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A Study of Similarity and Analogical Decision-Making in Collaborative Design

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A STUDY OF SIMILARITY AND ANALOGICAL DECISION-MAKING IN COLLABORATIVE DESIGN

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ABSTRACT

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The purpose of this study is to investigate the role of similarity and analogy in design communication and propose a descriptive representation of the analogical decision-making process in the context of engineering design. It is proposed that social, cultural, and contextual knowledge are brought to bear on statements of need in the form of analogy as a means to elicit and evince potential design solutions. A goal of this study is to identify communicative behaviors, representing process variables of analogical decision-making, that can be used to describe how design information is represented, manipulated, and conveyed in a collaborative design effort.

An observational and interactional analysis methodology is used to qualitatively examine communication and analogical decision making processes in collaborative design. Specifically, the methodology systematically identifies and describes communicative behaviors that occur in analogic discourse. An in-depth examination of verbal and nonverbal behaviors, observed in the design activities of a group of experienced

engineers, is performed to identify communicative behaviors that elicit or act on design information. A qualitative assessment of these behaviors in design discourse is made to support the development of a descriptive representation of analogical decision making. These behaviors are then applied as a coding scheme to recorded conversational data and are analyzed using the lag sequential analysis method to identify reoccurring patterns of communication and interaction in analogical decision making.

Qualitative assessments from this study indicate that a plethora of design knowledge and worldly experiences were used to satisfy explicitly stated or perceived needs. It was observed that technical and engineering knowledge, general knowledge gained through personal experiences, and fantastical projections are elements of analogic discourse. It was observed that communicative behaviors associated with analogical decision making facilitated the transformation of design information into new design requirements, heuristics, or design solutions. These behaviors included: requirement queries; and statements of comparison, proposition, confirmation, control, and held/acquired knowledge. Results from this study indicate that if these communicative behaviors are defined as acts that transform design information from one state to another, they can be analyzed stochastically to reveal patterns of communication and interaction. Cyclic dependencies among communicative behaviors, determined by the lag sequential analysis method, suggest that reoccurring patterns of communication exist in analogy discourse. These communication patterns suggest that analogical decision making can be viewed as a communication system.

It is concluded that the process of analogical decision making involves: the establishment of a context in which analogy discourse occurs; the selection, tailoring, and confirmation of potential solution sets which are

articulated as analogues and analogue attributes; and the derivation of either design requirements, heuristics, or physical descriptions and representations.

DEDICATION

I dedicate this work to Patricia, my wife and best friend.

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CHAPTER 1

INTRODUCTION

Purpose

The purpose of this study is to investigate the use of similarity and analogy in design communication and propose a descriptive representation of the analogical decision-making process in the context of engineering design. It is proposed that social, cultural, and contextual knowledge are brought to bear on statements of need in the form of analogy as a means to elicit and evince potential design solutions. A goal of this study is to identify salient aspects of design communication, representing process variables of analogical decision-making, that can be used to describe how design information is represented, manipulated, and conveyed in a collaborative design effort.

Background

As superintendent of the gardens at Chatsworth of England, Joseph Paxton demonstrated the inherent strength of the *Victoria amazonica* lily by placing his daughter on the giant water lily. Geometric patterns formed by ribs and cross-ribs on the underside of the floating lily provided the necessary strength and stiffness to support and keep afloat the load imposed by his daughter's weight. It was the observed structural relationship between intercostal leaf segments, ribs, and cross-ribs that Paxton used to design and construct the Crystal Palace for the First International Exhibition and World's

Fair of 1851[1]. This structure consisting of 60,000 cubic feet of timber, 4500 tons of wrought iron and 30,000 panes of glass, arranged to support static and dynamic loads imposed by the anticipated number of spectators, enclosed nearly 19 acres of London's Hyde Park and housed over 100,000 exhibits.

Paxton's design of the Crystal Palace illustrates one example of the role of similarity and analogy in engineering design. Analogy is recognized by researchers in the cognitive sciences and educational psychology as a tool for building, combining, and developing ideas, leading to creative solutions for unfamilar or complex concepts. Brunel's concept of submerged cassions which was based on observations of boring ship worms and used by Washington Roebling to lay foundations for the Brooklyn Bridge (Cross, 1989), Archimedes' bath-taking experience that provided him with an approach to determine the volume of a tyrant's gold crown (Keane, 1988), and Paxton's design of the Crystal Palace are examples of analogical reasoning that characteristically represent a transfer of relational and relevent information from conceptually different but familar domains (commonly referred to in the cognitive sciences as the *base* domain) to domains to be explained (the *target* domain). Vosniadon and Ortong (1989) propose the following as a general process of analogical reasoning:

1. Access to an appropriate analogue which implies that there exists a perceived similarity between the base and target domains.
2. Correspondences made between domain properties and a transfer of relational structures.

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[1] A historical discussion on Joseph Paxton's design of the Crystal Palace is provided in *To Engineer is Human* by Henry Petroski, 1985.

3. The generation of general rules, heuristics, or representations.

Such a process might describe how analogy facilitates the acquisition of new knowledge, and in the context of engineering design, the derivation of potential design solutions.

Even though analogy is recognized for its efficacy in creative thinking, it is not without shortcomings. Spiro et al. (1989) argued that simple analogies are prone to hinder a more complete and fuller understanding if not lead to complete misunderstanding of newly presented concepts. They attribute this to what they refer to as the "reductive force" of analogy which acts to oversimplify knowledge by "seducing learners into reducing complex concepts to a simpler and more familar analogical core" (pg. 498). Spiro contends that when analogies are used to effectuate a preliminary understanding of complex concepts, the resulting incomplete representation, incomplete because not all relational aspects of a *base* domain are transferable to a *target* domain, often remains as the only representation used in understanding the target concept. As Spiro points out, "....when analogies are used to "start simple," the knowledge ultimately acquired often *stays* simple."

Spiro et al. investigated analogy-induced misconceptions held by medical students and determined that the instructional use of analogies led to, in some instances, misunderstanding of physiological concepts that resulted from either inadequate, misleading, incorrect overextensions or ommissions of information from the source domain. For example, the "rowing crew" analogy used by instructors to describe the contractile mechanics of muscle fibers conveyed erroneously that force-producing muscle components act in synchrony. Spiro concluded that knowledge

acquired about a topic (the target domain) is often represented only by the information mapped by the analogy from the source domain.

Unfortunately, the "reductive force" of analogy can be traced to failures in engineering design. Petroski (1982) suggested that a source of human error that resulted in the collapse of the suspended walkways at the Hyatt Hotel in Kansas City was the perceive *redundancy* of new structural details that lead to a false sense of security. The original structural details, changed by the contractor to provide a more producible design, significantly altered the load distribution which eventually caused the connections to fail under the weight of hotel guests. It is proposed from the perspective of this study that the construct of redundancy, commonly applied in engineering to obviate complete system failure resulting from a single failure point, was erroneously applied analogically in the development of the new details. Even though the number of structural elements was increased, which might be considered as a *superficial* aspect of redundancy, the *relational* aspect that defines redundancy, i.e., that each element functions to support another reciprocally, was not applied in the development of the new details. As a result, the complete failure of the walkway system occurred from the failure of a single structural element which was forced to carry the entire weight of the walkways and hotel guests. Petroski referred to this example as an error in design logic and is perhaps, from an analogical perspective, more descriptively an error in analogical reasoning.

Consider another example that Petroski (1991) suggests illustrates a *misunderstanding of principles of scale,* one paradigm for human error in engineering design. Renaissance shipbuilders attempting to build larger ships, found that scaling-up the design of smaller ships based on proven rules of geometry led to the immediate failure of larger ship hulls upon launching.

It was not until Galileo showed that while a ship's weight increased by the cube of its dimensions and its hull strength increased only by the square, that Renaissance shipbuilders were able to successfully design and launch ships of larger size. This example not only illustrates an oversimplification of the problem at hand through analogy, but also illustrates how principles from one domain were inappropriately mapped to another, even though both domains appeared logically similar.

