purely technical sense.

If a device works according to its operational principle, it is considered a success; if something breaks or otherwise goes so wrong that the operational principle is not achieved, the device is a failure. The operational principle provides an important point of difference between engineering and science. It originates outside the body of scientific knowledge and comes into being to serve some innately technological purpose. Polanyi (1962) underscores this difference: "complete [i.e., scientific] knowledge of a machine as an object tells us nothing about it as a machine" (p. 330).

A second aspect of fundamental design concepts involves the normal configuration for the device in question. This means the general shape and arrangement that are commonly agreed to best embody the operational principle. Whatever the details, the preferred configuration for a given device with a given application is knowledge that has to be learned by the engineering community, usually by experience with different configurations in the early stages of a technology. Vincenti (1990) asserts a shared operational principle and normal configuration define the normal design of a device. Essentially engineers attempt the improvement of the accepted tradition or its application under new or more stringent conditions. Thus operational principle and normal configuration provide a framework within which normal design takes place. Engineers doing normal design bring these concepts to their task without thinking about them. To translate these concepts into a concrete design requires knowledge from the categories that follow.

It is noteworthy that radical design involves a change in normal configuration and possibly also operational principle. In the latter event, the configuration must in fact be established ab initio since it obviously cannot be known at the outset. Radical designs that fall short of revolutionary may involve a modification of operational principle in contrast to complete change. Distinctions in radical design are relative and not always easily defined.

Another category of engineering design knowledge involves criteria and specifications. In order to design a device embodying a given operational principle and normal configuration, the engineer must have at some point specific requirements in terms of the hardware. Translation of the utilitarian and usually qualitative goals of a device into concrete technical terms - using criteria and specifications - is crucial for engineering. Both of these elements become part of the stored-up knowledge about how things are done in engineering.

An important point of difference exists between science and engineering.

Scientists, in their search for understanding, do not aim at rigidly specified goals. Engineers, in order to carry out their design task, must work to very concrete objectives; this requires that they devise relevant design criteria and specifications. Engineers also use a wide range of theoretical tools. This category includes intellectual concepts for thinking about design as well as formal mathematical methods and theories. Both the concepts and methods cover a spectrum running from things generally regarded as part of science (highly scientific and specifically mathematical) to items of a peculiarly engineering character (intensely practical and explicitly physical).

At the scientific end of the spectrum, one finds purely mathematical tools that have no physical content. Engineers acquire many of these (as "engineering science")from prior mathematics, either directly or with some modification. Next along the spectrum is mathematically structured knowledge that is essentially physical (in contrast to purely mathematical) and has scientific interest for its explanatory power.

Farther in the direction of engineering are theories based on scientific principles but motivated by and limited to a specific device or class of phenomena; these make up what Polanyi (1962) calls "systematic technology" (p. 179). Still more toward the engineering end of the spectrum one finds theories that, while they may go back to scientific principles in part, involve some central, ad hoc assumptions about phenomena crucial to the problem. Such phenomenological theories, which are often device specific, have little explanatory power or scientific standing. Engineers devise them because they must get on with their design task and the phenomena in question are too poorly understood or too difficult to handle otherwise.

At the far end of the engineering spectrum lie quantitative assumptions introduced for calculative expedience but too crude or ill defined to be called theories. They are used for practical reasons and because they are known from experience to produce conservative and acceptable results. Vincenti (1990) asserts, without these assumptions, a great deal of everyday engineering design would not get done.

Another category essential for engineering design is quantitative data. These are usually obtained empirically and they divide into two kinds of knowledge, descriptive and prescriptive. Descriptive knowledge is knowledge of how things are. Prescriptive knowledge is knowledge of how things should be to attain a desired end; it says, in effect, "in order to accomplish this, arrange things this way" (Vincenti, 1990, p. 217).

Much of the design procedure of the next category, practical considerations, is also prescriptive in the sense that it suggests to the engineer how to go about achieving a required design. For their work, engineers often need a wide range of less sharply defined considerations derived from experience in practice, considerations that frequently do not lend themselves to theorizing in a formal sense. Such considerations are mostly learned on the job rather than in school or from books. They tend to be carried around, sometimes more or less unconsciously, in engineers' minds. Frequently they are hard to find written down and often take the form of "design rules of thumb" (Vincenti, 1990, p. 218); these are reflected in all branches of engineering.

For one category, design instrumentalities, Vincenti (1990) notes an interesting characteristic of engineering activity. Besides the analytical tools, quantitative data, and practical considerations required for their tasks, engineers need to know how to carry out those tasks. The design instrumentalities procedure actually involves developing a design or solution that will effectively respond to the given problem. Engineers often see themselves as attaining an optimizing solution in this procedure. However, because of the complexities and uncertainties in the problem, they often achieve no more than what Simon (1996) calls "satisficing" solutions to a problem. These solutions may not be “optimal” but they are satisfactory or “workable” in a given design context (p. 28).

In engineering design, procedures for satisficing (a term engineers rarely use) are less formal than for optimizing and depend more on judgmental skills and practical considerations. Vincenti (1990) asserts most engineering design is a satisficing procedure; given the large number of interacting variables in most of their problems, engineers are seldom able to truly optimize. Satisficing is reflected, either explicitly or implicitly, in the iterative techniques of most design solutions. How to employ these techniques effectively constitutes an essential part of design knowledge.

The categories of engineering design serve as a framework for what Vincenti (1990) calls "ways of thinking" (p. 220). By this he means the habitual ways in which design engineers formulate their thoughts during a problem-solving activity. Vincenti identifies three ways of thinking in design. First, engineers think in ways that start from a particular mode of thinking and find concepts to fit the situation. This type of creative thinking is by analogy.

A second mode of thinking has a different nature entirely. Engineers think also in ways that are "not easily reducible to words" (Vincenti, 1990, p. 221). Such nonverbal thinking uses for its language, not the expressible concepts noted above, but an object, a picture, or a visual image in the mind. Vincenti states "outstanding designers are invariably outstanding visual thinkers" (Vincenti, p. 221). Knowing this, engineering schools make efforts to teach this form of knowledge; courses and textbooks exist with visual thinking in their titles.[126] Finally, engineers need the pragmatic judgmental skills required to seek out solutions and make design decisions. Such skills, like visual thinking, call for insight, imagination, and intuition, as well as a feeling for elegance and aesthetics in technical design.

According to Laudan (1984), this thinking often involves the perception of a new technological possibility, that is, that "some technical advance is conceivably in the cards though no one has an idea how to achieve it" (p. 84). Whatever the situation, knowledge of how to exercise both visual thinking and judgmental skills is mostly tacit. Though the skills can be pointed out to engineering students in the classroom, they can be learned in the end only through practical experience. This must include experience not only with what works but also with what does not. As Gutting (1987) notes, "the mere fact that a system fails to perform properly in certain circumstances in itself constitutes a piece of knowledge essential to the technological enterprise" (p. 63). Thus a wide range of experience from past and present practice must underpin visual thinking and judgmental skills.

Vincenti identifies specific engineering activities and he asserts they reflect his assumption that the knowledge used in normal design is derived mainly from

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[126] An example of this type of engineering text is R.H. McKim. (1980). Experiences in visual thinking. (2nd ed.). Monterey, CA: Brooks/Cole.

engineering activities themselves. The knowledge-generating activities are described under these headings (which overlap and intersect as do the knowledge categories:

1. Transfer from science
2. Invention
3. Theoretical engineering design
4. Experimental engineering design
5. Design Practice
6. Production
7. Direct Trial

Transfer from science involves knowledge transferred from theoretical science (prior, well-established science) or current scientific activity and it often entails reformulation or adaptation to make the knowledge useful to engineers. Vincenti (1990) affirms that, while engineering design is an art, it is an art that utilizes (increasingly) knowledge from developed and developing science. This is far from saying, however, that science is the sole or even major source and that engineering is essentially applied science. Another activity, invention, is the source of the operational principles and normal configurations that underlie normal design. Contriving such fundamental concepts, or "coming onto them by serendipity" (Vincenti, p. 230), is by definition an act of invention. Other activities may contribute to invention but it is this elusive, creative enterprise that produces those concepts. Though invention is apart from normal design, Vincenti feels, without the appropriate fundamental concepts for the device in question, the engineer doing such design could not do it.

A large number of engineers conduct theoretical engineering research in academic institutions and industrial and government research laboratories. In this instance, engineers work at producing knowledge via theoretical activity - an activity that is synonymous with mathematical activity. Theoretical activity in engineering is very similar to theoretical research in science. Like scientific research, it is systemic, conceptually demanding and often mathematically difficult. Another similar activity is experimental engineering research. An even larger number of engineers engage in this activity and it is serves as the major source of quantitative data. Since quantitative data of some kind are essential to design in any engineering field, so also is experimental research from which the data are derived.

Experimental research in engineering is difficult to separate entirely from experimental research in science. Approach, techniques, and instrumentation are basically similar. Overall, however, differences are greater than with theoretical research. A great deal of engineering experiment has a character very much its own. In particular, engineers may employ procedures of destructive testing, that is, pushing a given device beyond its apparent limitations or specifications to learn at what point it may destruct. This is a procedure that would have no standing at all in modern science. Vincenti (1990) states experimental and theoretical research "spark and depend on each other" (p. 232) and although he separates them for epistemological analysis, they are most productive when done together or at least in interactive proximity.

In direct trial, engineers deliberately test the devices they design and build; this activity provides essential design knowledge. When feasible, engineers conduct intentional proof tests to determine if their designs perform as intended. They want to find out how well a device achieves its goals and meets its technical specifications. If the design is not a success, the results serve as an indicator of how the device might be redesigned or corrected. Direct trial is an essential part of engineering. Though aimed at design-specific information, the check it provides between predictions and attainments contributes to the growth of an engineer's judgmental skills. If a series of such checks gives consistent differences, it can also supply empirical correction factors or quantitative data useful in future designs. Proof tests are essential forforming an operational principle. Knowledge that certain things do not work in practice is an important result of testing.

The knowledge-generating activities, like the knowledge categories discussed above, provide a framework for orientation and analysis rather than a rigid set of distinctions. Vincenti asserts this framework and the ideas behind it apply to all branches of modern engineering. Moreover, it contributes to the view, by historians of technology, of engineering knowledge as a distinct epistemological species. Although such knowledge does share elements with science, other features are peculiar to engineering. Operational principles and normal configurations lie outside the domain of science. Criteria and specifications, practical considerations, and design instrumentalities are, almost by definition, the province of engineers.

In general, all knowledge for engineering design can be seen as contributing in one way or another to implementation of how things ought to be. That, in fact, is the criterion for its usefulness and validity. Such implementation obviously requires procedural knowledge, that is, "knowing how," of both the prescriptive and tacit varieties; it also requires a great deal of descriptive knowledge, which is synonymous with "knowing that" or knowledge of how things are. Part of this knowledge comes from science, but much of it arises within engineering itself. Though the sciences deal with how things are, they are not the sole source of such knowledge. If engineering knowledge is to be understood in any appropriate sense, it must be addressed on its own terms.

From his examination of knowledge categories and knowledge-generating activities, Vincenti (1990) is able to make certain inferences about the nature of engineering knowledge. He further explores the idea growth of knowledge in engineering can be described in terms of a blind-variation-and-selective-retention model. Vincenti uses Campbell's (1987) model for knowledge growth as a springboard. Campbell contends some version of the variation-selection model is fundamental to all genuine increases in knowledge, from that embodied in genetic codes arrived at by biological adaptation to the theoretical structures of modern science. Vincenti bases his approach on two essential elements of Campbell's model, mechanisms for introducing variations and consistent selection processes. The newer model is presented as an exemplar of the variation-selection approach in engineering that is more explicit than usually appears in epistemological or historical studies. The model encompasses, though not always explicitly, the categories of knowledge and knowledge-generating activities.

The notion of blindness - the focus of much of the criticism with regard to scientific advance - enters via the mechanisms for introducing variation. Any variation that leads to new knowledge - knowledge that has not been attained before - must be blind in the sense of "going beyond the limits of foresight or prescience" (Vincenti, 1990, p. 242). It is important to note "blind" in this sense does not mean "random" or "unpremeditated" or "unconstrained." It simply denotes the outcome of the variation cannot be foreseen for the matter in question; if it could, the knowledge obtained would not be new. Knowledge grows, that is, blindness is reduced, through extension of the limits of what can be foreseen or predicted.

Vincenti (1990) asserts the notion of blindness is valid in engineering design. Blindness, however, is far from absolute. Popper (1974) also addresses this point: "To the degree that past knowledge enters, blindness is only relative: it begins where the past knowledge ends" (pp. 117-118).[127] For much of normal design, the degree of blindness involved in the generation of new knowledge may be small. The important idea is that when the outcome is not completely foreseeable, the variation must in some degree be blind.

Vincenti (1990) notes an element important here: final selection takes place by visible, direct trial of a number of variations. To arrive at these, the engineer must go through some kind of mental pre-selection process to winnow the much larger number that would certainly be conceivable. Vincenti regards such thought trials as part of the mechanisms of variation and he takes variations to mean only those that are in some way examined "overtly". Engineers do a great deal of visible sketching and doodling as they think. Design itself constitutes a variation-selection process of knowledge

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[127] Vincenti asserts Popper's views on "blindness" have direct implications for engineering design, and he states they are "well worth reading" (p. 317). Refer to Popper, K. (1974). Replies to my critics. In P.A. Schlipp (Ed.). The philosophy of Karl Popper. (pp. 413-462). London: Routledge & Paul.

generation. This statement holds true not only in the early stage of a new technology when the knowledge sought is that of a workable general configuration; it applies also after the configuration is settled and the object of design is a particular instance of it.

In this more normal situation, the desired knowledge is how to arrange and proportion that particular device so as to accomplish its task given the constraints of the normal configuration. The engineer usually lays out a number of plausible variations on some basis and selects the final design by some sort of analysis or experimental test or combination of both. More often than not, the process takes place iteratively, with the results from one variation suggesting or pointing to the properties and proportions of the next. Vincenti (1990) focuses on the mechanisms of variation and processes of selection within the framework of design. He prefaces his examination with specific assumptions.

Normal design requires detailed knowledge from the categories discussed above. This knowledge, too, to the extent it is (or was at some time) truly new, has to come from a subsidiary variation-selection process located in the knowledge-generating activities; it is subsidiary from the point of view of design. These processes may in turn call upon knowledge derived from still other subsidiary variation-selection processes of design activity. The overall scheme, then, is one of a "nested hierarchy" (Vincenti, 1990, p. 245) of blind variation-and-selective retention processes in which the knowledge produced at one level or stage is used in the process at the next outer level.[128] All interior levels contribute finally to the knowledge required in the primary process of design.

The details of how the variation-selection process works in engineering are not static; they evolve over time. In a broad sense, the cumulative growth of engineering knowledge as the result of individual variation-selection processes acts to change the nature of how those processes are carried out. This long-term methodological shift complicates the attempt to generalize about the process. The character of the shift itself, however, can be described fairly simply.

At all levels of hierarchy in engineering design, growth of knowledge acts to increase the complexity and power of the variation-selection process by:

> - modifying the mechanisms for variation, with resulting effects on degree of blindness and size of the field of overt variation (that is, the number of variations from which visible selection is made)
> - expanding the processes of selection by trying out overt variations "vicariously" through analysis and experiment in place of direct trial in the environment. (Vincenti, 1990, p. 245)

Vincenti's idea of selection mediated vicariously instead of by direct trial is an essential part of his general variation-selection model.

With the above overview, Vincenti (1990) examines the two elements of the variation-selection process in relation to normal design and how these elements evolve over time. The mechanisms for producing overt variations, whether at the level of

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[128] Vincenti's ideas on a "nested hierarchy" of blind variation-and-selective retention processes are more fully articulated in Lang's (1996) evolutionary "generation-test-regeneration" (g-t-r) heuristic of engineering design that is hierarchically layered (p. 70). Also note Sanitt's (1996) concept of the "constantly repeating pattern of nested hierarchies" that stimulates evolution of questioning ability in human organisms (pp. 81-82).

design or at knowledge producing levels within the nested hierarchy, include some hidden, mental activities:

- search of past experience with similar situations to find knowledge that has proved useful and a review of knowledge about variations that have not worked
- conceptual incorporation of whatever novel features come to mind as called for by new circumstances and that might have some chance of working

To the extent these features depart from what has worked in the past, the resulting variation can only be in some degree blind, even though the engineer may sense a high probability of success in their working mental winnowing of the conceived variations to pick out those most likely to work. The criterion in this hidden pre-selection process is: “if it were to be tried in some way would it be likely to work (or would it be likely to help in the design of something that would work)?” (Vincenti, 1990, p. 246).