The decision to investigate the role of similarity and analogy in collaborative design resulted from an interest to understand how engineers construct design information and how they convey this information to other engineers. If failures in engineering design, such as those previously discussed, are attributable to errors in analogy, then it becomes worth while to examine the process of analogical decision making in a collaborative setting. The goal of this study is to obtain a better understanding of the role of similarity and analogy in collaborative design, how similarities and analogies are communicated and acted upon to support the design evolution of a final artifact. This study does not focus on the cognitive analogical processes of individuals, rather it focuses on communication processes that characterize the analogical decision-making of groups in a collaborative design effort.

Chapter Organization and Overview

Chapter Two reviews literature pertinent to the development of a framework for this study. This framework is based on three perspectives. The first is a communication perspective of design, which views design as a social process where communication plays an organizing and supporting role. The second is a systemic perspective on group communication and decision making. The assumption is that a communication system consists of

reoccurring and recognizable patterns of interactions which are influenced by the occurrence of communicative behaviors. Therefore, analogical decision making, if viewed as a communication process, should be observable and amenable to analysis. The final perspective considers analogy as a means to combine multiple perspectives and language systems that facilitate the activity of designing. To develop this perspective, two dominant theories of analogical reasoning are reviewed. Chapter Two concludes by identifying research objectives of this study.

Chapter Three describes the research methodology that is used to develop a descriptive representation of analogical decision making in collaborative design. The methodology encompasses an observational and qualitative approach to identify and describe salient behaviors of design communication that represent process variables of analogical decision making. These process variables are then used to develop a representation of analogical decision making. The final two chapters, Chapters 4 and 5, discuss the analysis and results, and conclusions of the study.

CHAPTER 2

THEORETICAL BACKGROUND AND LITERATURE REVIEW

Perspectives on Engineering Design, Group Decision Making, and Analogical Decision Making

The contemporary study of engineering design can be considered to follow two broad avenues. The first focuses on *what* designers design resulting in methodologies and tools that facilitate the analysis of physical systems and the decision making of the designer. Boothroyd's *Design for Assembly* methodology (Boothroyd and Dewhurst, 1987), which is used to minimize assembly costs within constraints imposed by other design requirements, and Taguchi's statistical approach, which is used to minimize less-than-optimal part interactions caused by external factors such as manufacturing process variation, operation, and environmental effects (Phadke, 1989), are examples of tools that aid the pursuit of optimal designs.

Suh (1990) argues that these tools do not support a theory of design and proposes an axiomatic approach that defines basic principles for design analysis and decision making. Suh's approach is based on the perspective that design consists of the mapping of a functional space to a physical space, facilitated by design axioms that represents basic principles of analysis and decision making. This axiomatic approach results in criteria for judging the "goodness" of a proposed design solution based on the degree of independence of functional requirements (the *Independence Axiom*) and the degree of information required to satisfy functional requirements (the

Information Axiom). According to Suh's approach, an ultimate design is represented by a functionally uncoupled design that has a minimum of information content.

The second avenue taken in the study of engineering design is concerned with the *activity* of designing, and represents the direction of this study. This avenue attempts to determine what is it that designers do when they design and how the activity of designing is accomplished. For example, Akin (1986), Erersley (1988), and Chan (1990) used a protocol analysis methodology to explore cognitive mechanisms, and problem solving and search strategies used by designers to solve a variety of design exercises. Based on an information processing model, Akin identified 15 heuristic rules designers use in reducing the complexity of design problems. In addition, using Problem Behavioral Graphs (PBG) and primitive problem solving processes proposed by Newell (1972), Akin was able to identify problem solving sequences used by individual designers.

In theoretical explorations of design, Cross (1986) argued that design is a distinctive form of human intelligence. Cross suggested that design is predicated on non-verbal codes or languages and design competence is associated "with the acquisition and manipulation of non-verbal codes which exist within the material culture" (p. 14). Goldberg and Costa (in Cross, 1986) proposed relationships between thought processes, cognitive strategies, and appropriate language systems. They suggest that there are three types of codes that are involved in design cognition:

1. Natural Languages which are shared by all members of a given speech community.

2. Codes which develop as individual or individuals engage in new task.
3. Codes communicated through special notations and are culturally dependent and acquired through use and communication.

Citing work from Van Sommers (1984), Cross proposed that designers have a kind of graphic intelligence that assists in exploring the semantic content of a given task. Van Sommers illustrated how the meaning of a representation affects the strategy by which it is produced, linking drawing and sketching to the semantics of a particular task.

These studies, however, are primarily focused on cognitive processes of individual designers. An alternative view point is that design is not limited to any individual designer, but is instead a social process requiring the contributions of many designers and engineers in a collaborative effort. From this perspective, Weeks and Steier (1992) propose that the practice of engineering includes more than detailed analyses and drawings, but also the maintenance of certain traditions, beliefs, and values. This perspective suggests that design is a social process where communication plays a supporting and organizing role. It is proposed that engineers of various backgrounds, with respect to discipline and product culture, employ a variety of symbols, acronyms, words, phases, allegories, sketches, drawings, computer images, etc., to describe and communicate numerous physical aspects of a single artifact. Their multiple representations facilitate not only the design efforts of individuals, but also serve to coordinate design activities of multiple engineers. Schon (1988) concluded from observations of design activities:

> "An architect, contractor, structural engineer, a user of the building each operates within a world, a design world of their own with its own language, its own rules, for understanding the design. In the case of an architect, the design is composed of formal elements and functions (edge, boundary, zone, for example) and the rules are expressible in such terms as "implication", "consistency", "stability", "intensify", and the like. In the case of a building contractor the design is a system of building processes, and its rules are related to efficiency of construction, maintenance or management, operations onmaterials, ease of handling, time to complete and the like. In the case of the structural engineer, the design is a building understood as a frame structure subject to physical forces, a structure described in terms of its stability, load-carrying capacity, factors of safety." (p. 56)

This suggests then, where a collaboration of multiple language systems is required to support the development of a final artifact, that within a design process there exist design cultures based on past knowledge, experiences, design idiosyncrasies, heuristics, and value judgments of the participants. However language differences among these design cultures may influence communication patterns and the effectiveness of collaborative design activities. Sarbaugh (1988) proposed that interlocutors with similar world views, normative patterns, code systems, and perceived relationship and intent, experience less difficulty when communicating than those dissimilar in these attributes. This suggests that the ability of a design team to simultaneously consider multiple aspects of a design may depend on how well a shared understanding is developed of not necessarily specific technical requirements (syntactic descriptions), but of experiences, engineering assumptions, value judgments, and paradigms that become embedded in the emerging design. An observation made by Radcliffe and Lee (1989) was that

communication of technical information, knowledge, and experience between members of a design group appeared to influence the quality of the design. This observation appears consistent with Fisher and Ellis' (1990) proposal that groups create their own culture through a convergence and sharing of common symbols. It is therefore proposed in this study that by expressing ideas, experiences, values, and judgments through similarity and analogy, group participants eventually gain a common understanding of multiple and interdependent aspects of a design, as well as, a common set of symbols to describe the design.

Tang (1989) used an interaction analysis methodology to study design activities in shared workspaces, specifically focusing on the representation and manipulation of design information through nonverbal codes. Tang used recordings of group activities to analyze nonverbal, communicative behaviors that occurred in design sessions. He observed that listing, drawing, and particularly gesturing were important in conveying design information in shared workspaces. Tang concluded that these nonverbal behaviors were used to store information, support the expression of complex ideas, and mediate interaction within the design group.

Bucciarelli (1988) studied design activities of two engineering firms from an ethnographic perspective using participant-observation techniques. Bucciarelli concluded that design is a social activity, characterized by the synthesis or overlaying of different views or perceptions of the artifact being designed. Bucciarelli pointed out that participants have different "object-worlds" from which to view the developing design and result in different representations of the design. It was observed that it was through the process of communication that participants were able to overlay different perspectives in the pursuit of design solutions.

Bucciarelli identified three types of discourse in the observed design process. The first two, constraining and decision discourse, were concerned with the determination of performance specifications from which the design effort proceeded and with discussions that aided the overlaying of perspectives. The third involved the invention of names which "....conjure up different visions of form and function within the minds of different design participants.." and serve "...to label a particular focus of common concern" (p. 165).

A common goal of these studies was to describe or relate to some process that effectuates the translation of held knowledge and experiences into physical representations that satisfied an implied or stated goal. Waldron (1987) suggested that designers transform semantic descriptions into syntactical and physical representations by invoking an appropriate exemplar or archetype held by the designer. Waldron suggested that artifacts carry with them a labeled set of experiences which invoke appropriate variables and methods that are applied to a design problem. The process of problem formulation therefore depends on the context and experiences of the designer. Additionally, assuming that experienced designers rely on prototypes and context, Waldron proposed that it is familiarity with a design approach which is most relevant.

Waldron also proposed that conceptual design activities are characterized by the translation of a problem definition to a functional specification, aided by social, cultural, and environmental knowledge. This occurs through semantics of the problem which establish the context in which a design resides. Waldron considers a design process to involve the transformation of semantic descriptions to syntactical and physical descriptions.

The question still remains concerning how the transformation of semantics to physical representations occurs in a collaborative setting, particularly the variables that effectuate the process. A goal of this study is to identify these variables that groups may employ in design decision making. Unfortunately, a literature review of small group research revealed that little has been done to investigate communication processes of groups in the domain of engineering design. Small group research has primarily focused on deriving models of decision-making and communication that can be applied to groups in general, regardless of task type or task complexity, and are therefore predominantly focused on social dimensions such as leadership, coordination, motivation, and commitment (Goodman, 1986). Hirokawa (1990) and Mabry and Attridge (1990) contend that task characteristics significantly influence group performance and communication:

> " A task is a significant component of the stimulus complex group members react to in constructing a psychological context for interaction. Thus tasks create a frame of reference for group interaction and outcomes and, if only indirectly, causally link together process and product dimensions of small groups."
> (Mabrey and Attridge, p. 316)

An underlying assumption of this study is that engineering design presents a unique frame of reference for group decision making. The task of engineering design is typically ill-structured in the sense that information required to "solve" a design problem is extremely broad, contains semantic rather than syntactic descriptions, and includes the customs, experiences, and values of the users (Akin, 1986). Akin also pointed out that the goal states of design problems are typically under specified and lack explicit evaluation criteria

that can be used to identify solutions. Therefore, problem solving strategies and solutions must be supplied by the designer:

> "The solution to a design problem is usually defined culturally, through insight and experience and evaluated via example and analogy during the process of design." (Akin, p.22)

If design solutions and problem solving structures are made available to a designer through experiences and interpretation of the design context, then how is synthesis of design information accomplished and agreement on design solutions achieved in group settings? The following models of group communication and decision making are reviewed to provide a perspective and an approach for the qualitative investigation of analogical decision making.

Fisher and Ellis (1990) propose that descriptive models of group decision-making best encompass communication and the group process. Descriptive models are concerned with how groups make decisions and are derived by observing what groups do and the interactions and communication processes that occur. Fisher and Ellis identify the Equilibrium and Phase models as the most popular linear models in small group research. The Equilibrium model of group behavior was proposed by Bales (1950) in which he hypothesized that groups must adapt to the instant environment which causes the group to continually strive to achieve a balance between solving the task at hand and maintaining group solidarity. Bales hypothesized that for a group to solve a task, social dimensions of the group, such as group cohesion, must be compromised to some degree. Concurrently, as the group strives to uphold social dimensions, performance of the task is hindered.

To measure task and social dimensions, Bales created categories that described task and social dimensions of group processes. These categories included: problems of orientation; evaluation and control; and problems of decision, tension-management, and integration. Bales used these categories to classify acts and interacts as solving either task or social problems as the group made decisions.

Phase models attempt to describe group activity over time. These models attempt to account for the stages as well as the interactions that groups progress through over time. Bales and Strodtbeck (1951) proposed a three-phase model to describe group decision-making. Using Bales interactive process analysis, Bales and Strodtbeck concluded that group problem-solving is cyclic and consists of three phases: orientation; evaluation; and control. They observed that as a group passed through the three phases and completed one decision-making task, the group would return to the initial orientation phase to begin a new task.

Recognizing that these models are slanted more toward social dimensions, Fisher and Ellis (1990) propose a more task oriented phase model that includes orientation, conflict, emergence, and reinforcement phases. They described these phases as consisting of patterns of interactions and more closely approach a nonlinear model proposed by Scheidel and Crowell (1964). This nonlinear model consists of a process of *anchoring* and *reach-testing* new ideas. When an idea is presented it is agreed or disagreed upon or expanded or revised until the group reaches agreement on the idea. If agreement is reached, the idea becomes "anchored" from which new ideas are generated, presented, and evaluated (referred to as reach-testing). Initial anchor points are returned to if a new idea is rejected.

Scheidel and Crowell's model is focused on the development of ideas during early phases of group decision making and contrasts previous models discussed which are concerned with work accomplished in later stages. In addition, their model implies that decisions made early in the process provide the basis for subsequent decisions. The relevance of this model to this study is that it captures a systemic perspective on group communication. The continual process of anchoring and reach-testing suggests the reoccurrence of communicative behaviors. Morris' Pragmatic Perspective on communication (1946) considers human communication as a system of behaviors which act to constrain and influence a communication system. From Watzlawick, Beavin, and Jackson's (1967) second axiom of human communication, communication acts are assumed to consist of information (data) and information pertaining to relationships (how the data are to be interpreted). They propose that these relationships are determined by the "punctuation" of communication sequences between interlocutors (their third axiom of communication). Fisher (1978) proposes that it is through punctuation that recognizable patterns of interaction are defined and provide the understanding of a communication system.

This systemic perspective of group communication suggests that if analogical decision making is viewed as a communication process, then process variables which act to constrain, direct, and influence design decision making should be recognizable, reoccur through out a process, and are amenable to analysis and description. However, a review of the literature revealed that the construct of analogy has not been fully operationalized in the context of engineering design. Results from related research have only concluded that analogy and analogical reasoning exist as part of design decision making. For example, Klein and Weitzenfeld (1982)

observed that aircraft engineers use a type of analogical problem solving method referred to as *comparability analysis* to determine the reliability of newly-designed systems.

A goal of this study is to lay groundwork for operationalizing the construct of analogy in *collaborative design.* The aim is to describe the role of analogy in design discourse in lieu of investigating individual processes of analogical reasoning. However, research and theories on analogical reasoning as a cognitive process provide a spring board for extensions in terms of hypotheses and propositions for the decision making processes of groups. Therefore, theories of analogy from the cognitive sciences are reviewed as a means to further develop a framework for this study.

In the context of engineering design, Jones (1981) proposed that analogy facilitates the elicitation of design solutions and categorized types of analogies as:

Direct Analogies- represented by analoques from the biological world.

Personal Analogies- consists of a projection of one's self into a particluar situation as a means to better understand a problem through experiential comparison.

Symbolic Analogies- characterized by the use of metaphors and similies where attributes of a preexisting idea are extend to another.

Fantasy Analogies- characterized by imagining things as they are known not to be, such as if we all spoke the same language.

These analogy types, when used in a group setting, represent a creative design methodology referred to as synectics (Cross, 1989). As Cross explains, the role of synectics in design is to make the strange familiar through a familiar analogical core which provides an understanding of the problem state and key elements to be solved. In addition, the difference between brainstorming and synectics is that brainstorming is characterized by uninhibited, random promulgation of ideas. In contrast, synectics is goal-oriented and constitutes a juxtaposition of concepts and ideas.