These activities do not take place sequentially; rather, they go on concurrently and interactively in a more or less disordered way in the mind of the engineer. Much of the process takes place unconsciously and is obviously fallible. A priori discarding and mistaken winnowing may narrow the area for overt search unduly, with the result that useful variations may be missed. The process may produce variations that when overtly tried do not in fact work - the blindness leads down a wrong path. In retrospect, the entire process tends to seem more ordered and intentional or less blind than it usually is. Engineers prefer to remember their rational achievements and "forget the fumblings and ideas that didn't work out ... Luck can also play a role" (Vincenti, 1990, p. 246).[129]

Modification of these mechanisms of variation, and their incorporation into stored-up knowledge for engineering, takes place in several ways. First, the body of experience about what has and has not worked in the past increases, making a priori judgments easier. Second, experience within an established technology will for a time enhance the ability to conceive of novel features that have a chance of working. Ultimately, however, the degree of novelty that is possible tends to be exhausted (in the absence of some radical input from outside, in which case the technology is superseded, in effect, by a new technology). Third, expanded processes of vicarious overt trial enlarge the framework within which engineers conceive what is likely to work. They consequently develop more accurate feelings both for how a device or item of knowledge might work in direct trial, and how it might fare in an experiment.

The processes of selection, the second element in the variation-selection model, all involve overt trial of one kind or another. Growth of knowledge in a technology characteristically acts to expand the power of vicarious trial in place of direct trial. This expansion is achieved by two means:

- substitution of partial experiment or complete simulation tests for proof test or everyday use. Trial of this kind may aim for knowledge required to design a specific device or some component thereof or for some item of knowledge needed in design generally

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[129] Similarly, Gamble asserts "intentional" problem-solving will explain "constraints" in the blind randomness of search (introduced by the combination of purpose and assumptions about "already established" knowledge or tentatively trusted beliefs), however, it will not obviate the "wasteful fumbling" among alternatives that characterize all discovery processes. See Gamble, T.J. (1983). The natural selection model of knowledge generation: Campbell's dictum and its critics. Cognition and Brain Theory 6, 353-363.

- conducting analytical tests in place of actual physical trials. This also constitutes a form of vicarious trial; every performance or calculation made in the course of design is, a "test run on paper" (Vincenti, 1990, pp. 247-248).

Analysis can thus be seen as a means for vicariously trying out different variations. As with experiments and simulation tests, analytical tests sometimes produce items of general design knowledge as well as specific designs.

The intellectual framework provided by these means of vicarious overt trial gets incorporated into the hidden mental winnowing that goes into the choice of variations to be tried. The winnowing itself can be seen, in fact, as a kind of hidden vicarious trial. Although vicarious trial forms an essential part of modern engineering, in the end all designs and design knowledge must prove out in operation. This direct trial may be supplied by proof test of a completed device. It may also come from the everyday use that is any device's ultimate purpose. Devices or ideas that appear satisfactory in vicarious trial or proof testing may fail or otherwise prove inadequate when routinely employed. In direct and vicarious trial of both specific designs and general design knowledge, the criterion for selection of a variation for retention is: "Does it work?" or, more precisely, "Does it help in design of something that works?" (Vincenti, 1990, p. 248). This question, although sometimes not expressed, exists in the mind of anyone attempting to add to engineering knowledge, even in the most abstract sense.

At this point, Vincenti (1990) considers the notion of long-term change in blindness of variation. The entire variation-selection process is filled with uncertainty, and one may ask how, if at all, the level of this overall uncertainty changes with time.

One contribution to uncertainty comes from the degree of blindness in the variations. A second stems from what Vincenti calls "unsureness" in the process of selection. Changes in blindness and "unsureness," and their effect on overall uncertainty, can be viewed as advantageous. Uncertainty in the growth of knowledge in a given technology, that is, in the overall variation-selection process by which knowledge grows in that technology, must surely, in some sense, diminish as the technology becomes older. From what does this decrease in uncertainty stem, and why does it seem so evident? One is tempted to attribute the decrease in part to a decrease in blindness in the necessary variations.[130]

As a technology matures, increments of novelty become, on average, smaller; so too, does the degree of blindness involved in their pursuit. However, the advances are more difficult to come by and more sophisticated; the degree of blindness might thus be increased. Since blindness is a subjective attribute that resists measurement, the point is impossible to settle. Perhaps the temptation to see a net decrease stems from an illusion. Primary problems in a technology necessarily get solved early on, and the subsidiary problems that follow do not appear so critical or dramatic. Such problems also move to lower nested levels of hierarchy where they are less visible to outsiders. Whether blindness in variation really diminishes is thus difficult to determine. Engineers who struggle to advance a mature technology are not likely to think so.

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[130] For a "technical look" at the way engineers respond to uncertainty, blindness, and failure in the design process, see Kahneman, D., Slovic, P., & Tversky, A. (1982). Judgement under uncertainty. Cambridge, England: Cambridge University Press.

The element of "unsureness" exists likewise in the selection process and its effects are easier to assess. The vicarious means of trial generated within the nested hierarchy typically evolve concurrently with the variations they are being used to select; they are therefore often less than completely sure at a given time. Even direct trials of complicated devices suffer from "unsureness;" such complication can make it difficult to know how well a component of interest within the device is in fact working. The effectiveness of direct trials similarly increases as instrumentation and the understanding of complex systems improve. There can be little doubt that "unsureness" in the process of selection tends continually and progressively to decrease.

In the end, decreasing uncertainty in the growth of knowledge in a technology comes mainly from the increase in scope and precision (that is, the decrease in unsureness) in the vicarious means of selection. Just as expanding scope tends to widen the field that can be overtly searched, so also the increase in both scope and precision sharpens the ability to weed out variations that will not work in the real environment. Blindness in the variations may, by the same token, even increase - engineers may be increasingly blind in their trial variations as their means of vicarious selection become more reliable. That, in its essentials, is the variation-selection model.

Vincenti (1990) recognizes any theoretical model for the growth of knowledge is not a complete, final project. Nonetheless, he states the variation-selection model he proposes is universal to engineering knowledge: it characterizes all branches of engineering, applies across the categories of knowledge and appears, in whole or in part, in the variety of activities that generate such knowledge. He notes some research engineers may find the notion of blindness of variation difficult to accept for an enterprise as seemingly foresighted and self-critical as modern engineering. Yet Vincenti considers the concept of blindness as an illuminating, useful and even necessary idea. He concedes a more sophisticated way may be found to represent the element of "unknowing" that is inevitable in any extension of engineering knowledge. Any model of cognitive growth must undergo a variation-selection process with a considerable degree of blindness.

Vincenti (1990) asserts a comparison of his model for engineering with a corresponding model for science is not practicable at present. Campbell (1987) has pointed to the need for "spelling out in detail" how the growth of scientific knowledge reflects a variation-selection process and he has made some observations in that direction. However, the task remains to be completed. Whatever the details, a main difference from engineering must surely be in the criterion for selection. The criterion for retaining a variation in engineering must be, in the end: Does it help in designing something that works in solution of some practical problem? The criterion for scientific knowledge, however one frames it, must certainly be different, though its statement raises fundamental and debatable questions in the philosophy of science.[131]

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[131] Keller (1984) raises the issue quite clearly in asking: "Does it help in understanding some peculiar features of the universe?" (p. 169). "Explaining" could equally well be used in place of "understanding." Though difficulties are inevitable about details of the two criteria, other researchers state similar notions in different words. Laudan (1984) observes, for example, that "inconsistent scientific theories leave us unsure what to believe; ill-integrated technologies simply fail to work" (p. 88). The criteria also conform to Simon's (1996) distinction, mentioned above, between the sciences (as dealing with how things are) and engineering design (with how things ought to be). However one may phrase it, the essential difference is between intellectual understanding and practical utility.

Vincenti (1990) notes an essential asymmetry between the two criteria. In both cases the variation being judged is a means to an end - understanding in science and solution of a practical problem in engineering. In science, however, the means acts directly to the end; in engineering it acts through the intermediary of the "something," usually a material artifact, that is the immediate object of design. This is basically the same asymmetry noted in the statements about the uses of knowledge in science and engineering made in connection with the theories of knowledge and its generating activities. The distinctive nature of the engineering criterion has implications for both the form and content of engineering knowledge.

The two criteria are not mutually exclusive. The same element of knowledge can provide both understanding for the scientist and design assistance for the engineer. This commonality may, sometimes, lead to a blurring of the activities between the scientist and engineer. It may indeed be a source of the many misconceptions about the nature of engineering itself. These criteria can also operate in a partially or completely independent fashion. Some physically rigorous theories that are "cultivated in the same way as pure science" (Vincenti, 1990, p. 255) exist primarily because they work for engineers. Phenomenological theories, commonplace for utilitarian purposes in engineering, have little real scientific interest, and some theoretical tools useful in engineering are even known to be wrong - they explain nothing. They help with engineering design but they have no counterparts in the knowledge used by scientists. As indicated by the statement of the engineering criterion, whether or not something "works" has meaning only in relation to some practical problem or goal.

Vincenti (1990) attempts to map out in a general way the epistemological domain of engineering. The anatomy of knowledge is derived explicitly from considerations of modern engineering design, specifically in the twentieth century. The fundamental variation-selection process, in both its craft and modern forms, is something human beings had to learn over a period of time, presumably through some higher-order variation-selection process of its own. In the end, of course, engineering knowledge cannot - and should not - be separated from engineering practice. The nature of engineering knowledge, the process of its generation, and the engineering activity it serves form an inseparable whole. What researchers need to comprehend is the whole of engineering behavior - what it is "engineers really do" (Vincenti, p. 257).

These examples provide the basis for a model of engineering knowledge. Vincenti (1990) identifies the knowledge-generating activities in engineering as theoretical tools and data transferred from science, invention, theoretical engineering research, experimental engineering research, design practice, production, and direct trials. He concludes by exploring the idea that such knowledge grows by way of a blind-variation-and-selective-retention model put forward by the psychologist, Donald Campbell (1987). Vincenti points to the likelihood that indeed most engineering develops along its own path separate from science. He ends up postulating a variation-selection type model of universal applicability. He concludes by pointing to the need to study not so much what engineers know, but what engineers do and how they do it.

Vincenti's (1990) examples show the daily thinking of working engineers to be an untidy business. "As any engineer knows, the technological learning process always requires more effort in fact than appears necessary in hindsight.... The learning, in short, while it is going on, is messy, repetitious, and uneconomical" (Vincenti, p. 96).[132] To a large extent, Vincenti sees the engineering process as a battle against uncertainty. He shows how engineering design grows in the face of incomplete and uncertain information. Vincenti argues attempts to decrease such uncertainties through a complex interaction between theory and experiment became a significant in the growth of engineering knowledge. Over time, the engineering of any technology tends to reduce the level of uncertainty or loosely defined thinking toward precision and predictability.

Engineers see uncertainty - the spontaneous, the surprising, the subjectively debatable - as an expected but uncomfortable condition, a challenge to their expertise that demands painstaking testing and data gathering before it can be rationalized into helpful theories that will guide subsequent practice. Yet, Vincenti (1990) points out, uncertainty is also central to engineers' creativity, the force that drives the profession to reach beyond design orthodoxies. So when he talks of engineering knowledge as a messy business, he is referring both to the uncertain movement from subjective experience to precise theory and to the informal, collective way in which design decisions often arise. Vincenti's major contribution may be a believable image of the engineers, as experts who turn out to be ordinary human beings who are subject to the same play of uncertainty, surprise, achievement, and failure as the rest of humanity.

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[132] Staudenmaier (1991) states when Vincenti talks about engineering design knowledge "being a messy business, he is referring not only to the uncertain movement from subjective experience to precise theory but also to the informal, collective way in which design decisions often arise." The "untidy" cognitive processes that Vincenti reveals "belie the twentieth-century myth of precision in engineering design activity" (p. 67).

Chapter 6: Interdisciplinary Frames for Engineering Design

Debons, Horne, and Cronenweth (1988) assert an “interdisciplinarity” method can be effective in bringing together several disciplines and synthesizing their contributions to a specific problem, which is necessary for collaboration in Information Science. In particular, interdisciplinary thinking addresses the fact that problems cannot be “pigeonholed” according to academic disciplines but, rather, that a great deal of overlap exists among diverse areas of study that are represented in any given engineering design problem. Various disciplines generate potential theories that can stimulate development of a model of design activity. The task for this study is to discover what interdisciplinary ideas can effectively contribute to an emerging model of engineering design as a human problem solving process. This “interchange of ideas eventually lends insight into the variables” that must be considered to generate a “valid” model of design activity (Debons, Horne, & Cronenweth, p. 55).

Similarly, Boden (1983) asserts successful inquiry in information related disciplines requires "an interdisciplinary epistemology ... integrated with philosophical understanding and biological knowledge" (p. 235). Machlup and Mansfield (1983) add that such an approach could be equally useful for theory and model development in information engineering. Evolutionary epistemology is such an "interdisciplinary message" (Machlup & Mansfield, 1983, p. 4) for a model of engineering design.[133]

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[133] Contemporary debates on the subject of evolutionary epistemology with implications for engineering design are presented in Ruse, M. (1996). Contemporary debates. Monad to man: The concept of progress in evolutionary biology. (pp. 485-525). Cambridge, MA: Harvard University Press.

Plotkin's Theory of Adaptations as Instances of Knowledge

Henry Plotkin (1994) states "to know something is to incorporate the thing known into ourselves" (p. ix). This is not a literal process, of course, but the knower is changed by knowledge, and that change represents, even if very indirectly, the thing known. Skeptics might ask if these ideas are merely primitive folk-tales or just plain nonsense. According to Plotkin, this is not the case at all. He asserts knowledge is indeed a type of incorporation of the world but it is one of a special sort.

The object of Plotkin's (1994) work is to explore how and why humans, both as species and as individuals, came to know anything about their world and themselves. The author states human knowledge is closely connected to a fundamental feature of all living things; it reflects significant clues about the nature of the incorporation process itself. The apparent fit, the matching, of living things to the features and conditions of their world is a result of living creatures somehow incorporating into themselves those aspects of the world that are matched. This is the source of the sense of structural harmony between the organization of living things and the world about them. Sometimes the organization is extraordinarily complex, in other cases it may be simple but highly effective; yet simple or complex, match they do. Plotkin calls these seemingly clever and often dramatic forms of organization "adaptations" (p. xiii). Physical adaptations are generally formed by a long process of interaction between the environment and successions or lineages of organisms. They are crucial determinants of whether organisms survive and reproduce or not. Humans are just a particular form of animal, a "finely woven cloth of adaptations, as are all other animals" (Plotkin, p. xiv).

How can one make the connection between adaptation and knowledge? Here Plotkin (1994) notes knowledge, as commonly understood, and adaptations are closely related. However it is the vagueness of phrases like "closely related" that he wishes to eliminate; he says, in effect that "adaptation and knowledge are one and the same thing" (p. 116). That is, adaptations are themselves knowledge, themselves forms of incorporation of the world into the structure and organization of living things. This may seem to misappropriate a word, "knowledge," with a widely accepted meaning - knowledge usually just being something that only humans have somewhere in their heads. Thus it makes Plotkin's argument easier if the statement reads "adaptations are biological knowledge," and knowledge as one commonly understands the word is "a special case of biological knowledge" (p. xv). Plotkin's line of reasoning goes like this: the relationship of fit between parts of the organization of an organism, its limb structure or a particular cognitive process for instance, and some feature of the world in which it lives, such as the terrain or medium through which it must move, is one in which that organization is "in-formed" (p. xv) by the environment. The in-forming relationship underpins both the knowledge creation and incorporation processes.