In a theoretical exploration of analogy in engineering design, Oxman (1990) proposed a *knowledge-based dynamic model of design.* This model attempts to explain acquisition of design knowledge and its implementation into new design events. Oxman proposed that design knowledge is acquired through typification and generalization of design experiences and exists as prototypes, concepts, and context-dependent precedents that function to structure knowledge. It is through matching mechanisms such as cross-indexing and analogy that provide access to prior design knowledge by matching situation and solution types from previous knowledge to new applications. Oxman proposed that typification is the process of indexing "episodic events" to classes of events to aid memory storage.

In the field of cognitive science there two dominant theories on analogical reasoning: Gentner's Structure-Mapping theory; and Holyoak's Pragmatic Theory. In general these theories view analogical reasoning as the identification, selection, and transfer of relational information from an existing source of knowledge (the *base* domain) to a target problem (the *target* domain). However, they differ in assumptions about the process and mechanisms of analogical reasoning. Gentner proposes that analogies are

contextually free, relying solely on syntactical representations to identify and map relational commonalties between a base and target domain.

Holyoak's pragmatic framework stresses that the structures and interpretation of analogy are goal-oriented, arguing that the identification and selection of structural similarities of the analogues are influenced by context, i.e., the plan and goals of the problem solver. Keane (1988) synthesized aspects of both theories and concluded analogy as:

> "...the product of certain cognitive processes in which specific coherent aspects (i.e., causally-integrated aspects) of the conceptual structure of one domain are matched with and/or transferred into another domain. In the transfer of these specific conceptual aspects, relations will tend to be important, although attributes may also be important." (p.109)

Both theories generally consider the process of analogical reasoning to include; access to an appropriate analogue; mapping information from a known analogue to a target domain; and the generation of general rules and representations. Table 1 summaries differences between Gentner's and Holyoak's theories of analogy with respect to this general process of analogical reasoning.

Gentner uses propositional networks notions to represent held knowledge where domains and situations are viewed as systems of objects, object-attributes and relations (Gentner, 1989; Gentner and Landers, 1985; Keane, 1988). As part of this framework, objects or concepts are considered as distinct entities existing in a particular domain where they may also be combinations of smaller units. Gentner defines attributes as predicates having one argument and relations as predicates having two or more arguments. Gentner also makes a distinction between first and second-order

predicates. First-order predicates take objects as their arguments and second-order take propositions as their arguments. It is through these propositional and syntactical networks that Gentner proposes that an analogy is characterized by the structure-mapping of relational structures and commonalties rather than the attributes of objects:

> "Objects are placed in correspondence by virtue of their like roles in the common relational structure; there does not need to be any resemblance between the target objects and their corresponding base objects." (1989, p.201)

Gentner considers the structure-mapping process to include a mapping of lower order relations of the base and target domains; however, the selection of lower-order relations is limited to those which are constrained by higher-order relations (the Systematicity Principle). Processing rules therefore rely on the syntax or structure of knowledge represented, not on the context of the domain. Relations that do not fit the set of base relations that might apply to the target are discarded.

To conclude, Gentner proposes that analogy is the mapping of a system of relations, not attributes, from the source domain to the target domain. Structure-mapping is considered to be purely syntactic manipulation where semantics are ignored since entities (goals) of the relations do not affect the structure-mapping process. Gentner's structure-mapping theory is based on the syntax of representation rather than the context of a domain.

Holyoak's Pragmatic Theory of Analogy differs from Gentner's in that information transferred from the base domain to the target is assumed to be goal oriented. Holyoak's representation of knowledge also differs in that the base and target domain are assumed to be represented at different levels of

Process:	**Gentner's Structure-Mapping Theory** (Gentner 1985, 1989)	**Holyoak's Pragmatic Theory** (Holyoak 1985, 1986)
Accessing the Base Domain	Analogues are retrieved based on shared, superficially-similar concepts in both domains. Mere-appearance analogues are retrieved more often than true analogies.	Involves the detection of shared sematic elements such as a relation or an object between the target problem and a known base domain.
Mapping between Base and Target Domains	Correspondences between base and target are made and then mapped. Here analogy is characterized as a mapping of relational structures defined by first and second order predicates and selected based on a systematicity principle. Mapping from one domain to another is considered context free.	Partial mappings are made between initial states of the analogues, occurring at the abstract schematic level. Correspondences are made between goals, resources, operators, constraints, solution plans and outcome to generate proposed solutions
Generation of Rules and Generalizations	The interpretation of an analogy resides in the predicate matches between the base and target not in the base domain.	Process of Induction- a generalization of both analoques, capturing commonalties between initial states, solutions, plans, and outcomes, is made to form an abstract problem schema.

Table 1: Summary of Theories of Analogy

abstraction. Holyoak assumes that each analoque is structured hierarchically, consisting of an initial problem state, a solution plan, and an outcome (Holyoak, 1985; Holyoak and Koh, 1986). Holyoak proposes that the process of analogical problem solving consists of a process of retrieval, mapping, and induction as described in Table 1. Analoque retrieval is initiated by the recognition of some shared sematic element or elements between the target problem and a base analoque. In addition, a story, problem, or situation may contain elementary features such as properties or relations which activate memory representations of other situations.

Holyoak's model considers analogies to consist of surface and structural features. Surface features are entities that do not influence goal attainment, structural features do influence goal attainment. Surface features occur at the schematic level where relationships of the base and target domain exist at a summary level. Holyoak points out that the base and target domains might share many surface features but still be poor analoques of each other if they lack deep causal similarities (shared structural features). In addition, analogues might appear remotely related, sharing few surface features, but sharing many structural features. Paxton's design of the Crystal Palace, based on features of the giant water lily as discussed in Chapter One, is an example of analoques from vastly different domains that share few surface similarities but have deep causal similarities.

Holyoak proposes that superficially-similar situations tend to be retrieved more often than remote analoques, particularly in situations where there is a lack of understanding or unfamiliarity of the target problem and where structural features are more difficult to identify. If structural features can be identified, there is a greater probability that an analoque sharing those features might be retrieved. Medin and Ortony (1989) suggest surface

similarities are those things that are easily accessible and can be listed. Empirical findings suggest that the probability of retrieving an analogue increases when surface similarity, consisting of simple descriptive properties, between the source and target domains increase (Gentner and Landers, 1985; Holyoak and Koh, 1986). However, when the source domain is remote from the target domain, access to an appropriate analoque becomes more difficult.

These two theories represent two different approaches to describe analogy. One is focused on syntactic manipulation, employing a principle of systematicity as a means to select predicate structures between domains. The other stresses the importance of context (goals) where relations are matched between domains or mapped from one domain to another. The advantage of Gentner's theory is that a syntactic representation of knowledge makes it easier to distinguish between analogy, metaphor, simile and other comparison types. Gentner proposes that comparisons exist on a continuum that defines the degree of shared attributes and relations. On one extreme, simile is characterized by many shared attributes and few relations, on the other, analogy is characterized by many relations and few attributes (Gentner, 1989, p. 207). The disadvantage of Gentner's theory is that it is considered to be contextually free which conflicts with the assumption that design is contextually dependent as defined through experiences, value judgments, and design paradigms. The advantage of Holyoak's theory is that its basic assumption of context dependency is congruent with these assumptions about design, it provides a framework for describing goals, solution plans, constraints, and outcomes of an analogy as they relate to design.

It is important to note that these theories attempt to describe cognitive processes of individuals and not decision making or communication processes of groups. They do however provide a starting point for this study.

Summary: Research Objectives

The perspective that design is a social process where communication plays a supporting and organizing role is founded on the proposition that objects and the collection of objects that constitute a complete design are embedded with *experiences* and *expectations*. Experiences in the sense that those practices, procedures, and assumptions used in previous designs are incorporated into a new design. It includes the maintenance of traditions, beliefs, and values reinforced by languages, verbal and nonverbal, that emerge from the activity and process of designing. Expectations become embedded into an emerging design through stated needs and goals, which are presented to the designer, and sub goals which are derived through the design activity. Emergent questions are: what communication processes and mechanisms facilitate this social process of design?; and, how do engineers and designers elicit, synthesize, and implement experiences and expectations that facilitate the construction, manipulation, and conveyance of design information? It is proposed that similarity and analogy are communication vehicles that effectuate the synthesis of multiple experiences and expectations, enabling designers to traverse technical (knowledge) domains and converge toward design solutions.

Based upon this perspective of design, the following are objectives of this study:

1. Qualitatively assess and describe analogical decision making as a communication process. Determine how episodes of analogical decision making are recognized in design discourse, identify indicators of these episodes, and determine how they are initiated, executed, and terminated.

2. Identify communicative behaviors that are used by a design group during analogical decision making and describe the role of each of these behaviors in the elicitation of design information and synthesis of design solutions.
3. Determine and describe how analogic discourse is organized, and how components of analogy (analoques and corresponding attributes) are assembled to support the synthesis of design solutions.
4. Determine if relationships among communicative behaviors suggest patterns of interaction, and for relationships that do exist, describe a communicative process for analogical decision making.

CHAPTER 3

RESEARCH METHODOLOGY

The objective of this study is to derive a *descriptive, communicative representation* of analogical decision making in engineering design. This approach is in contrast to *modeling* which instead must determine if a proposed model renders results congruent with generalizations and conclusions drawn from empirical data and observation. This study is considered to be exploratory in nature and is an exercise in the description and explanation of observational data.

Observational and interactional analysis methods described by Tang (1989), Suchman (1988), Bakeman and Gottman (1986, 1987), Sackett (1987), and Frey, et al. (1990) are used to investigate and describe communication and analogical decision making processes in collaborative design. Specifically, this study uses an observational approach to record, identify, and quantify communicative behaviors that occur in episodes of analogical decision making observed during design problem solving. A significant effort of this study focuses on the qualitative assessment and description of communicative behaviors that appear to elicit and act on design information during analogical decision making. These observed behaviors are applied as a coding scheme to recorded conversational data and analyzed to determine if reoccurring patterns of communication and interaction exist during analogical decision making. These patterns are then used to propose a descriptive representation of analogical decision making in collaborative

design.

Tang (1989), Suchman (1988, 1987) and others have demonstrated the use of observational and interactional analysis methods in the study of design. Tang used this approach to investigate workspace activities of design teams, attempting to observe unobtrusively teams performing design tasks. The approach ensured that the researcher did not intervene after work began on a given task, the execution of the task occurred through a process determined by the subjects. The responsibility of the researcher was to record and interpret activities as they occurred in the design session.

Tang's methodology was based on premises proposed by Suchman (1987) for the study of human-machine interaction using interaction analysis methods. Essentially Suchman described this method as attempting to strike a balance between the construction of situations "..to make certain issues observable.." and allowing processes to occur naturally. The goal of this approach is "..to construct a characterization of the 'interaction' that ensued, rather than to apply a predetermined coding scheme.." as means of uncovering "..a description of the structure of situated action" (Suchman, 1987, p.114). Tang furthers this point by proposing that:

> "Interaction analysis does not depend on accurate preconceptions of the activity in order to construct experimental studies. It does not attempt to separate specific aspects of an activity and study them in isolation. Rather, the activity as a whole is treated as the subject under investigation, and it is studied under conditions similar to those in which it is naturally experienced. Interaction analysis also does not depend on an artificial means for eliciting cognitive information, such as giving protocols. As a method based on video records of the actual activity as data, it is not susceptible to the incomplete reporting,

> faulty recollection, or post-rationalization that can occur in case studies or retrospective interviews." (Tang, p. 50)

Once a record of the "situated action" is obtained, data are analyzed to develop a description of observed behaviors and their occurrences, leading to research questions pertaining to their role in the situated action. This approach provides a means to postulate salient patterns of interaction that characterize the activities under study and that can be further investigated to gain confidence in and understanding of the observed interaction:

> "Reviewing the recorded activity helps formulate the research issues to investigate by identifying recurring issues or patterns of activity. A deeper understanding of a particular issue is obtained by collecting multiple examples of these recurring patterns, so that they can be analyzed by comparison and contrast. In this way, the record of the actual activity is used as data to inductively construct and support observations about the activity." (Tang, p. 50)

This approach is recommended by Bakeman and Gottman (1987) when research questions focus on the understanding of processes and mechanisms of social interaction. Specifically, Bakeman and Gottman propose systematic observational approaches to quantify behaviors of interaction using catalogs of behavioral codes. The quantification and description of social interactions as a system of recurring patterns is accomplished through the sequential analysis of behavioral data, which identifies contingent relationships among behavioral codes (states) based on conditional probabilities of their occurrence. This quantification is however proceeded by qualitative inquiry, the identification and description of an exhaustive set of mutually exclusive behaviors obtained through observations of the situated action.

Bakeman and Gottman consider a coding scheme that is derived from observational data as the basic measuring instrument of observational research, focused to address particular research questions and hypotheses inductively drawn from observational data. Bakeman and Gottman consider the activity of designing a coding scheme as a "theoretic act", providing a "lens with which an investigator has chosen to view the world" (1987, p. 822). The coding scheme therefore represents an hypothesis to be tested to determine the validity and accuracy of what was observed. If analysis of the coding scheme against collected segments of observational data reveals recurring patterns of interaction, then it is tenable that the coding scheme captures the essence of the observed activity.

Bakeman and Gottman (1986, 1987) and Sackett (1987) require that the coding schemes represent exhaustive sets of mutually exclusive behaviors. The argument is that each observed event must represent a distinct and separate behavioral state if a credible description of a systematic process is to be obtained. In addition, each observed event in the passing stream of behaviors must be identifiable to a particular behavioral code to obtain a comprehensive description of the process of interaction.

Tang and Suchman's observational method is an approach for initial investigations and descriptions of social processes and interactions. This qualitative approach is used in this study to further explanations and descriptions of similarity and analogical decision making provided by previous researchers, but in the context of collaborative design. Applying Bakeman's and Gottman's sequential analysis method, patterns of interaction observed in analogy episodes are analyzed to validate proposed patterns, interactions, and contingent relationships among behavior states, culminating in a description of an analogical decision making process. Specifically, the

observational and interactional analysis method used in this study includes the following steps:

1. Observe and record (audio and video) the activities of a group performing a pre-defined design exercise.
2. Transcribe the recorded dialogue and combine with observational notes made from the video recording.
3. Identify episodes of analogical decision making. Determine what constitutes an episode, how they are recognized, initiated, and terminated.
4. Using transcripts and the video recording, identify and describe communicative behaviors (verbal and nonverbal) that occur in episodes of analogical decision making. Use these communicative behaviors to develop a coding scheme.
5. Categorize and unitize transcribed data using the proposed coding scheme.
6. Apply the lag sequential analysis method to coded data to identify patterns of communication, interaction, and decision making.

Observational Method and Approach

The method and approach for observing and recording design activities associated with analogical decision making follows closely to the approach used by Tang (1989) to study workspace activities of design teams. Similar to Tang's approach, the goal is to observe design activities as unobtrusively as possible and provide a natural and unconstrained environment that allows participants to choose and tailor the direction and process of decision making. In Tang's studies, participants used either white boards (similar to chalk boards) or a central workspace located on a table top with large sheets of white paper that were used to record design information and solutions. Based on observations in industry, white boards or chalk boards and drawings

boards (large table tops) are common workspaces used by designers and engineers. The medium used in industry to capture physical elements of a design is usually a drawing, even when computer-aided design tools are used to create the design. In practice, a drawing laid across a table appeared to provide a focal point from which representatives from various technical disciplines gathered around to elicit, express, and resolve multiple and interrelated concerns. For this study a table top workspace therefore appears not to add unfamiliar constraints on the process of decision making and is used in lieu of white boards. Tang's studies suggest that a table top workspace improves the ability to record verbal and nonverbal behaviors, the use of a white board allows to much movement of the participants during the design session, making the logistics of video and audio recording and analysis difficult.