This is the only way to understand the effectiveness of adaptations. The adaptation arises from a "chance" change, but that change is sustained (or not) by its fitness. But adaptations, by definition, almost always work. This is because of the in-formed nature of adaptations resulting from the in-forming relationship between that adaptation and its environment.[134] This informing relationship between parts of organisms and their world is knowledge, or biological knowledge if one prefers. Human knowledge conforms to the relational quality of fit that adaptations have. When humans come to know something, they have performed an act that is as biological as when they digest something.

Brodie (1996) addresses Plotkin's ideas on "the relational quality of fit" in adaptations by placing them in the context of "survival of the fittest," that is, "survival of the thing that's best at replicating - at having copies of itself made" (p. 68). He notes:

> 'Fitness', in evolution, means the likelihood of being copied. The 'fitter' something is, the greater its chances of being copied. The word 'fit', in our model of how evolution works, means nothing more than that. There is no connotation of strength, agility, longevity, or extraordinary intelligence. If a replicator is fit, it is good at replicating. That's all. (p. 68)

The fittest replicators make the most copies of themselves and thus become more abundant than the rest. According to Brodie (1996), "'survival of the fittest' is just a bit misleading; it's more like 'abundance of the fittest'" (p. 69). If resources are scarce, the "gain" of the fittest replicators is at the expense of the less fit.

There is one more aspect of every adaptation that must be understood. An adaptation is some form of organization of the individual phenotype relative to some feature of environmental order. Every adaptation has this dual characteristic of organismic organization and environmental order. Plotkin defines phenotype as the

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[134] Similarly, Gould asserts "evolution, in Darwin's formulation, is adaptation to changing local environments, not universal 'progress'" (p. 82). Refer to Gould, S.J. (1995). Three facets of evolution. In J. Brockman & K. Matson (Eds.). How things are: A science tool-kit for the mind. (pp. 81-86). New York: William Morrow.

organism in flesh and blood or the expression of genetic information via the processes of development (e.g., an individual human). It is this relational quality of adaptations that gives the phenotype the "appearance" of being goal- or end-directed.[135] None of these adaptations should be viewed in isolation from the environmental factors that have provided the selection pressures for them. The relational quality of adaptations is the same as the relational quality of one's knowledge.[136]

In the case of knowledge as commonly understood, the relation is between a brain state and some feature of the world. In this context, human brains are "Darwin machines," and "the way in which they gain knowledge is another form of universal Darwinism" (Plotkin, 1994, p. 53) that is fundamental to all life forms everywhere. It is noteworthy that Plotkin cites Campbell's (1987) concept of "evolutionary epistemology" as the basis for his ideas here and, in particular, Campbell's application of universal Darwinism to learning, thought and science. In a similar vein, Smith (1996) comments on the Darwinian framework used by Plotkin and Campbell, and he posits an explanation for its use in other fields. After the "new synthesis" of Darwinism and

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[135] Sanitt and Dawkins indicate the effects of evolution on an organism (the phenotype) are "best seen as an effect upon the world at large, and only incidentally upon the individual organism - or any other vehicle - in which it happens to sit" (pp. 143-144). This theory of the "extended phenotype" is found in Sanitt, N. (1996). Science as a questioning process. (pp. 143-145). Bristol, England & Philadelphia, PA: Institute of Physics.

[136] Dupre (1993) asserts any "useful" model of evolutionary epistemology must focus on the phenotype at the individual level of "interactive fitness" with the environment. This approach "dispenses with the reductionist illusion" that these processes reveal the singular "operation of hidden underlying mechanisms of the geneticist's beanbag." It is an alternative perspective to scientific thinking on this topic and it and is a potential way to avoid "burying our heads in the sand on the edge of this epistemological abyss" (p. 141).

genetics - which established natural selection as the motor of evolution - scientists and philosophers began to realize "the variation-selection-reproduction sequence that drives evolution is a powerful template for thinking about other life processes" (Smith, p. xiii). These thoughts gave rise to the concept of universal Darwinism and its potential application to a wide range of disciplines and fields of study.[137]

Plotkin (1994) develops a theory of "exaptation" that becomes a critical component of an emerging image of engineering. He states a phenotypic structure or behavior might exist and serve a function now that is different from that for which it was originally selected. In particular, an exaptation suggests an adaptation has assigned a functional requirement to a phenotypic trait that either originated as a non-adaptive feature or first evolved for some other use. In this case the adaptation might depart considerably from what an engineer would consider to be optimal design. Plotkin recognizes adaptations need not be, indeed are most often likely not to be, perfect functional solutions to current demands.They take time to form and during that time the conditions may change. Thus many adaptations may lag behind the circumstances that the current holders of the adaptations are experiencing.

Brodie (1996) views Plotkin's concept of adaptations from another perspective while questioning the fundamental link between evolution and engineering. He posits evolution "reflects the haphazard and baroque result of an ongoing struggle and not the

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[137] Using the concept of a "cognitive ladder" in interdisciplinary research, Margolis attempts to "sketch out how a continuous Darwinian path might run from the simplest forms of pattern-recognition through finely controlled habitual muscular patterns to the most sophisticated forms of reasoning" (pp. 42-43). See Margolis, H. (1987). A cognitive ladder. Patterns, thinking, and cognition: A theory of judgment. (pp. 42-62). Chicago: University of Chicago Press.

product of a brilliantly engineered design"(p. 69). He then questions this assertion:

> What's the difference between evolution and engineering? Engineering is the designing of a whole out of parts suited to their individual purpose. Evolution is the process of tiny incremental changes, each making some small or large improvement in the ability of the thing to survive and reproduce. A good engineer avoids the 'kluge' - jargon for the use of a part not particularly suited to its purpose. But evolution favors, even cherishes the kluge. Suddenly finding a new purpose for a part without significantly diminishing its old function is a staple of the evolutionary process. (p. 70)

If adaptations are instances of knowledge (and adaptations lag or often lack perfect fit), then it follows knowledge is only partial and incomplete. The relationship or relational fit between internal structure and external order is never perfect. Plotkin (1994) uses the concept of epigenesis to further describe the complex and contingent nature of adaptation. Epigenesis indicates adaptive structures are not necessarily invariant in form; sometimes they vary quite widely as a consequence of the dynamic, integrated relationship between the organism and its environment. Epigenesis lends a "developmental plasticity" (Plotkin, p. 124) to the nature of adaptations and, for Plotkin, the process of epigenesis itself becomes an important factor in adaptive or knowledge gaining devices. It allows emergence of a variety of adaptations within specific parameters.

In addition to the above considerations, one has to examine the effects of structural and historical constraints and the restrictions imposed by the actual building materials at hand. Most adaptations, therefore, are a compromise between some perfect functional solution and what can, in fact, be achieved. This "muddling through" view of adaptations is reflected in Simon's (1996) neologism, "satisficing," which means "the adoption not of optimal solutions but of practical, satisfactory ones" (pp. 28-30). Plotkin (1994) further defines "satisficing" as the adoption not of the best or optimal solution to a problem but of one that is good and satisfactory. An "it will do" solution in contrast to an "it is the best" solution (Plotkin, p. 254).

Smith (1996) proposes an evolutionary framework that bears mention here. Although it is expressed in different terms, it reflects some of the dynamics that underpin Plotkin's ideas on adaptation and exaptation. According to Smith, the principle of natural selection involves three moments. One begins with an initial stage of variation that is followed by a process of selection. In the natural world, local environmental conditions select which variants are to survive. This selection process can be viewed as a kind of filter that favors those creatures that are best able to adapt to their environment. The third stage is the reproduction of those variants that have been selected, which gives rise to a new stage of variation, and so on. If one interprets Smith's use of a "variant" as an "adaptation" or "exaptation," one can see a viable link to Plotkin's concepts. Furthermore, both Plotkin and Smith clearly imply the selection-variation process is an iterative one; a similar process is reflected in engineering design.

In sum, Plotkin (1994) argues "all adaptations are instances of knowledge and human knowledge is a special kind of adaptation" (p. 117). He sees adaptations in terms of their relational quality rather than in seeing them in terms of their contribution to survival and reproduction (or what biologists call "fitness"). He asserts researchers take too static a view of the notion of adaptations, they are too much inclined to see adaptations as the solutions of passive creatures to the dominating forces of the environment. Living creatures change the world in which they live in a variety of ways and they are in a dynamic, in-forming interaction with it. The capacity of most animals for movement, if anything, increases the dynamics of the interaction. So adaptations are not static solutions to static problems. The dynamic nature of adaptations is pervasive. And Plotkin believes it is only by casting the analysis of adaptations into the context of their relational character rather than by considering their contribution to fitness, that one can properly account for the dynamics of adaptations, and thus begin to understand adaptations as instances of knowledge. In effect, Plotkin asserts adaptation is critical to an understanding of the nature and processes of human knowledge.

Langs and the Emotion-Processing Mind

Langs (1996) outlines a comprehensive theory of the evolution of the "emotion-processing mind" that complements the epistemological notions of Plotkin (p. 179). The central propositions are derived from the broad applicability of the Darwinian principles to adaptive entities and their functioning in immediate situations. Langs extends his theory into universal Darwinism as a set of principles that apply not only to competitions and interactions between species but also to the adaptive resources within species and individuals. Langs moves beyond the simple “selfish-gene” theory in which “living organisms are merely the ‘machines’ that genes use to copy themselves into new organisms” (Lynch, 1996, p. 27). This narrow perspective attributes virtually all of the power of evolution to competition between genes for self-replication, "leaving human beings as little more than passive vehicles and gene carriers" (Langs, 1996, p. 63).

Langs (1996) attempts to determine the extent to which these universal principles apply to the operations of the emotion-processing mind; specifically, he seeks to establish a dynamic union between psychoanalysis and evolution using Plotkin's ideas as a framework. He asserts Plotkin's (1994) theory of evolutionary epistemology is the most comprehensive theory of evolution currently available and it is one that fits well with the broad issues he explores in terms of both the history of the emotion-processing mind and its present adaptive functioning. Langs notes Plotkin's theory centers on the concept of adaptations as a mode of knowledge acquisition. Furthermore, Plotkin's approach to evolutionary epistemology includes a conception of emotional adaptation based on a hierarchy of factors that contribute to the adaptive resources of human beings. Although genetic influence is considered most basic, Plotkin also includes developmental factors and both individual and culturally shared intelligence.

Langs (1996) supports his choice of Plotkin as a theoretical framework by noting Plotkin's emphasis on the equivalence between adaptation and knowledge acquisition - this establishes cognitive capacities as central to understanding the psychological adaptive resources of humans. Thus, the selection of the mental module of emotional cognition for delineating the evolution of the mind seems appropriate.

Within the framework of Plotkin's evolutionary epistemology, Langs (1996) outlines the essential evolutionary paradigm as a sequence of phases defined as "variation, test or selection, differential reproduction, and the creation of fresh variants for a new round of testing and selection" (p. 63). The principles that guide and constrain this historical sequence are understood to be relevant not only to the evolution of individuals, species, and populations, but also to many other phenomena, including the fundamental nature of current adaptations themselves. The central question for Langs is whether the emotion-processing mind can be viewed as a so-called Darwin machine. That is, is this mental module an entity - a basic human adaptive processing structure - which operates according to the Darwinian principles of evolution? Does it function according to the rules of universal Darwinism? The fitness of an adaptation - its advantages over other existing or possible adaptations - generally involves a reduction in energy needs or costs and/or an increase in supplies of energy.

All living organisms are adapted to their respective environment or "fitness landscapes" (Langs, 1996, p. 67) and they negotiate issues of survival and reproductive success within those partly stable yet ever-changing environmental conditions. In addition to these issues, all organisms must negotiate a number of other basic issues common to all life forms; these include stability versus instability; order versus disorder; simplicity versus complexity; and symmetry versus asymmetry.[138] Choices in these areas made by organisms, based on unlearned instincts or on learning and intelligence, affect the organism's fitness and survival as well as the evolutionary history of their species. The emergent attributes and properties of human beings and their adaptive armamentarium, as well as their distinctive fitness environments, speak

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[138] Lynch (1996) advances a similar conceptual basis for understanding memetics that is based on the theory of "fitness." Memes evolve by natural selection in a process similar to that of genes in evolutionary biology. What makes an idea a "potent" meme is how effectively it out-propagates other ideas in relation to the evolving environmental context in which it is situated. In memetic evolution, the "fittest" ideas are not always the truest or the most helpful but the ones best at self-replication (pp. 17-39).

for discontinuities and unprecedented adaptive capabilities seen in the human species alone - whatever their earlier and fragmentary antecedents may have been.

Like Plotkin, Langs (1996) makes a strong argument for a hierarchy of evolutionary forces. He asserts an organism's survival and adaptive capabilities depend primarily on genes and givens (instincts) that account for adaptations to slowly changing, long-term environmental events - conditions that change slowly enough to allow time for genetic alterations. However, other factors also account for evolutionary and adaptive change. These include epigenesis (development as it unfolds in a particular environment), individual cognitive structures and intelligence (phenotypes), and cultural or conspecific adaptations (socio-cultural considerations). These factors are especially critical to successful competitive adaptations in response to environmental changes that occur with some rapidity over the short term. Thus, while genes are constrained to respond to changes over the long term, individual and conjoint uses of intelligence enable humans and other organisms to respond to more sudden and unforeseen environmental happenings or "uncertain futures" (Langs, 1996, p. 69). This approach to both evolution and adaptation proposes the existence of a nested hierarchy of factors with secondary control features. Also, this layering of knowledge-acquisition mechanisms provides a broader perspective on the origins of human adaptations.

Considerable stress has been placed on the so-called environment of evolutionary adaptation, the period during which adaptive mechanisms are selected and structuralized. On the genetic level, virtually all of these choices were made hundreds of thousands of years ago during the Pleistocene era, during which savannahs and other natural settings were the locales for hominid nomadic, hunter-gatherer species and their ways of life. But this situation creates a likelihood that current genetically determined adaptations will fail to match present environmental conditions with any notable degree of effectiveness - genetic selection requires long periods of time to catch up with environmental conditions. However, the existence of additional sources of adaptive resources frees human beings from enslavement to the genetic factors in adaptation and allows for the use of human intelligence to generate better matches between contemporaneous environments and adaptive capabilities.

Hierarchical layering is essential to both Plotkin's and Langs' work with evolutionary epistemology in which adaptations are seen as an organism's ways of knowing its environment and world. A central theorem of this approach is adaptive entities that operate according to the general rules of teaming, memory, intelligence, and cognition do so by adhering to principles that are comparable to the rules of evolution. Thus, an organism's means of learning or acquiring knowledge of the environment, including aspects of emotional cognition and other mental or psychological functions operate according to the so-called evolutionary analogy or the principles of universal Darwinism - as Darwin machines.

The essential point of this proposition is captured in what Langs (1996) calls the "g-t-r (generation-test-regeneration) heuristic" (p.70) which defines the means by which an organism adapts to its environment in general, and to uncertain futures in particular. The g-t-r heuristic models all structures of adaptation that draw upon and follow evolutionary principles - it is a universal model of learning and adaptive change.

Specifically, the elements of the g-t-r heuristic are:

- the generation of variety, due largely to chance caused by mutations or variable environmental factors that occur during epigenesis
- a test phase, during which selection operates to effect the favored reproduction of adaptively successful strategies
- regeneration of the favored forms plus the introduction of new chance variants (and perhaps inventive, environmentally guided variants as well).

Heuristic strategies are hierarchically layered. The primary, fundamental heuristic is that of biological genetic development, which programs the organism selectively to know and adapt to its environment. There are also secondary heuristics that lie within the individual's phenotypes. The secondary heuristic systems include the human brain, the physical basis for human adaptation; the human mind, including its cognitive mental faculties like intelligence and language; and aspects of emotional cognition. Finally, there is a tertiary heuristic that stems from culture and the sharing of knowledge among individuals.