For this study, recording equipment and the researcher are located in one room of a recording studio and the design group located in another. Two cameras are used to record verbal and nonverbal communicative behaviors as shown in Figure 1. One camera is located at the open end of the table on a tripod, providing a frontal view of the subjects. A second camera is located directly above the workspace to record activities that occur on or near large sheets of paper. Video signals from these two cameras are combined to produce a split screen. The split screen aids the analysis of design events by displaying simultaneously verbal and nonverbal communicative behaviors (verbal descriptions, explanations, gestures, and sketching). During the transcription of conversational data, nonverbal communicative behaviors and other observational data are recorded on forms as shown in Figure 1.

The design session begins with a brief introduction of what is to occur within the next hour. The subjects are told that each will receive a statement

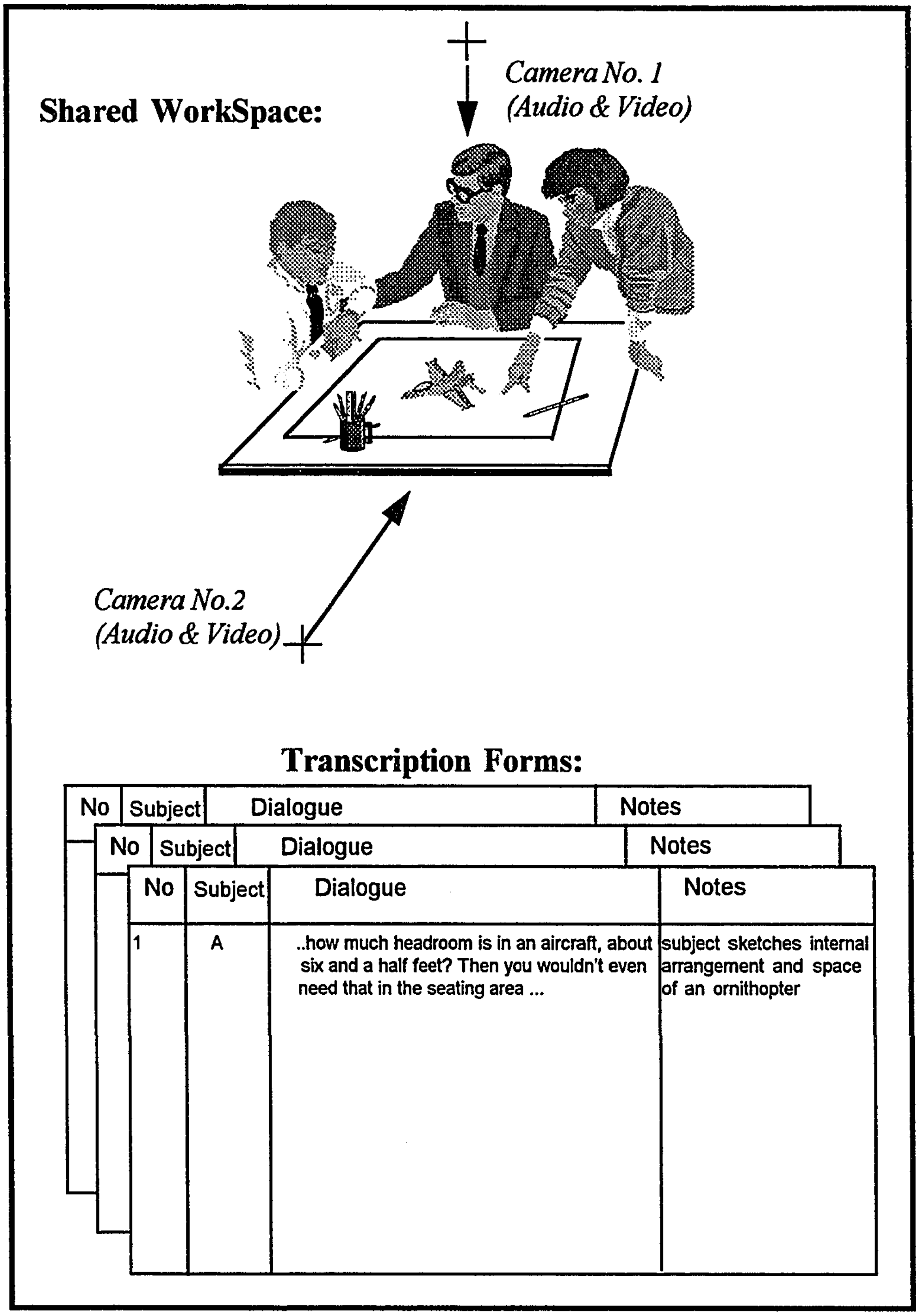

Figure 1: Observed Workspace and Recording Methods

of the design problem and that they are to work as a team to develop a design solution. The subjects are required to develop a sketch of their design solution on large sheets of paper located in front of the group. These sheets may also be used to record any information that is pertinent to the design task. Because colored markers are used for marking on the sheets, colored video film is used to aid recognition of who draws what facet of the design solution or records what information.

The design problem developed for this study, shown in Appendix A, is distributed to the group and the researcher remains to answer any initial administrative questions. When the group begins the task, the researcher leaves the room and monitors the session from the equipment room and does not return until one hour has elapsed. After completion of the task, a questionnaire is given to each participant to determine (a) if conditions of the room and workspace environment inhibited their design efforts and (b) the individual's and group's familiarity with the task. This questionnaire is shown in Appendix B.

Design Task Definition and Group Composition Requirements

As proposed in Chapter 2, a task provides the context for social interaction. Therefore, in constructing a design task the potential influence on analogical decision making processes must be considered. Keane (1988) proposed that situations where analogical processes are important are those that are unstructured and incomplete. In situations that are familiar to decision makers, information can be categorized using general knowledge structures from a familiar (base) domain. In these situations both surface and structural similarities are used to access and generate analogies. In situations that are unfamiliar, categorization structures from a base domain are not

readily applied to a target problem, making the decision making task more difficult.

An objective of this study is to understand how group members explore proposed analogies that aid design decision making, if in fact they do this. It is anticipated that an unfamiliar task domain will generate greater discussion and exploration of surface and structural similarities as the group attempts to generate potential design solutions. Therefore, the design task should be developed from a knowledge domain unfamiliar to group members where surface cues might be used more frequently to initiate group interaction and communication.

An additional factor to consider in the design of a task is the influence of task complexity on group performance. Hirokawa (1990) argues that a group's awareness of the task goal, the means and methods available to achieve the goal, and the number of operations to perform and barriers to overcome, influence the degree of group interaction and communication. If a task is deficient in the first two attributes or the number of operations to perform and barriers to overcome is overwhelming, a greater degree of group interaction and communication is required to perform the task. Therefore, the design task used in this study is designed to be complex and unstructured, lacking familiar problem solving structures and processes used in more familiar knowledge domains. The perception held by group members in regards to the complexity and familiarity of the task is evaluated through the questionnaire shown in Appendix A. These task requirements led to the following criterion which were used to select group members for this study:

1. Participants must not be familiar with the topic of the task, meaning that participants have no prior design experience with the product to be designed as defined by the task.

2. Participants must be practicing engineers from industry with enough design experience to be considered competent by their peers.

3. Participants must be from the same engineering discipline and have participated in the design of similar products.

The second criterion minimizes effects of differences in problem solving strategies. Akin (1986), Anderson (1985) and Chase and Simon (1977) determined that experts use problem-solving strategies not used by novices. Experts were observed to use breadth-like problem structuring and solving, and abstract representations.

The purpose of the third criterion is to provide a degree of control over what design information (experiences and expectations) is used during decision making. Based on Bucciarelli's observation that names "..conjure up different visions of form and function within the minds of different design participants..." (see Chapter Two), a goal of this study is to determine how a shared design language, which provides a common reference point for all participants, is used in an unfamilar task domain.

In addition, in order for the researcher to access the "design world" of the subjects, subjects having a similar technical background to that of the researcher are selected for the study. This enables the researcher to recognize and access design knowledge and language that might otherwise remain elusive.