Hierarchies capture and help to organize the complexities of biological nature. They involve the "patterned ordering" of entities according to such criteria as scale, influence, dominance, power, functions, energy level, size, importance, and the like. One particular type of hierarchy[139] cited by Langs (1996) is the structural or nested

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[139] In reference to "nested patterns" or hierarchies, Pickover (1995) asserts the physical world "often seems chaotic, exhibiting a limitless and complex array of patterns." Yet these patterns belie highly structured, nested hierarchies in nature. From an evolutionary standpoint, biological themes, structures, and "solutions" are repeated when possible, and inanimate forms are constrained by physical laws to a finite class of patterns. The "apparently intricate fabric of nature and the universe is produced from a limited variety of threads," which are, in turn, organized into a "multitude of combinations" (p. viii).

hierarchy. It is characterized by "containment" so that one entity is nested or contained within another entity, or one entity within a system builds its functioning on the basis of another, more fundamental entity. This dependency and nesting pattern can repeat itself on as many deeper or more basic levels as actually exist in the system, until some seemingly irreducible, fundamental level is reached.[140] A crucial feature of nested hierarchies is that, in general, the more fundamental levels exert the most powerful effects and constrain the operations of the levels lying above them. That is, higher levels on a hierarchical scale are not only dependent on lower levels, but cannot violate any principle that pertains to the more fundamental levels in the hierarchy.

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[140] Sanitt states the "constantly repeating pattern of nested hierarchies" has stimulated evolution of the questioning ability in human organisms: "We understand the world through problems, and our tentative solutions are the web of questions and answers which we create" through hierarchically layered networks (pp. 81-82). Refer to Sanitt, N. (1996). Evolution and intelligence. Science as a questioning process. (pp. 81-102). Bristol, England & Philadelphia, PA: Institute of Physics.

Chapter 7: Results

Each qualitative analysis requires the researcher to "devise" his or her own technique for presenting the results. Despite some disagreements about technique, both qualitative and quantitative researchers agree the primary issue is "making sense of the data" (Rudestam & Newton, 1992, p. 113). According to Guba and Lincoln (1985), "What is at issue is the best means to 'make sense' of the data in ways that will facilitate the continuing unfolding of the inquiry, and, second, lead to a maximal understanding of the phenomenon being studied" (p. 224).

"Context charts" or bar graphs (Miles & Huberman, 1984, p. 92) are an appropriate technique for presenting the categories derived from content analysis of engineering design distillations.[141] This technique provides the reader with a visual overview of salient categories on design activity for each author. It is also an appropriate technique for making sense of the categories in the context of engineering design. In particular, it facilitates response to the "grand tour" question, what is the nature of engineering design as a human problem-solving process?

There is a bar graph for each author's distillation, and each graph has two components. First, there is a key-word-in-context (KWIC) list of categories of design activity (arranged alphabetically to facilitate location of a given category) accompanied

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[141] Miles and Huberman state bar graphs can function as "context charts" in presenting results of qualitative research. This type of graph or chart "maps in graphic form" the interrelationships among activities that make up the context of a human phenomenon under investigation (p. 92). Hicks, Rush, and Strong (1985) characterize this type of visual display as an "association map" or "schemapiric representation" of a given document (pp. 90, 104).

by a word-frequency count for each category.[142] The categories inductively derived from the KWIC and word-frequency techniques are visually displayed to illuminate salient engineering design categories for each author. Second, the categories on design activity for each author are then displayed in ascending order based on the word-frequency list. The reader is able to see the most and least salient categories on design activity for each author. In a broad sense, the categories inferentially "capture the essence" of themes and patterns of design activity.

The last graph is a visual display of dominant categories of engineering design implied by each author's salient categories. These integrated categories are presented as a KWIC list in descending order by word-frequency count. A bar graph illuminates the degree of salience for each category. The dominant categories are then displayed as a pie chart that shows the integrated KWIC list by word-frequency percentile. This particular context chart reflects the rich, "context bound" (Creswell, 1994, p. 51) categories and themes of design activity, and it reveals an emerging, holistic image of engineering design as a human problem-solving activity. As per Rudestam and Newton (1992), it represents the "current version of the researcher's map of the territory being investigated," (p.33) and it may change as the study evolves.

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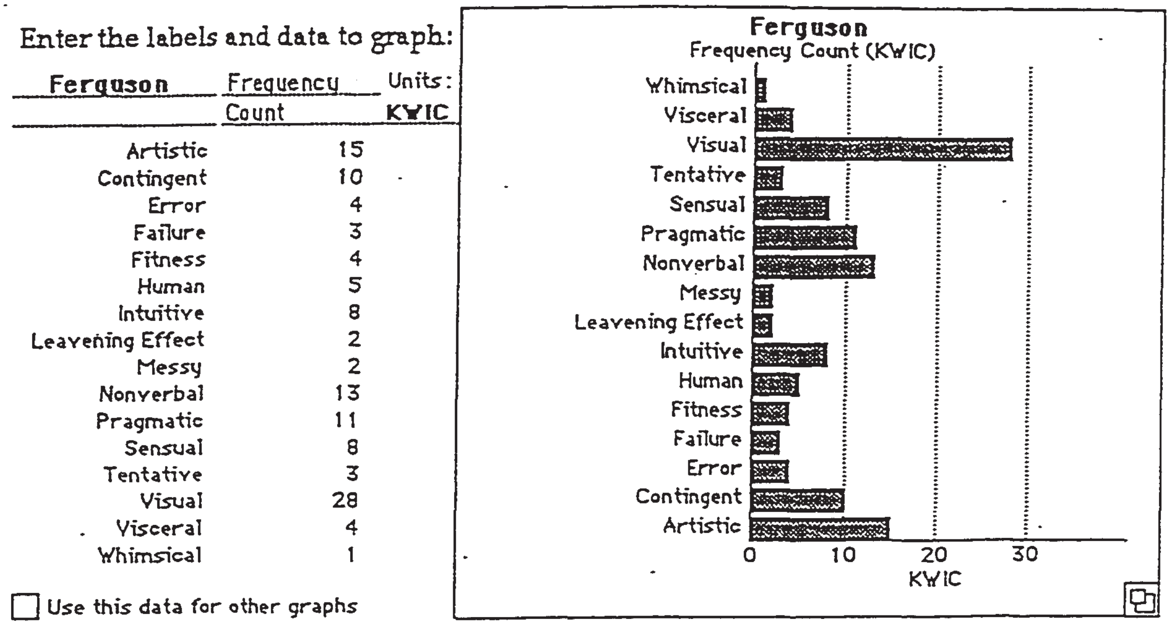
[142] The KWIC categories of design activity meet the criteria for variables in qualitative research cited by Rudestam and Newton (1992, p. 89). The categories are mutually exclusive in that no single design activity fits into more than one category, and they are exhaustive in that it is possible to eventually place each activity in one category (Guba & Lincoln, 1983, pp. 243-244). Missing values - words which are "deemed meaningless" (Hicks, Rush, & Strong, 1985, 9. 64) and which do not fit logically into meaningful categories of design activity - are accounted for in Appendix D.



Enter the labels and data to graph:

Ferguson	Frequency Count	Units: KWIC
Artistic	15	
Contingent	10	
Error	4	
Failure	3	
Fitness	4	
Human	5	
Intuitive	8	
Leavening Effect	2	
Messy	2	
Nonverbal	13	
Pragmatic	11	
Sensual	8	
Tentative	3	
Visual	28	
Visceral	4	
Whimsical	1	

☐ Use this data for other graphs

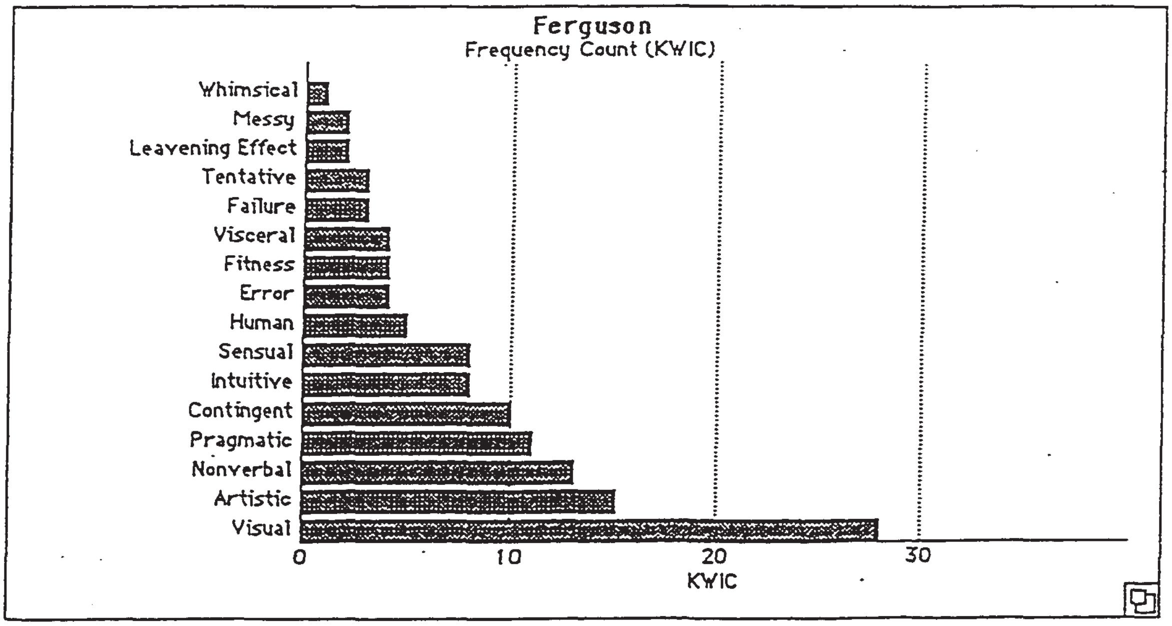
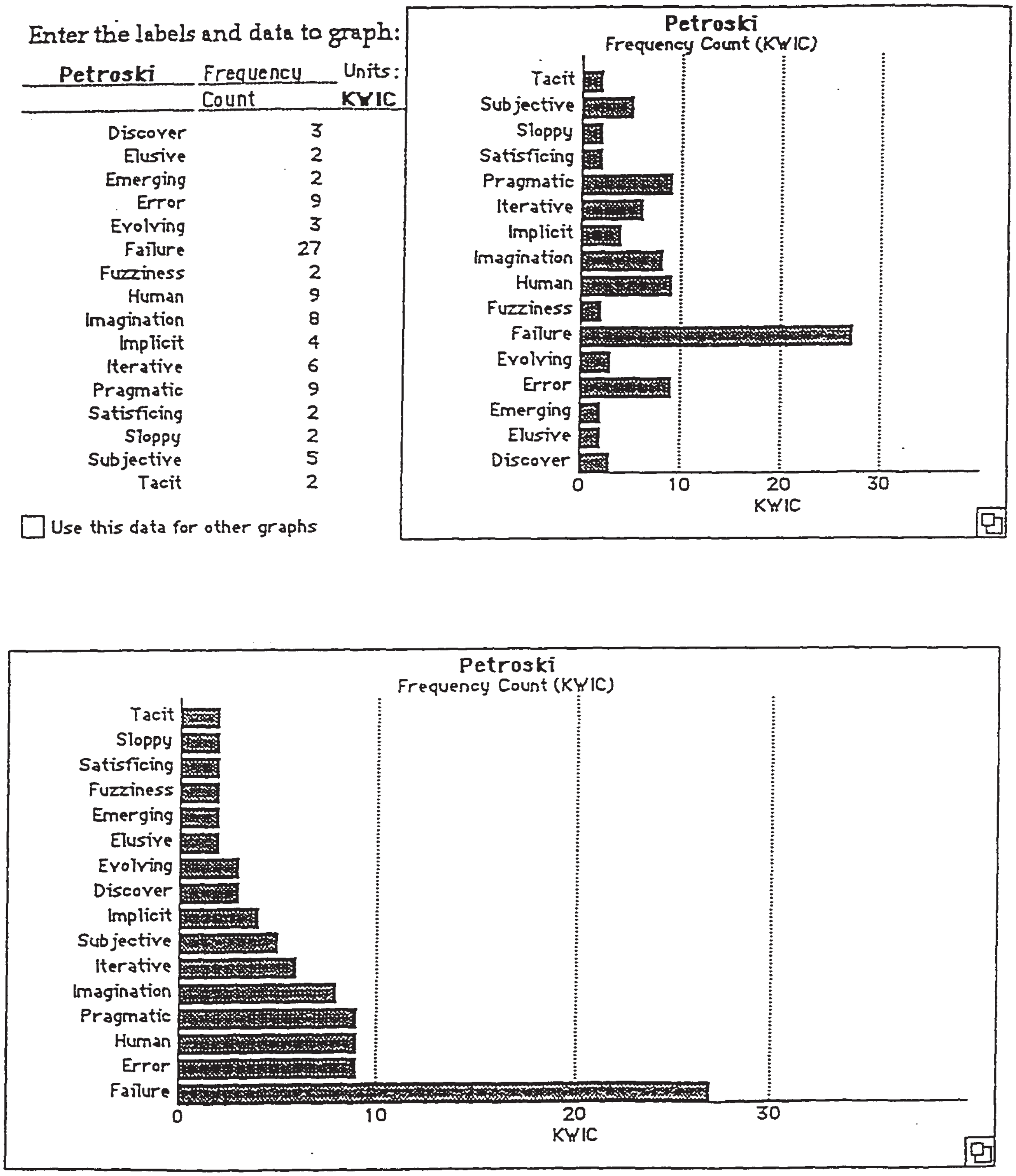


Table 1: Ferguson Content Analysis

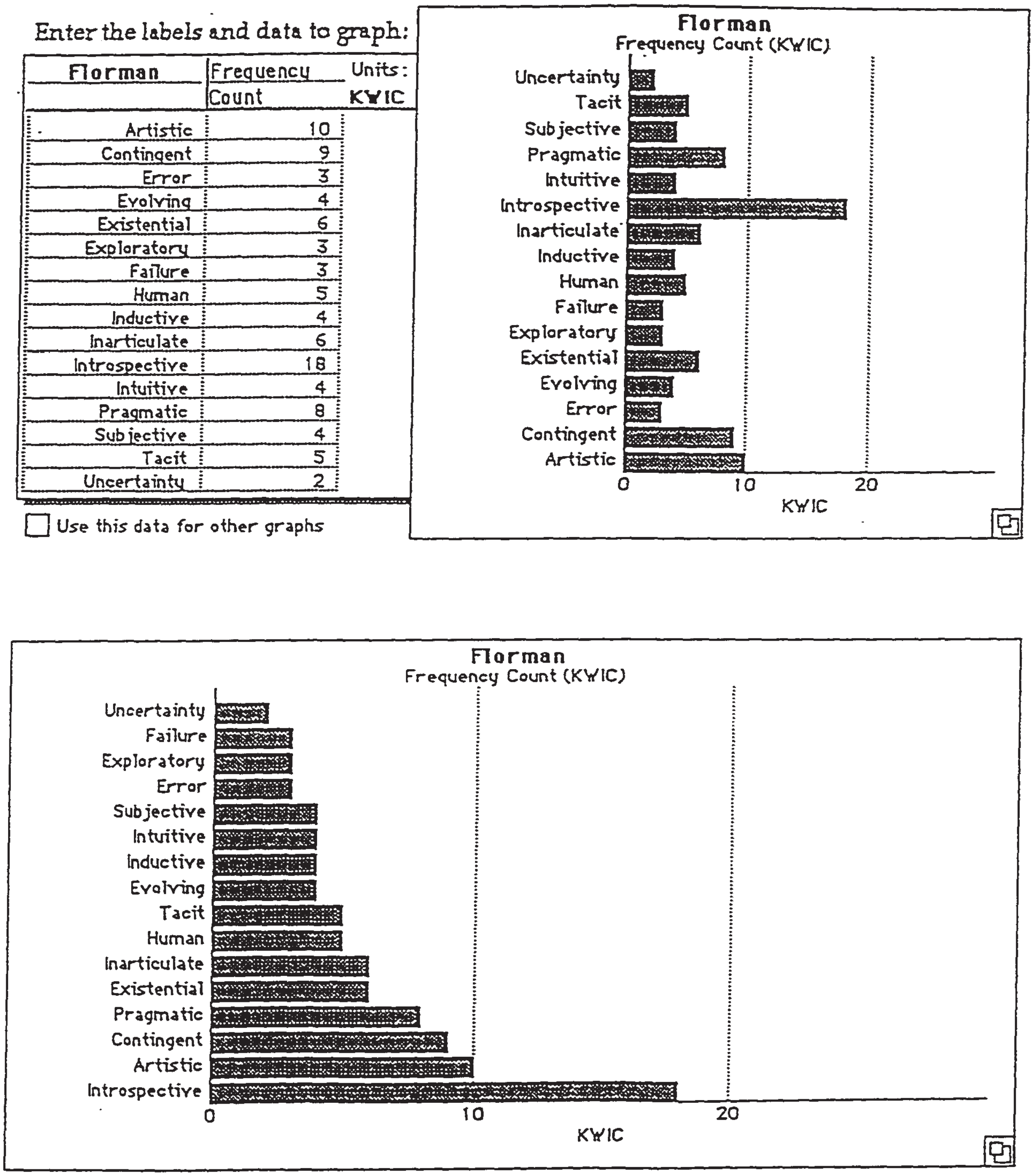


Enter the labels and data to graph:

Petroski	Frequency Count	Units: KWIC
Discover	3	
Elusive	2	
Emerging	2	
Error	9	
Evolving	3	
Failure	27	
Fuzziness	2	
Human	9	
Imagination	8	
Implicit	4	
Iterative	6	
Pragmatic	9	
Satisficing	2	
Sloppy	2	
Subjective	5	
Tacit	2	

☐ Use this data for other graphs

Table 2: Petroski Content Analysis

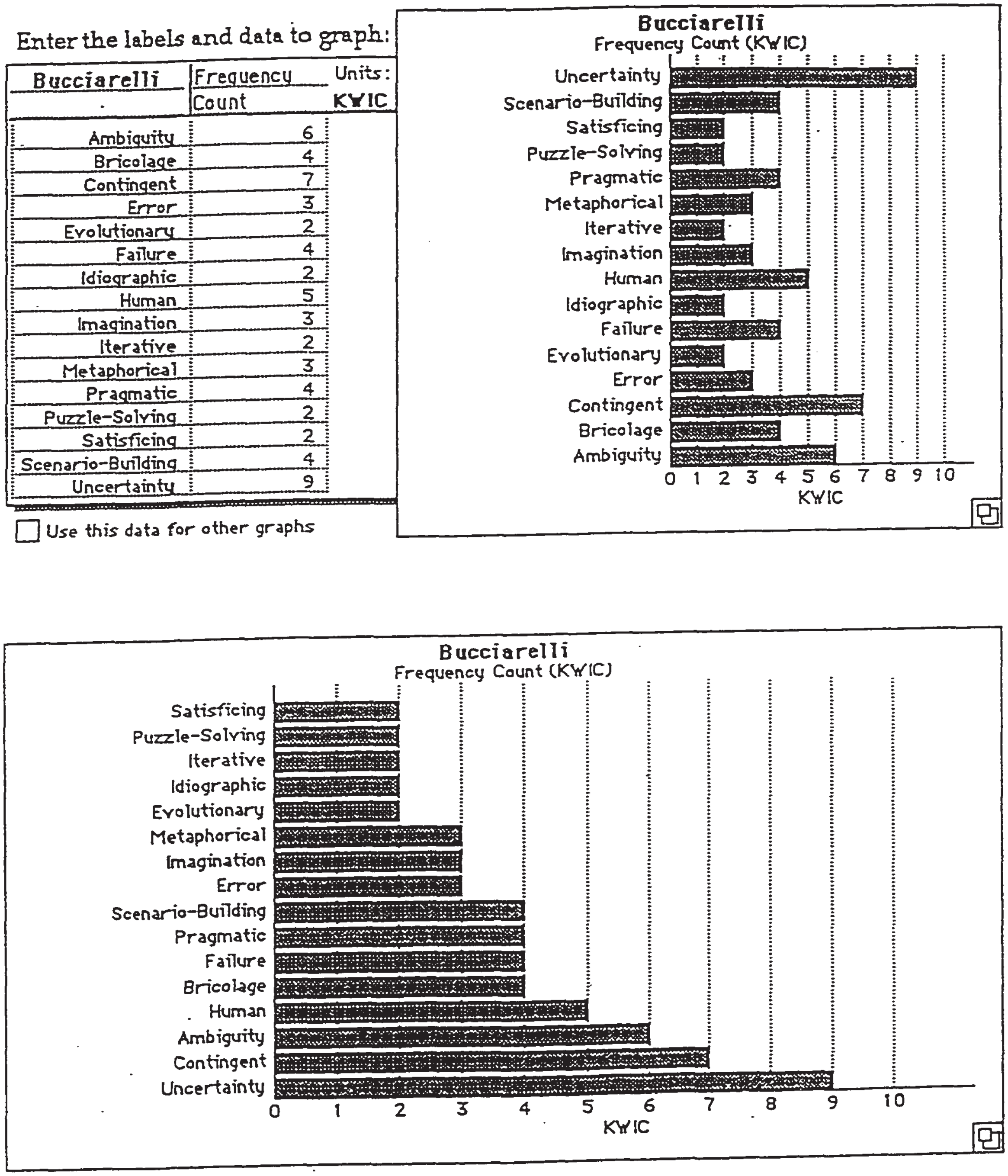


Enter the labels and data to graph:

Florman	Frequency Count	Units: KWIC
Artistic	10	
Contingent	9	
Error	3	
Evolving	4	
Existential	6	
Exploratory	3	
Failure	3	
Human	5	
Inductive	4	
Inarticulate	6	
Introspective	18	
Intuitive	4	
Pragmatic	8	
Subjective	4	
Tacit	5	
Uncertainty	2	

☐ Use this data for other graphs

Table 3: Florman Content Analysis

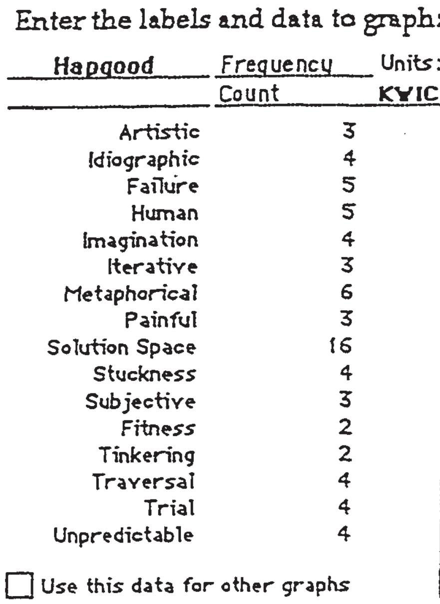


Enter the labels and data to graph:

Bucciarelli	Frequency Count	Units: KWIC
Ambiguity	6	
Bricolage	4	
Contingent	7	
Error	3	
Evolutionary	2	
Failure	4	
Idiographic	2	
Human	5	
Imagination	3	
Iterative	2	
Metaphorical	3	
Pragmatic	4	
Puzzle-Solving	2	
Satisficing	2	
Scenario-Building	4	
Uncertainty	9	

☐ Use this data for other graphs

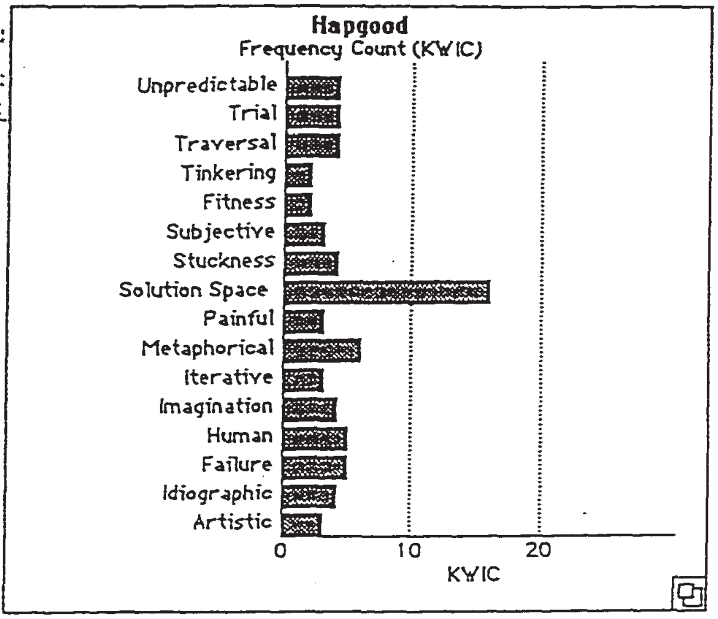
Table 4: Bucciarelli Content Analysis



Enter the labels and data to graph:

Hapgood	Frequency Count	Units: KWIC
Artistic	3	
Idiographic	4	
Failure	5	
Human	5	
Imagination	4	
Iterative	3	
Metaphorical	6	
Painful	3	
Solution Space	16	
Stuckness	4	
Subjective	3	
Fitness	2	
Tinkering	2	
Traversal	4	
Trial	4	
Unpredictable	4	

☐ Use this data for other graphs



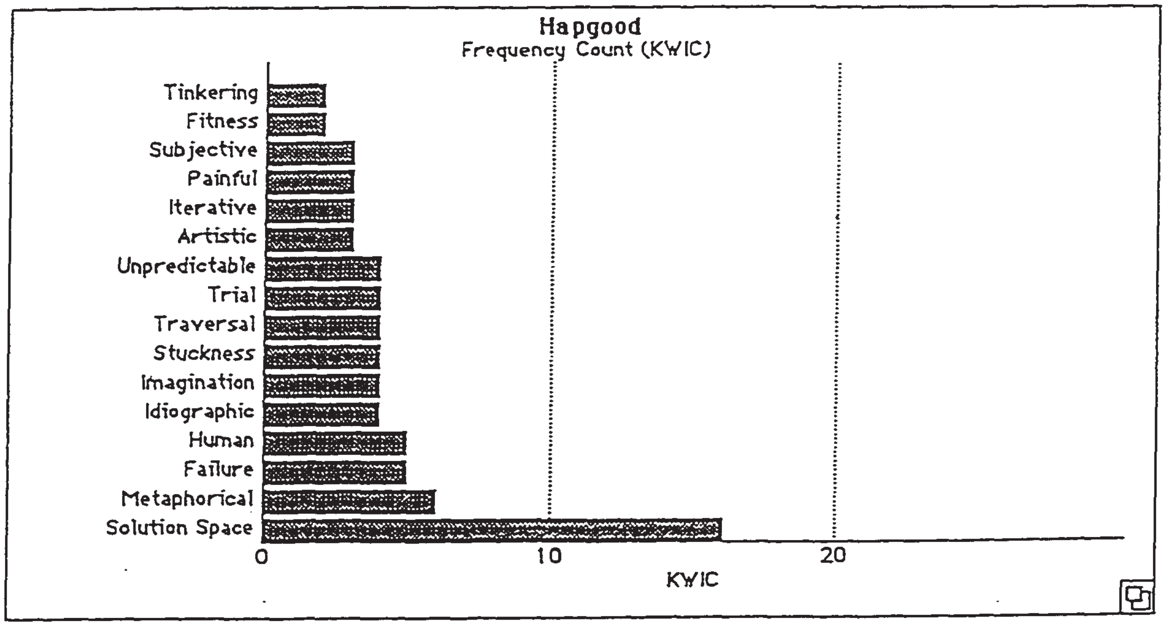
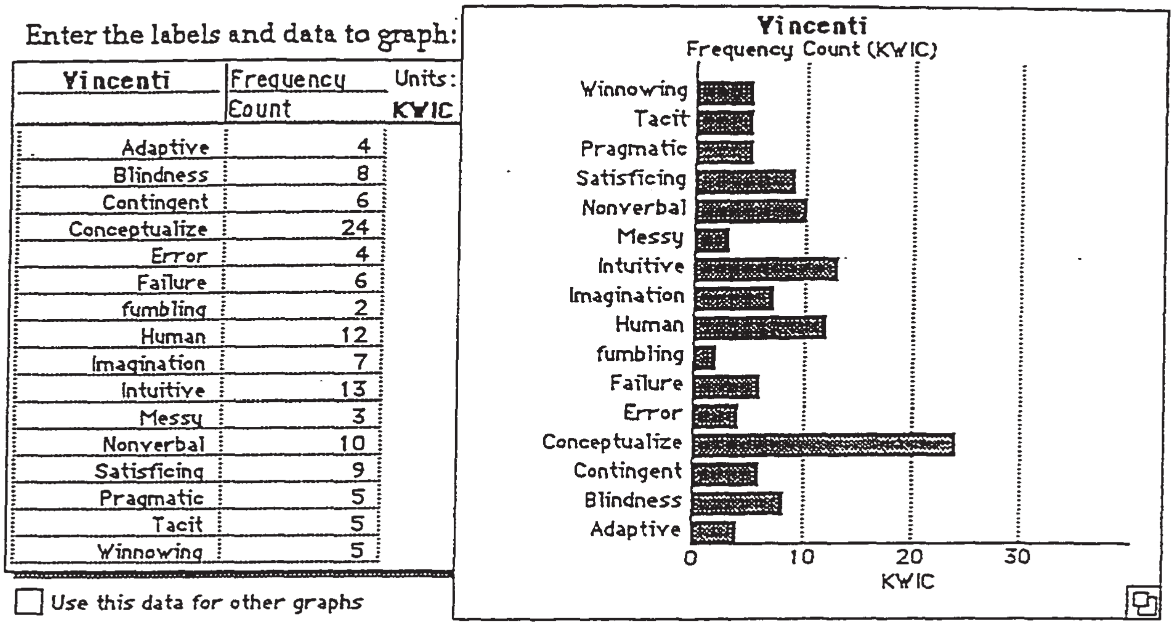


Table 5: Hapgood Content Analysis



Enter the labels and data to graph:

Vincenti	Frequency Count	Units: KWIC
Adaptive	4	
Blindness	8	
Contingent	6	
Conceptualize	24	
Error	4	
Failure	6	
fumbling	2	
Human	12	
Imagination	7	
Intuitive	13	
Messy	3	
Nonverbal	10	
Satisficing	9	
Pragmatic	5	
Tacit	5	
Winnowing	5	