Three subjects from the shipbuilding industry were selected for the study. Each subject had at least five years of design experience as a structural engineer. In addition, all had experience in the design of submarines, none had experience in the design of aircraft or aircraft structures which is the topic of the design task. These subjects knew each other and

had worked together on a number of projects. The subjects were approach informally by the researcher and asked to participate in a study on design methods. The researcher had worked with each of the subjects on various projects at different points in time over a ten year period. The study was described as an exploratory study that would attempt to identify methods for improving design decision making in group settings, particularly focusing on requirements for a concurrent engineering environment. The subjects were told that they would work as a design team on a specified task and the session would be recorded to support analysis of decision making activities.

Lag Sequential Analysis Method

The lag sequential analysis method is used to identify patterns of communication and interaction. This analysis technique was developed by Sackett (1979, 1987) to identify contingent relationships among a stream of categorized events (behaviors). Sackett suggests that this technique can be applied to any research situation where categorical events are measured as ordered and potentially contingent events. Neidermeier (1988) used this analysis approach to further test and expand on Scheidel and Crowell's Anchor Spiral Model discussed in Chapter Two. Neidermeier concluded that the lag sequential analysis approach provided a methodology to operationalize discrete communication elements and a "precise description of a communication process over time." The basic objective of the lag sequential analysis is to identify non random conditional probabilities among categorized communicative events.

To accomplish this, recorded conversations from the design session are studied to identify process variables of analogical decision making. These process variables are applied as a coding scheme to transcribed,

conversational data. Descriptive statistics are then derived to identify sequential aspects of the data. Descriptive statistics include frequencies and transitional probabilities (conditional probabilities) which represent the probability of occurrence of a particular behavior given the occurrence of an antecedent behavior.

To illustrate the lag sequential analysis method, consider the following hypothetical behavioral chain:

A-B-C-A-C-A-C-B-C-A

Each behavior in this chain is assumed to be mutually exclusive and the set exhaustive. To begin the analysis, a behavior is selected as the criterion and counts are made to determine the number of times (frequency) the criterion is immediately followed (referred to as matching) by itself (autolag) or by other behaviors (crosslag). A behavior that matches the criterion as the very next behavior represents a *lag one* event. For example, behavior B followed A once and C followed A twice with behavior A as the criterion. To complete the count for all possible lag one events, each behavior takes its turn as the criterion and subsequent behaviors are counted. Frequencies for lag one events determined for the hypothetical chain are:

		Subsequent Behavior (Sb) at Lag One			
		A	*B*	*C*	*Total*
Criterion (Cr)	*A*	-	1	2	3
	B	-	-	2	2
	C	3	1	-	4

Transitional probabilities are now computed using these frequencies. The transitional probability represents the probability that a subsequent

behavior will follow the criterion. The transitional probability is expressed as:

$$p(Sb_i/Cr) = \Sigma(Sb_i/Cr)/\ \Sigma_{total}(Sb/Cr)$$

where Sb_i represents the subsequent behavior of interest that matches a particular criterion behavior (Cr). The transitional probability for a particular event is therefore the ratio of the total counts made for a particular subsequent behavior to the total counts made for all subsequent behaviors (Sb) given the occurrence of a particular criterion. Therefore, based on frequencies from the previous table, the transitional probability for the occurrence of behavior B given that A has occurred, represented as p(B/A), is 1/3 of the total observed matching events in the chain with A as the criterion. Using frequencies shown in the previous table, transitional probabilities for other matched events at lag one are:

		Subsequent Behavior (Sb) at Lag One			
		A	*B*	*C*	*Sum*
Criterion (Cr)	*A*	-	.33	.67	1.00
	B	-	-	1.00	1.00
	C	.75	.25	-	1.00

To detect sequential aspects of the hypothetical chain, frequencies and transitional probabilities must be computed for subsequent behaviors that match the criterion at other lags. To do this, behaviors that match the criterion as the second and third behavior, and so on, to a maximum lag under investigation, are counted. For example, at lag two, behaviors A, B, and C each matched the criterion A once, resulting in a transitional probability for each behavior of .33. At lag three, behavior A followed the criterion A once

and C followed the criterion behavior A twice, resulting in transitional probabilities of .33 and .67 respectively. This analysis is illustrated in Figure 2 for lags one through four for the hypothetical behavioral chain.

To graphically illustrate potential patterns of interactions, transitional probabilities are graphed for lags one through four as shown in Figure 2. These graphs are referred to as criterion profiles. Referring to graph (a) of the figure, there appear to be cyclic dependencies between the criterion behavior A and behaviors B and C. Behavior C appears excited at lags one and three, more so than at lags two and four. Behavior B also appears dependent on the occurrence of the criterion behavior A. This graph suggests that at lag one behavior C is more likely to follow A than behavior B. Thus a possible pattern of the hypothetical chain is A-C. To determine which behavior is more likely to follow C, Behavior C is held as the criterion as shown in graphs (b) and (c). These criterion profiles clearly indicate that behavior A is more likely to follow C than behavior B at lag one. In addition, the criterion profile shown in (b) indicates a cyclic dependency between A and C, where graph (c) indicates no dependency between behaviors B and C (there are no alternating minimum or maximum values). Therefore, a possible pattern of interaction for the hypothetical chain now becomes A-C-A.

Significance testing is however required to validate the proposed pattern of interaction. Bakeman and Gottman (1986) suggest the use of the Z-score binomial test or chi square goodness-of-fit test to determine if conditional probabilities are non random. However no significance testing is performed in this study because of the limited sample size collected from the data. The lag sequential analysis method is used only to propose and illustrate potential patterns of interaction that occur in analogy episodes. As stated earlier, this study is a qualitative assessment of communication

Behavioral Chain: A-B-C-A-C-A-C-B-C-A

Lag One		Frequencies A	Frequencies B	Frequencies C		Transitional Probabilities A	Transitional Probabilities B	Transitional Probabilities C
Criterion	A	-	1	2	A	-	.33	.67
	B	-	-	2	B	-	-	1.0
	C	3	1	-	C	.75	.25	-

Lag Two		A	B	C		A	B	C
Criterion	A	1	1	1-	A	.33	.33	.33
	B	2	-	-	B	1.0	-	-
	C	-	-	3	C	-	-	1.0

Lag Three		A	B	C		A	B	C
Criterion	A	1	-	2	A	33	-	.67
	B	-	-	1	B	-	-	1.0
	C	2	-	-	C	1.0	-	-

Lag Four		A	B	C		A	B	C
Criterion	A	1	1	1	A	.33	.33	.33
	B	1	-	-	B	1.0	-	-
	C	-	-	2	C	-	-	1.0

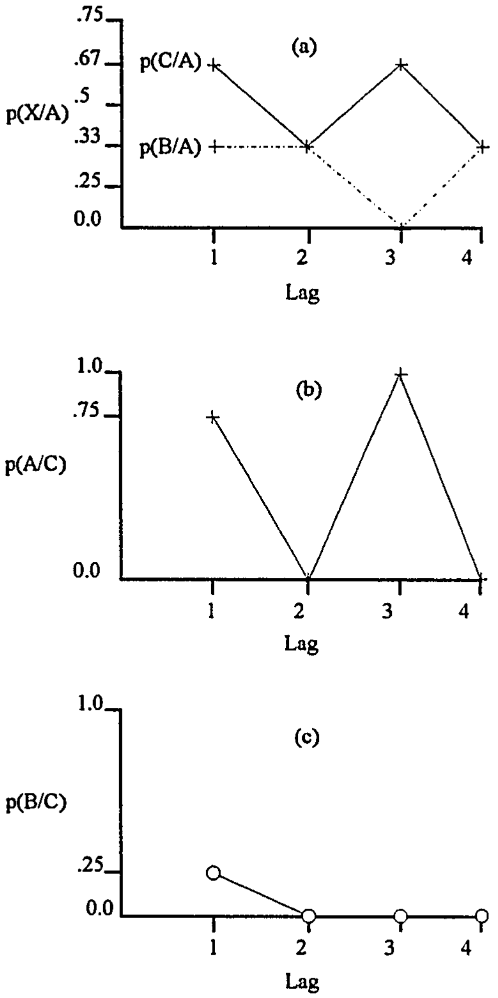

Figure 2: Example: Frequencies, Transitional Probabilities and Criterion Profiles

processes and behaviors and not a statistical analysis of data. The technique is used, however, to illustrate a proposed communication process for analogical decision making that can be tested in future studies.