☐ *Use this data for other graphs*

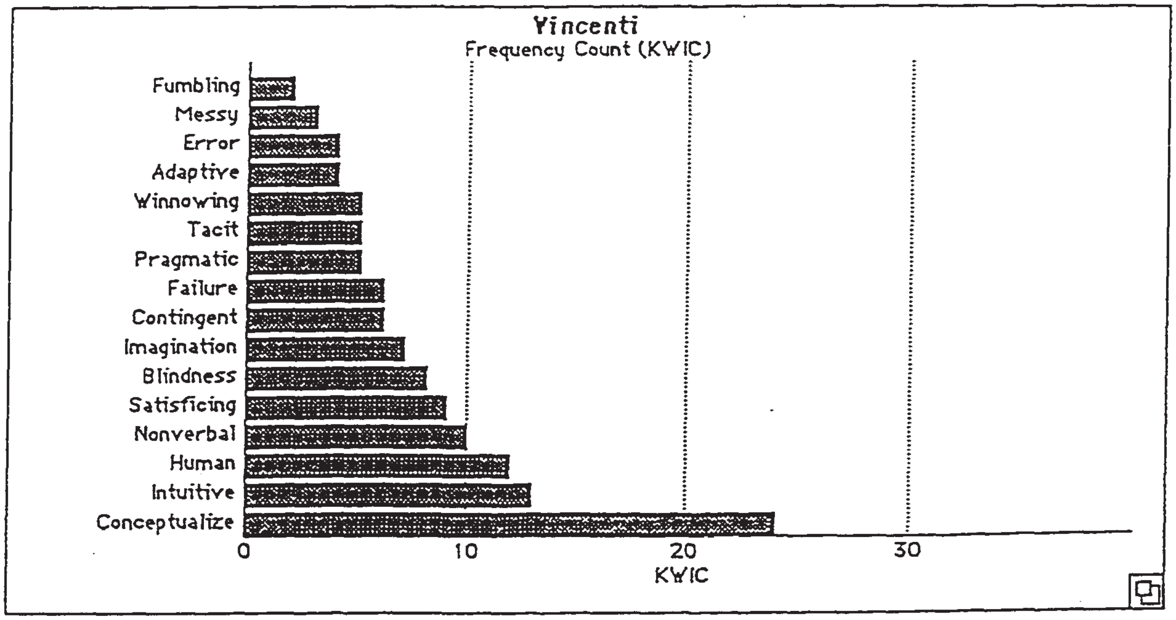
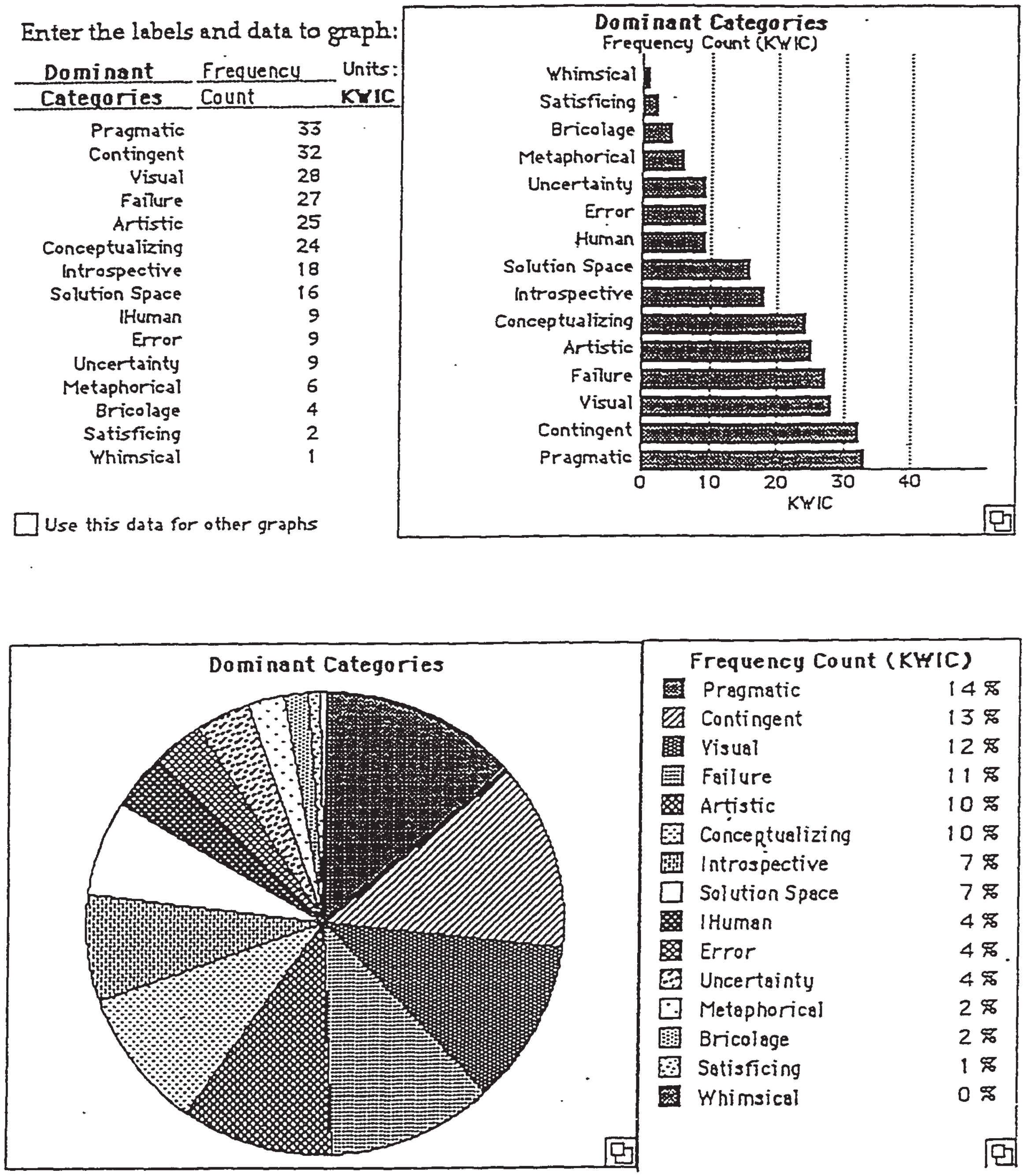


Table 6: Vincenti Content Analysis



Enter the labels and data to graph:

Dominant Categories	Frequency Count	Units: KWIC
Pragmatic	33	
Contingent	32	
Visual	28	
Failure	27	
Artistic	25	
Conceptualizing	24	
Introspective	18	
Solution Space	16	
IHuman	9	
Error	9	
Uncertainty	9	
Metaphorical	6	
Bricolage	4	
Satisficing	2	
Whimsical	1	

☐ Use this data for other graphs

Frequency Count (KWIC)

▨	Pragmatic	14 %
▨	Contingent	13 %
▨	Visual	12 %
▨	Failure	11 %
▨	Artistic	10 %
▨	Conceptualizing	10 %
▨	Introspective	7 %
□	Solution Space	7 %
▨	IHuman	4 %
▨	Error	4 %
▨	Uncertainty	4 %
▨	Metaphorical	2 %
▨	Bricolage	2 %
▨	Satisficing	1 %
▨	Whimsical	0 %

Table 7: Dominant Categories

Chapter 8: Discussion and Implications

Do the findings (salient categories and themes of design activity) "vindicate" the method selected for the study? [143] Specifically, what do these categories reveal about engineering design as a human problem solving activity? Does the research design "fit" (Creswell, 1994) the assumptions of an inductive, qualitative study of engineering design? The researcher forwards his conceptual argument on the basis of the data obtained and evaluates the extent to which the study answered the "grand tour" questions posed at the outset of the investigation.

There are no formal guidelines for discussing the results of an inductive, qualitative research design.[144] Yet Creswell (1994) and Rudestam and Newton (1992) suggest a direction that is useful for discussing the implications of findings on design activity. It is an opportunity for the researcher to "move beyond the data and to integrate creatively" (Rudestam & Newton, 1992, p. 121) the salient themes on engineering design. It is largely an exercise in inductive thinking, grappling with discovery, meaning, and understanding in the rich "context bound" (Creswell, 1994, p. 5) data of design activity. Inductive, qualitative research is exploratory; it is very much a "treasure

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[143] The notion of "vindicating" the method selected for exploring design activity was suggested by E. Camara (personal communication, April 30, 1997).

[144] Neill (1992) states it is standard practice in all social science research to include a final section in dissertations indicating other studies that are needed to advance the field. The purpose of this is to "cover the author" in two ways. First, by identifying further research, one can show one's own dissertation to be crucial to the development of the discipline. The second purpose is to "cover the author's physical and intellectual failings - the author can hide these errors and omissions under the guise of 'further research'" (p. 163).

hunt" (Rudestam & Newton, 1992, p. 124) that seeks to make sense of the emerging categories of engineering design.

The researcher allows the data and implications "to be judged on their own merits and not on [his] amplification of them" (Rudestam & Newton, 1992, p. 124). The reader will discover that the data infer impressions of design activity as a human problem solving process. In a broad sense, the findings are "conceptually informative" and address problematic issues identified in Information Science. In particular, they are a response to the gap in the "ongoing dialogue" (Marshall & Rossman, 1989, p. 89) in the field of engineering design. As substantive theory on design activity, the data or categories of engineering design can be inductively linked to a "larger explanation" or "grand theory" (Merriam, 1988, p. 94) for an "interpretive, artistic, [and] systematic" (Smith, 1987, p. 66) treatment of the phenomenon, and "for developing a story or patterns from detailed categories or themes" (Creswell, 1994, p. 44) of design activity.[145] The categories and themes imply "broader conceptual and theoretical statements" (Rudestam & Newton, 1992, p. 123) for model development in the field of engineering design.

To stimulate discussion of the findings of this inquiry, the reader may ask: "So

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[145] Van Maanen states impressionist tales or stories "typically highlight the episodic, complex, and ambivalent realities that are frozen and perhaps made too pat and ordered by realist or confessional conventions." Impressionist stories, "with their silent disavowal of grand theorizing, their radical grasping for the particular, eventful, contextual, and unusual, contain an important message. They protest the ultimate superficiality of much of the published research in social science - ethnographic or otherwise" (p. 118). Refer to Van Maanen, J. (1988). Impressionist tales. In Tales of the field: On writing ethnography (pp. 101-124). Chicago: University of Chicago Press.

what" (Rudestam & Newton, 1992, p. 12) for engineering design? If the researcher allows the data "to speak for themselves" (Weber, 1990, p. 62), what do they imply about design activity? The categories derived from content analysis of the distillations make "explicit certain entities" (Marr, 1980, p. 20) or salient themes of design activity by each author.[146] Specifically, each author reveals categories or themes that suggest a "tentative conceptual framework" (Creswell, 1994, p. 97) for engineering design. What "explicit entities" does each author contribute to an emerging "pattern of interconnected thoughts [for] making sense" (Neuman, 1991, p. 38) of design activity? What contextual themes infer “thick description” (Rudestam & Newton, 1992, p. 39) for a substantive theory of engineering design?

Ferguson (1992) perceives engineering design as a highly visual, artistic, and nonverbal process involving pragmatic and contingent themes. One sees an intuitive and sensual image of design activity. Human error and failure in design activity are placed in a rich context of intuitive, visceral, and even “messy” activities. The process is further characterized by whimsical, erratic, and unpredictable patterns of behavior. Ferguson suggests engineers often reach tentative solutions to problems; this essentially involves a relational fit between solution and problem characterized by a leavening effect in design activity.

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[146] Krippendorff refers to emerging patterns or themes as "illuminating configurations" (personal communication, April 28, 1997) whereas Creswell (1994) calls them "meaningful data chunks" (p. 167). Berelson (1971) cites a "purely pragmatic" criterion for identifying "latent" categories from inductive content analysis. He asks: “Are the categories ‘useful’ in suggesting relationships within the context of an emerging conceptual framework?” (pp. 170-171).

For Petroski (1985, 1989), human failure (or error) is a dominant theme in a pragmatic, iterative, and subjective context involving the engineer's imagination. The engineer engages in an emerging, discovery process that often leads to satisficing solutions to problems. It is a design context characterized by sloppy and somewhat fuzzy categories of activity. The themes of design activity are highlighted by tacit and implicit qualities that are elusive in nature to the engineer who experiences them.

Hapgood (1993) describes engineering design as a metaphorical traversal through solution space in which explicit themes of human failure, imagination, and stuckness surround design activities. It is an idiographic and unpredictable experience that often involves a painful series of trials or iterations in solution space. The engineer is seen as a tinkerer who engages in activities within an artistic and subjective context.

According to Florman (1994), the salient themes of design activity are tacit; they are often difficult for the engineer to articulate. Design context is an introspective, artistic activity that is fundamentally pragmatic and contingent. Florman reveals it as a human process shaped by evolving existential patterns within an inductive and intuitive framework. This subjective process is highlighted by evolving themes of uncertainty, failure, and error.

Bucciarelli (1994) interprets design activity as a contingent problem solving process characterized by a high salience or degree of uncertainty. The engineer as bricoleur uses scenario-building techniques in an evolving context of ambiguity. Human failure and error come into play as the engineer searches for a pragmatic, satisficing solution to problems. This is an idiographic task, a metaphorical and imaginative process, an iterative technique forming a bricolage as a tentative solution.

From Vincenti's (1990) perspective, engineering design is a highly conceptual and intuitive human technique shaped by contingent and pragmatic categories of activity that are tacit and nonverbal in nature. The engineer often engages blindly in a design context, adaptively using imagination, failure, and error in a mental winnowing process to achieve satisficing solutions to problems. Vincenti suggests engineering design is sometimes an overtly messy, fumbling activity.

Each author contributes "meaning" and "understanding" (Creswell, 1994, p. 145) to an emerging image of design activity. Yet these salient themes provide a "fragmented framing" (Entman, 1993, p. 51) or "contingent" perspective (Creswell, 1994, p. 22) of engineering design. Integration or "re-contextualization" of the salient frames (or dominant categories) "results in a higher level of analysis [by providing] a larger, more consolidated picture " (Tesch, 1990, p. 97) of this phenomenon. It reveals an emerging, holistic image of design activity as a human problem solving process that is explicitly pragmatic, contingent, and visual in character. The integrated themes imply the design engineer's engagement in solution space is a highly introspective and conceptual activity stimulated by instances of failure, error, and uncertainty. In a metaphorical sense, the engineer acts simultaneously as artist and bricoleur to discover satisficing solutions to problems. A salient pattern of “whimsical” activity suggests an underlying sense of humor in engineering design.

The integrated themes are the "vehicle that [inductively] communicate" (Miles & Huberman, 1984, p. 24) an emerging, substantive theory of design activity to the researcher. Yet how does one move from "substantive theory" or "thick description" of engineering design to a "larger explanation" or "grand theory" (Merriam, 1988, p. 94) for interpreting this human phenomenon? What "interpretive, artistic" grand theory can the researcher use to create a visual model of design activity? How does one "systematically" model a "context bound" substantive theory of engineering design?

Blair (1990) cites two possible alternatives for developing a model of design. The researcher could adopt Nagel's (1979) scientific theory as an interpretive, systematic "grand theory" (Merriam, 1988, p. 94) and use its "abstract calculus" and "operational principles" (Nagel, 1979, p. 83) to develop a model of design activity. This scientifically assumptive formula would compel the researcher to develop a list of attributes that define a normal scientific model (such as Nagel's) and then use them to systematically interpret design activity. The researcher could cite those scientific qualities or categories that engineering design lacks and then propose means to remedy the lack of fit between engineering activity and the scientific model. The researcher could "upgrade" [147] the themes of engineering design so that they match the attributes of

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[147] Why does Blair even consider a scientific "stance" for interpreting data on engineering design? Why must one feel compelled to scientifically "legitimize" the categories of design activity? Blair questions the fundamental nature of Information Retrieval from a scientific perspective and wonders if the field is a "legitimate science" (1990, p. 277). Perhaps Blair feels compelled to respond to the "compulsive force" (Fleck, 1975, p. 39) of a "prevailing" positivist epistemology in the field (Harris, 1986, p. 529). Even Machlup and Mansfield (1983) note the "guilt feelings" and "inferiority complex" researchers experience when their research designs do not garner the "honorific designation" of "hard" science (p. 13).

an objective, rational scientific model.Does this sequential, linear approach fit the assumptions of an inductive, qualitative study of design activity? Does it respond to the impressions of engineering design as a human problem solving activity? What entities of design activity are illuminated or made explicit (or indeed, overlooked) by this technique? Does it allow for "artistic" interpretation of the phenomenon?

Shortland (1981) challenges Nagel's scientific assumptions and asserts his theory is "ambiguous, confused and lacks precision" for application to any given field of study, not to mention engineering design. He further asserts "the trouble with Nagel is not so much with what he examines as in the serious things he has left unexamined" (p. 475). For Shortland, the "greatest danger" lies in Nagels' assumptions about use of scientific theory as a basis for generating models in the social sciences. He cautions against adopting "arbitrary and incoherent" approaches "that imply a strong, positivist orientation in their line of inquiry" (Shortland, pp. 476-477).

Blair (1990) agrees Nagel's "straightforward" theory may serve as "symbolic generalizations or operational definitions" (p. 279) for developing models in natural sciences, but finds it inappropriate for inductively generating a model of design activity. Nagels' theory is a powerful "thought style" that "predetermines what researchers think they see" (p. 282) by exerting a "compulsive force upon their thinking" (Fleck, 1975, p. 39). It unconsciously frames the way researchers interpret the phenomenon of engineering design by deluding them “into thinking that they see pure facts in a reality unadulterated by preconceptions" (Blair, 1990, p. 281). Nagel assumes facts are objective and context free. According to Blair, they are not. Facts or data are "intimately connected to an endless number of other facts" and they achieve degrees of "salience" or distinction only within the context of a model that emphasizes some aspects of a given phenomenon over others (Blair, pp. 281-282).

Kahneman and Tversky (1984) further suggest the implications of using scientific theories or frames to generate a model of engineering design. Framing as a technique selects and illuminates some feature of reality while omitting others. In other words, while frames may call attention to particular aspects of the phenomenon of design activity, they simultaneously, and logically, direct attention away form other aspects. Most frames are defined by what they omit as well as include, and the omissions of potential problem definitions, interpretations, and solutions may be as critical as the inclusions in guiding the researcher. In addition, Edelman (1993) notes the character of any given phenomenon becomes "radically different as changes are made in what is prominently displayed, what is repressed and especially in how observations are classified" (p. 232). Engineering design can be viewed as a "kaleidoscope of potential realities, any of which can be readily evoked by altering the ways in which observations are framed and categorized" (Endelman, p. 232).

Weber (1990) asserts a traditional, positivist approach such as Nagel's often "overlooks or misses" data derived from inductive use of content analysis (p. 52). In addition, it "tends to destroy semantic coherence ... making interpretation extremely difficult, if not impossible" in qualitative designs (p. 43). The "rich" substantive theory that implies a model of engineering design in a human context "may not surface" (Creswell, 1994, p. 7) or find an opportunity for expression in Nagel's scientific definition for models.

Ferguson (1992) argues Nagel's scientific "formula" attempts to frame engineering design as a formal, sequential process that is deductive in nature. Design activity is defined as a step-by-step process (diagram) of discrete, linear segments which, if followed according to Nagel's prescribed rules, leads to predictable outcomes. For Ferguson, this static approach inevitably leads to other "block diagrams" (Appendix C) of engineering design. It overlooks or misses salient themes (and categories) of design activity that emerge from inductive content analysis of engineering distillations.

Blair's (1990) argument for a model of engineering design grounded (embedded) in "perspicuous examples" of design activity does not fit the positivist assumptions of Nagel. The "growing undercurrent of urgency" (Blair, p. viii) for new, alternative models of engineering design becomes "unthinkable and unimaginable" in a strong positivist "thought style" (Fleck, 1975, p. 39). Thus, Blair remains a "Pickwickian prisoner" (Popper, 1970. p. 56), caught in the framework of the "older language" and unable to break out of it to propose a new, more appropriate model or metaphor for translating design activity. So too, Laudan's (1984) "apologia" for more appropriate theoretical models in engineering cannot be "translated with validity" (Weber, 1990, p. 78) into Nagel's straightforward definition. For Laudan, model building remains "embryonic" and "locked inside an impenetrable black box" of technology (p. 1).

In a broader sense, Harris' (1986) use of "extended argument" to stimulate models for problem solving in Information Science finds no dialectical expression in Nagel's scientific framework. There is no opportunity to generate alternative models to challenge the "prevailing" positivist epistemology in the field. Thus, the "dialectic of defeat" is sustained through "scientistic delusion" and "ludicrous misapplication" of positivist technique (Harris, 1986, pp. 515, 529).

Guba and Lincoln (1985) and Creswell (1994) caution researchers concerning "lack of fit" between purpose, approach, and theory in qualitative designs. According to the authors, the "lack of fit" becomes clearly evident when "findings and implications seem to make no apparent sense in light of the original questions" (Guba & Lincoln, 1985, p. 226). A scientific interpretation of themes of design activity makes "no apparent sense" in light of engineering design as a human problem solving process. In addition, a scientific technique, such as Nagel's, is not appropriate for inductively developing an emerging model of engineering design based on "thick descriptions" of engineering distillations. Engineering has been "barking up the wrong metaphor" by attempting to adopt a scientific model of design activity.

Blair (1990) suggests an alternative approach for developing a potential model of engineering design. It is based on the "perspicuous examples" in which design activity is embedded. His notion of perspicuous examples fits the assumptions of themes inductively derived from "thick description" or "context bound" substantive theory of engineering design. Sniderman, Brody, and Tetlock (1991) would characterize

Blair's thoughts on design activity as a "potential counterframing" of the topic (p. 52). The authors argue a rigid, scientific model constrains and inhibits any attempts at counterframing engineering design. Similarly, Machlup and Mansfield (1983) assert "indoctrination with an outmoded philosophy of science, with persuasive (propagandist) definitions of science and scientific method" is a "mischievous" (p.13) practice that precludes development of creative counterframing techniques.

Yet counterframing can provide the researcher with alternative ways of thinking about design activity and, perhaps more importantly, they stimulate alternative perspectives for viewing problem definition, interpretation, and solution within the rich context of engineering design. For Trenn and Merton (1976), these alternative modes of thinking are the "counterframes" that challenge a thought collective's normative assumptions on design activity. They are a potential source for generating alternative "pathways of thought" that can extend beyond the "perceptual dissonance" and "intrinsic constraint" of a "dominant metaphorical thought style" (pp. 158-160).

How does the researcher advance a "potential" counterframing of design activity that will enable him to be "more spontaneous and flexible" in exploring an emerging model of this human phenomenon? How can he elaborate a "countervailing trend"[148] that "calls for sidestepping the artificiality and narrowness" (Rudestam & Newton,

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[148] Slater offers an initial response to this question. He cites the need to develop theory and models in the social sciences from an inductive, qualitative stance. He exhorts researchers to begin this effort by "picking over the detritus and shards" of data overlooked by scientific methods. Slater hints at a rather "eclectic conceptual montage" for generating models "derived from neglected avenues of exploration" (p. 101). Refer to Slater, P.F. (1967). Microcosm. New York: John Wiley.

1992, pp. 29, 32) of Nagel's scientific formula? Smith's (1987) reference to an "interpretive, artistic, [and] systematic" (p. 66) treatment of human phenomena suggests a viable path for counterframing engineering design. It is an inductive, exploratory approach that involves taking "risks inherent in an ambiguous procedure"; it allows the "biases, values, and judgment of the researcher" to come into play (Creswell, 1994, pp. 4-5, 10). Yet it is this subjective mode of inquiry that stimulates "nondirectional thinking"[149] about a potential counterframing model. It focuses on elaboration of a "systematic" schema of design activity and then extends to "artistic interpretation" of engineering design themes within the context of this tentative conceptual framework.

The researcher inductively generated tentative models of design activity simultaneously with data collection and analysis. This "reflexive" technique involves the "speculations, feelings, problems, ideas, hunches, impressions, and prejudices" of the researcher (Bogdan & Biklen, 1992, p. 121).[150] Further, it is a "trial-and-error" process in which the researcher moved between the themes or "substantive theory" of engineering design and a "grand theory" (Guba and Lincoln, 1983, p. 245) for interpreting an emerging model of the phenomenon.

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[149] Creswell (1994) contrasts "nondirectional thinking" in inductive, qualitative designs with the "directional" thought style prevalent in deductive, quantitative techniques. The nondirectional approach conveys the language of an emerging design of research (i.e., it seeks to explore, discover, describe, and understand the nature of engineering design) (p. 71).

[150] Damasio characterizes this type of mental, problem-solving activity as "hunches pack decisive punches." He further asserts "You gotta know when to hold'em, know when to fold'em - but keep in mind that an ounce of intuition trumps a pound of pondering, hands down" (183). See Damasio, A. R. (1997). Behavior. Science News, 151,183.

What are the architectural impressions of an emerging model of design activity? Are there conceptual blueprints that can provide a “glimpse” of this evolving configuration? Mintzberg, Bohm, and Black advance ideas for systematically shaping a model of design activity. In particular, Mintzberg (1994) asserts researchers who attempt to model human problem solving activity often emphasize only one salient aspect of the phenomenon. "Heeding the advice of any one of these researchers" must of necessity lead to a "lopsided" perspective on problem solving as a human activity. Mintzberg stresses it is critical to "show all components" of a model in a single integrated diagram. Only in this way can scholars understand the "richness" of this human phenomenon. Also, it reminds scholars "at a glance" of the various components of a model of human activity cannot be "conceptually separated" (pp. 21-22). [151]

Mintzberg (1995) advances thoughts on constructing a model:

> I think there is something to the fact that the model preceded the text. What matters in developing theory about human activity, in my opinion, is not so much the fully articulated text as the comprehensive representation of the model. People need to 'see' the various dimensions that appear to constitute the phenomenon all in one place. That way, they can begin to discuss human activity comprehensively and interactively. I found this to be true as I started to use the model to develop the theory, and when I drew the diagram on a napkin at dinner one evening. (p. 363).

Mintzberg's (1995) model emerged within an informal context and preceded any textual articulation of underlying theory. The researcher's model of design activity emerged from dominant themes of engineering design before a textual

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[151] Mintzberg's reference to researchers' "lopsided" view of human problem solving activity is reflected in the "fragmented frames" or distillations on engineering design.

narrative or interpretive script was developed. The systematic structuring of the model's physical impressions or visual outlay were probed before an artistic interpretation evolved. A structural impression or visual outlay of a model of design activity emerged before an interpretive script was articulated by the researcher.

A schema for an integrated model of engineering design was systematically elaborated from the "inside out," beginning with the "core values" of design activity and then inductively working out from there, "layer by layer" (Mintzberg, 1994, p. 12).[152] With the core values of design activity at the focal point of the model, the researcher could bring into consideration the "milieu" ("thick description" or "rich context") in which these particular values are embedded. The core values act as "a kind of magnet" that holds the rest of the emerging model together, while the themes of design activity are integrated around a framework of concentric circles. The circles act a "permeable membrane" that stimulates "inner flow" among the themes of engineering design while allowing "outer flow" (Mintzberg, 1994, pp. 11-22) with the external environment.

Bohm's (1980) theory of the rheomode (or language) for expressing "undivided wholeness in flowing movement" (p. xv) suggested an impression of elliptical instead of concentric circles surrounding design activity. The spontaneous, undefinable nature of these circles "create a new structure that is not so prone to fragmentation" (Bohm, p. 31) as traditional models based on concentric formats.

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[152] Mintzberg (personal communication, March 1, 1996) affirms his thoughts on how to model human activity as an "evolving" phenomenon were shaped by his experiences as a doctoral student at the Sloan School of Management at MIT. In particular, his ideas for an "integrated" model "all came together, quite literally so in a framework of concentric circles."

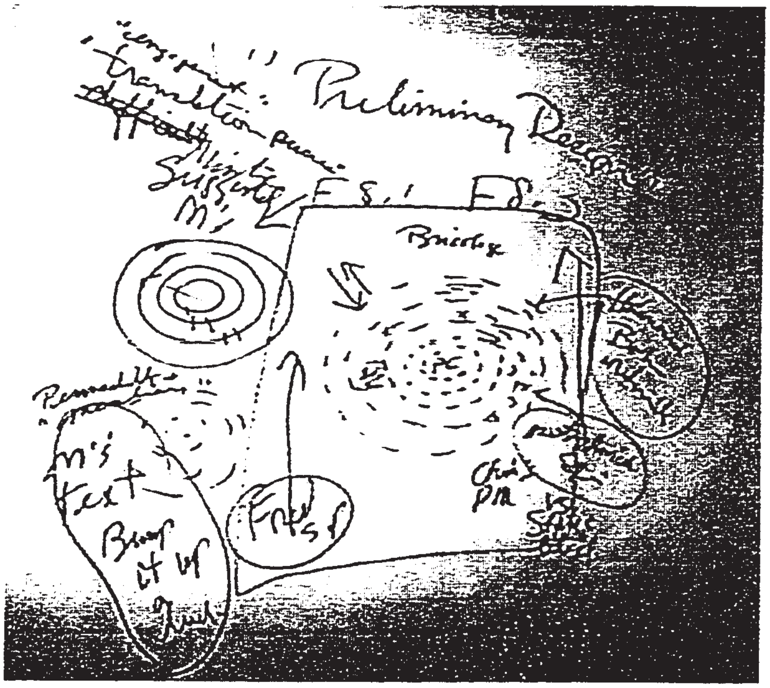

Figure 5. The emerging schema for the researcher's model is seen here in its visual and messy form.

The circles reflect the active, verbal nature of human problem solving activity and "relevate" or lift up salient themes of design activity for the researcher. The holomovement configuration "implies an unrestricted breadth and depth of meaning, that is not fixed within static limits" (Bohm, p. 35). It relevates or makes explicit the "whole implicate or enfolded order" (Bohm, p. 154) of engineering design.

After exploring Mintzberg's and Bohm's criteria for systematically structuring the design model, the researcher discovered a potential avenue for artistic interpretation of the phenomenon. Black (1962) asserts all intellectual pursuits, including development of theoretical models, "rely firmly upon the imagination" (p. 242) of the researcher. The "heart of the method consists in 'talking' in a certain way [and seeing] new connections" for "rich, speculative" (Black, pp. 228-237) interpretation.

A dominant principle for a model of engineering design at this point is "isomorphism," the degree to which an artistic interpretation of the model can accurately capture the dominant themes of design activity. If a model is indeed a "heuristic fiction" (Black, p. 228) that points to a potential mode of interpretation, what is the artistic interpretation that can yield a "rich, speculative" narrative or script for describing engineering design?

According to Weber (1990), "time, effort, skill, and art [153] are required to

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[153] Hicks, Rush, and Strong (1985) state the researcher's "imagination" is the driving force that stimulates the creative art of interpretation in inductive, content analysis techniques (p. 102). They consider the interpretive process a "practical art form ... motivated by the requirements of particular problem solving" (p. 478).

produce results, interpretations, and explanations that are theoretically 'interesting'" (p. 69) for engineering design. Weber further suggests :

> interpretation is in part an art. Those who naively believe that data or texts speak for themselves (the doctrine of radical empiricism) are mistaken. The content analyst contributes factual and theoretical knowledge to the interpretation.... It is not the validity of an interpretation per se that is at issue, but rather the 'salience' of an interpretation given one or another theory. Just as it is true that quantitative data do not speak for themselves (i.e., that the doctrine of radical empiricism is false), so is it true that texts do not speak for themselves either. The investigator must do the speaking and the language of that speech is the language of theory [and model development]. (pp. 79-80)

The "salience" of an interpretation of engineering design must of necessity be derived from the dominant themes of design activity, that is, from the pragmatic and contingent themes of engineering design. Cahoone (personal communication, May 1, 1997) stated pragmatic and contingent patterns of engineering design as a human problem solving process are "conceptually promising clues" to an emerging postmodern interpretation of design activity. In addition, the perspective of engineer as bricoleur would provide the narrative text or supportive script for a visual model in this context. Rorty (personal communication, January 6, 1997) indicated a model of engineering design interpreted through a postmodern lens of pragmatics and contingency would be an "interesting" concept.[154]

The pragmatic and contingent themes of design activity are the core values for

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[154] Denzin implies a postmodern or postfoundational approach is appropriate for interpreting the "messy" data derived from qualitative research designs. This approach "embraces" critical interpretations that are "always incomplete, personal, self-reflexive, and resistant to totalizing theories" (p. 183). Refer to Denzin, N.K. (1995). Messy methods for communication research. Journal of Communication, 45 (2), 177-184.

an artistic interpretation of engineering design - they are the "magnetic core" that holds the other themes of design activity together. The engineer as bricoleur engages in design activities that are contingent upon the type of resources he/she may have on hand. The engineer's method is an "emergent construction" (Weinstein & Weinstein, 1991, p. 161) that takes new forms as “different tools, methods, and techniques are added to the puzzle” (Lincoln & Denzin, 1996, p.2). In a context of ambiguity, paradox, and dissonance, the engineer as bricoleur understands solutions shaped by patterns of error and uncertainty. Apparent failure signals opportunity for "retooling." If new tools have to be invented, or pieced together, then the engineer will do this. "Like the bricoleurs of Levi-Strauss," engineers often create solutions to problems with "makeshift equipment, spare parts, and assemblage" (Lincoln & Denzin, 1996, p. 584). Which tools to use and where to move in solution space are not always set in advance.

The engineer is adept at intensive introspection that is sometimes characterized by whimsical patterns of behavior. The product of the engineer's labor is a bricolage, an artistic, "reflexive, collagelike creation" (Lincoln & Denzin, 1996, p. 3) that metaphorically represents the engineer's understandings and interpretations of human problem solving. Bricolage is a pragmatic,[155] practical solution to a problem, often a satisficing, less than optimal solution that works in a given design context.

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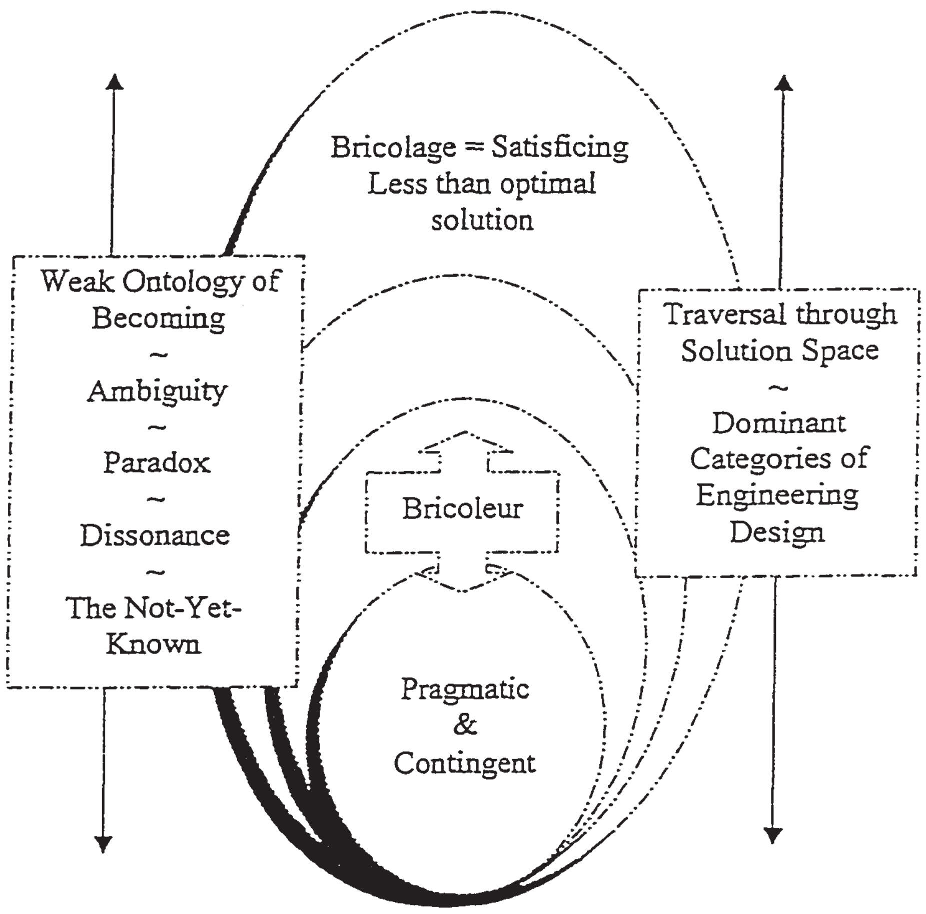
[155] Gaggi (1989) asserts "only to the extent that a later theory is better at solving problems - that is, only to the extent that it is pragmatic - can it be regarded as an improvement over earlier theories." He further asserts "the improved problem-solving ability of later theories is not a result of their more closely approximating the truth but rather of different environments" (p. 52). Gaggi, S. (1989). Modern/postmodern: A study in twentieth-century arts and ideas. Philadelphia, PA: University of Pennsylvania Press.

From within the field, Wilson (1977) has called for "a reorientation toward the functional rather than topical or disciplinary" (p. 120) in the organization and representation of documents; this shift is "one that explicitly recognizes the primacy of the need to bring knowledge to the point of use" (p. 120) in problem solution in Information Retrieval and Information Science. The "growing undercurrent of urgency" (Blair, 1990, p. viii) imposed by the technological explosion echoes Wilson's ideas and provides impetus to look beyond the traditional, positivist approach to problem solution. Wilson further asserts :

> the final test of the adequacy of decisions is in the consequences. If we are happy, or at least satisfied, with the results of our decisions, we have no cause to complain about the antecedents of those decisions, including the information supply on which they were based. If events turn out well, in our eyes, then we have no basis for criticism of our role in bringing about the events or of the information supply we used. (1977, p. 68)

Following the positivist mode of thinking leaves no avenues to address the problems cited by Harris (1986), Blair (1990), and Laudan (1984). Indeed, there is an increasing sense of "incredulity" in the ability of a "legitimized scientific metanarrative" to solve these problems (Lyotard, 1979, pp. xxiv, 27). Wittgenstein's (1968) "perspicuous examples" are the critical link to understanding that information seeking is a pragmatic and contingent activity. Florman (1996) states engineers are experiencing a "heightened level of awareness" that there are alternative modes for problem solving based on perspicuous examples of engineering design.



The "Engineer as Bricoleur" Story

Resistive Future Imperfect vs. Reactive Illusion of Past Perfect

Figure 6. A Model of Engineering Design in Its Current Instantiation

Postmodernism gives expression to some of these emerging modes of thinking. In particular, Foster (1985) illuminates the postmodern context that is appropriate for a model of engineering design as a human problem solving activity. The "reactive" postmodern approach to problem solving involves "recycling old and discarded concepts - it deals in claimed certainties, 'the perfection of the past' or the 'past-perfect' - even though the past to which it refers is not the actual past but merely a nostalgic illusion of it." (p. 36)[156]

In contrast, the "resistive" version of postmodernism "deals with the real uncertainties of the world, 'the imperfect future' or 'future-imperfect.'" Whereas reactive postmodernism can never offer more than more of the same thing recycled, resistive postmodernism does at least offer the possibility of a "radically new understanding" of problem solution in a human context (Jackson & Carter, 1992, p. 16). Resistive postmodernism "inescapably presents itself as a new language" that can de-center the "albatross of scientific rationality" for problem solution (Foster, 1985, pp. 13).

A resistive postmodern perspective involves the "fundamental questioning of a totalizing rationality based on science" (Jackson & Carter, 1992, p. 12). It illuminates potential problem solving methods that "a dominant modernist style of thinking pushed into the shadows" (L. Cahoone, personal communication, May 1, 1997).

Engineering, perhaps surprisingly, provides a substantive manifestation of

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[156] Similarly, Foucault states a reactive postmodern approach ignores the knowledge that it is an illusion that the past can ever be known, let alone certain. Refer to Foucault, M. (1972). The archeology of knowledge. (A.M. Sheridan-Smith, Trans.). London: Tavistock.

resistive postmodern sensibilities. It “seeks not to recycle old [scientific] concepts” (Carter & Jackson, 1992, p. 16) as a reactive response to problem solution; instead, it is a resistive approach that explores the possibility of redefining the language and models of solution space. Engineering design, as a reflection of human activity and as a problem solving epistemological entity freed from positivist assumptions, offers a means for getting us to “the right train station” and for determining which train to board.

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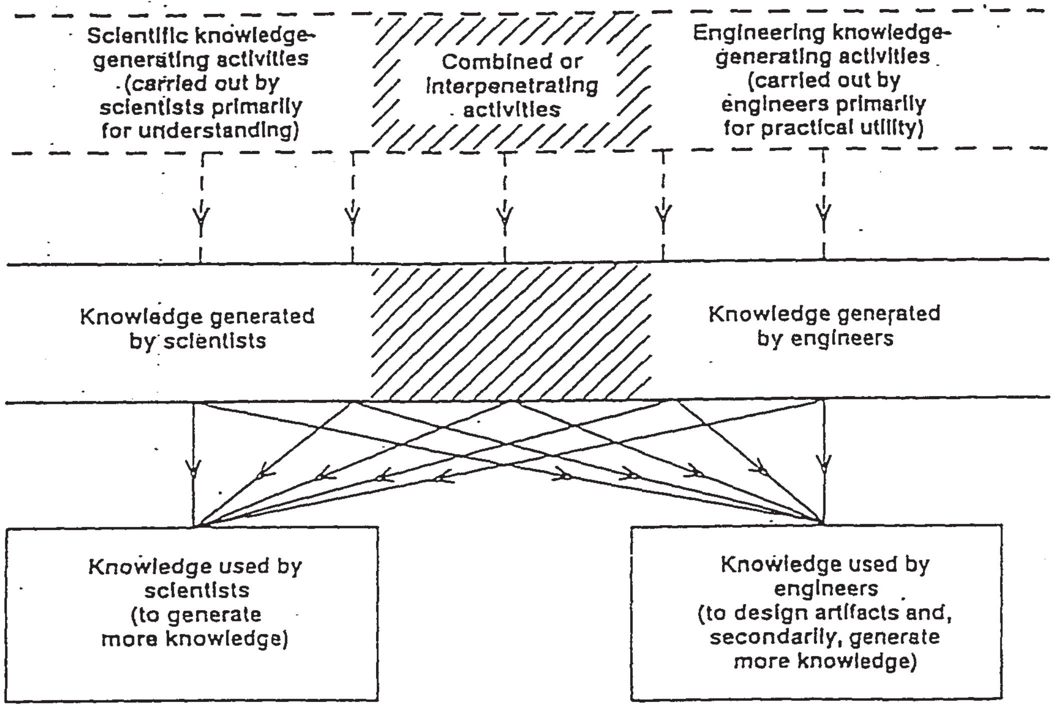
Appendix A: Vincenti on Engineering Knowledge

What Engineers Know and How They Know It



WALTER G. VINCENTI

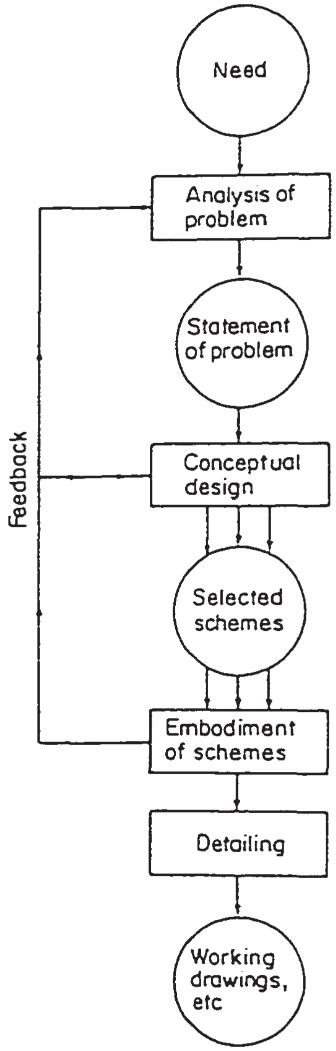
What Engineers Know
and How They Know It

Analytical Studies from
Aeronautical History

Appendix B: Anatomy of Design Knowledge

Categories Activities	Fundamental design concepts	Criteria and specifications	Theoretical tools	Quantitative data	Practical considerations	Design instrumentalities
Transfer from science			X	X		
Invention	X					
Theoretical engineering research	X	X	X	X		X
Experimental engineering research	X	X	X	X		X
Design practice		X			X	X
Production				X	X	X
Direct trial (including operation)	X	X	X	X	X	X

Appendix C: Sample Block Diagram

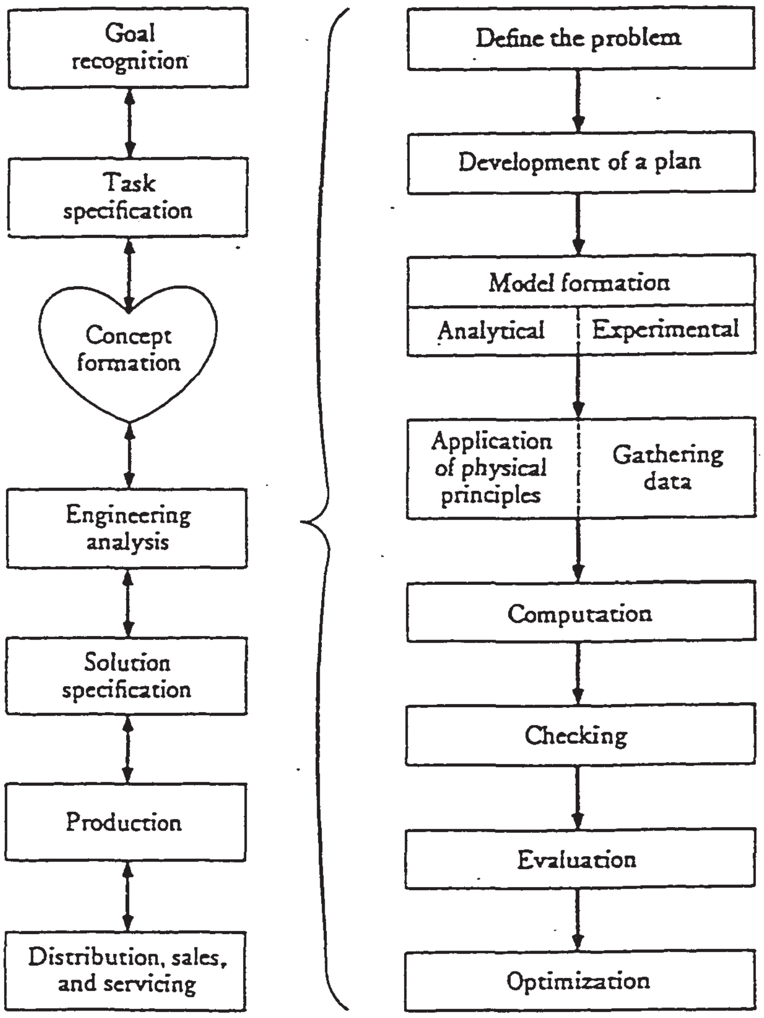


A block diagram (which many people call a flow diagram) embodies the engineering conviction that any problem can be solved if only it can be broken down into enough parts, or steps. This diagram illustrates M. J. French's idealization of the design process.

Appendix D: Content Analysis Stop List

```
DATA the,a,can,may,of,in,with,and,without,get,is,are
DATA The,May,A, Is, Are, Were, Because,Will,If,Let, For, Most
DATA Be, While, An, Between,Had, How, It, Also,On,One, Some
DATA There, This, Typically, Usually, What, Which, All, Our, Not
DATA be, were, because, will, if, let, or,  for, I, most, out,
until
DATA Within, Up, Would, These, But,Routinely, Often, Another
DATA Now, Their, We, When, After, Always, He
DATA while, an, any, been, between, by, cannot, do, etc,
far,faster
DATA from, given, had, has, have, how, it, also, might, more,
much
DATA no, on, one, other, same, some, than, that, them, there,
this
DATA to, too, two, typically, usually, what, which, all, our, as,
per
DATA well, so, at, again, merely, use,recently,over
DATA even, whether, however, along, upon, particular, therefore,
unless
DATA they, ought,not,within,up,whole,would, these,but, its, each
DATA require, could,yet, routinely,often, very,large,
numerous,recent
DATA another, little, almost, thus,among, currently, indeed,
many, now
DATA we,when, about,after,always,easily,generally,good, greatly
DATA he, hence,highly,his,hisher,her,into,just,latest,likely
DATA must,ones,only,put,says,
should,something,their,then,thing,those
DATA three,totally,where,whereas,you,your,youre
DATA Rd, OF, ON, OR,Needless, No,My,Mr,Mrs, MY,IN,His,Her, Ave,At
DATA am,became,being,did,him,me,my,she,us,who
DATA BoldHP,IIPHPLASIIP,ItalicCourier,LaserJet,
PRSxtEyXXdxxxxXXxxxxvxNhMXHxxxx
DATA
WPCfBJZxCourier,cpiCourier,cpi,Each,both,first,make,through,wXnd
DATA
Dr,was,shall,depends,mere,affords,thee,yield,especially,seeks,con
fer,receive
DATA
rather,resulted,suggested,commenced,partly,Other,proceeded,exist
DATA contains,
affect,chief,means,existing,nor,following,whatever,additional
DATA
begun,principally,laid,passed,around,occasionally,ourselves,happe
ned,whom,ever
DATA
To,th,arrived,here,already,towards,gives,become,try,preceding
DATA
every,hitherto,Its,seeming,never,before,You,made,early,fix,began,
mine,effected
```

Appendix E: Bucciarelli's Design Model



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Signature of Author

October 28, 1997
Date

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John Schwenn
Dean of Graduate Studies and Research

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