Limitations of an Observational Approach

There are a number of limitations of the observational approach used in this study. Tang (1989) succinctly discussed several of these limitations as they occurred in the study of shared workspaces and are discussed here but in the context of this study.

As Tang points out, the duration of the situated action under study can be limited by the amount of data to be collected and processed. Because of the abundance of observational data that can be collected from a social activity, some limit on the period of observation is necessary. The issue is then whether the situated action under study resembles a time period that occurs in a naturalistic setting and more importantly, does the time period of observation support objectives of the research. In this study, the observed design session occurred over a one hour period and is considered a limitation. In industry, collaborative design efforts can occur over greater periods of time. However, because this is an exploratory study, a one hour period was selected because of the anticipated amount of data that was collected and the period of time subjects were available to participate in the study.

Tang also identified the potential influence of the activity of observing on the situated action under study. To mitigate potential affects, all recording equipment (except for cameras) and the researcher were located in a separate room during the design session. Tang reported, in the study of shared workspaces, that design activities appeared unaffected by the observational method. Only a few isolated comments by subjects concerning the video

taping of the session were made. In regards to psychological affects, as Tang reports, Kelly and Thibault (1969) provide evidence that effects of being observed diminish with time.

An additional limitation of an observational approach, which Tang does not discuss, results from the proximity of the researcher to the situated action. It is assumed that what is observable and how it is observed is influenced by the researcher's location relative to the activity being studied. In this study the researcher is external to the situated action, thus the activity is observed from a perspective that might be different from that of the participants in the study. This is epitomized by the derivation of a coding scheme that the researcher constructs based on what is externally observed. It represents a window that is constructed to provide a view of what the researcher believes to be most important in the observed activity. What might be more informative, in terms of describing a communication process, is the view subjects might have of the activity in which they participate.

The concern here is the development of a credible description of an observed process. In this study, the proximity of the researcher to the activity under study is particularly important because what is being studied is a communication process. If the act of designing is considered to involve the creation of a language system for the item being designed, what is omitted from the researcher's perspective is the *experience of influencing* the development of a language system. Clearly this experience must be relevant to any process description that might be proposed for an activity under study.

To improve the ability of an external observer to describe an activity under study, subjects with similar design experiences and technical backgrounds to those of the researcher are selected to participate in the study. Essentially what the researcher observes is an enactment of a familiar

language system and its role in constructing a new system for the item being designed. Familiarization with an existing language system might provided greater insight into the communication process and aid the development of a more complete description.

CHAPTER FOUR

DATA ANALYSIS AND RESULTS

The first section of this chapter describes how episodes of similarity and analogical decision making are identified from data collected during the observed design session. Various examples of design discourse, involving the use of similes, analogies, and other comparative statements, are used to illustrate the initiation and termination of these episodes.

The second section provides a qualitative assessment and description of communicative behaviors, verbal and nonverbal, that were identified in analogy episodes. Using transcripts and other recorded data obtained from the video recording, these behaviors are described in regards to how they were recognized and the role they played in design decision making.

In the third section, the structure of similarity and analogy in design discourse is described which represents the initial step towards a description of a process of analogical decision making. The efficacy of knowledge domain comparisons, explicitly stated and implied design goals, and analogy attributes in the derivation of design requirements, heuristics, and embodiments is described.

The fourth section develops a general process of analogical decision making. Using communicative behaviors defined earlier and analogy decision making graphs, the lag sequential analysis is used to identify possible patterns of interaction that might characterize a process of analogical decision making

during a collaborative design effort. The final section provides a summary of the results.

The Identification of Epsiodes of Similarity and Analogical Decision Making in Design Discourse

The analysis of analogical decision making in collaborative design began with the transcription of conversational data recorded during the design session. After review of the transcripts and other recorded data obtained from the video recording, the following observations were made concerning the identification of analogy episodes.

First, numerous statements of similarity and analogy can be identified from the data. In some cases these statements appeared random and are assumed to facilitate the decision making of an individual, not of the group. This study does not address or attempt to explain the cognitive processes of individuals; instead, the focus is on the communication process and aggregate communicative behaviors of the group, hopefully which can be described as a communication system that supports design decision making. Therefore, only data that represent a collective engagement of group members in design discourse, involving statements of similarity and analogy, are considered as potential episodes of analogical decision making.

Secondly, the identification of episodes of analogical decision making occurred through the recognition of key words and phrases. The primary key word identified in the data that suggests the occurrence of an episode is the preposition "like." This preposition was observed to occur in comparative utterances, such as:

> "...so these things [ornithopters] take off and land just *like* a helicopter..."

This utterance clearly represents a stated comparison of two different items (ornithopters and helicopters). If ornithopters and helicopters were considered or determined to represent two conceptually different domains, the comparative statement would be considered a simile. Utterances or statements that compare shared attributes of conceptually similar knowledge domains, such as a '93 Ford is like a '94 Ford, are referred to as literal similarities.

In other occurrences analogy episodes are identified by declarative statements, such as:

"...the wings [of an ornithopter] *are* the parachute..."

In literature this is considered to be a metaphor, lacking the preposition "like" and implying a deeper comparison of the items in the utterance as compared to a simile. However, the distinction between similes and metaphors is irrelevant to this study for two reasons. First, because we do not always construct and organize our speech with the same rigor used when we write, the distinction between whether an utterance was meant to be a simile, metaphor, or analogy is not always clear. Whether the preposition "like" was used or not in a comparative statement, continuing discourse aimed at identifying shared attributes or determining how domains (analogues) were similar was observed in analogy episodes. The two utterances, "ornithopters are like helicopters" and "the wings of an ornithopter are the parachute", led to subsequent discourse that determined how analogues were similar. Therefore, the distinction between a simile, metaphor, or analogy is irrelevant.

Secondly, it is assumed that our ability to distinguish between similarity and analogy is based on the current state of knowledge of the analogues being compared. Consider two examples provided by Gentner (1989) that compare known and familiar analogues:

"Milk is like water"

"Heat is like water"

Gentner considers the first comparison as a literal similarity where analogues, milk and water, share many object attributes (both are fluids) and relationships (both flow down hill). The second comparison, however, is considered by Gentner to be an analogy because the analogues, heat and water, share more relationships than object attributes, such as, temperature differences cause heat flow and pressure differences cause water flow. These two comparative statements are intuitively different because we understand the concepts of heat, milk, and water. In reference to the second comparison, because we are familiar with the concepts of heat and water we intuitively know to search for deeper relationships in order to describe how heat is like water. The point being made is that the ability to say something is *like* something else or *is* something else depends on what is known about the two domains. Consider for example, can it be stated that an ornithopter is *like* a helicopter? Is the intention of the comparative statement to imply only superficial similarity or deeper relational structures between the two analogues? These questions are difficult to answer because a description of an ornithopter or an understanding of what an ornithopter is remains to be determined. This is clearly the task of the design group in this study. For these reasons the distinction between similes, analogies, and other types of comparative statements is unimportant to this study, but they are used as indicators of potential episodes of analogical decision making. Instead, as

proposed by Gentner, similarity and analogy are considered as extremes on a continuum that defines the depth of comparison among knowledge domains. Therefore, discourse involving comparisons between similar or different knowledge domains is simply referred to as episodes of similarity and analogical decision making, representing a continuum of varying degrees of shared attributes and relations.

It was also observed in the data that nonverbal behaviors, such as gesturing, are involved in comparisons that initiate analogy episodes. For example, in the utterance,

> "see now when a bird flies when it lands the body actually tilts like that ..[gesture] we can't have that I mean I don't know about you if I'm sitting in a plane and all of a sudden the plane did one of these numbers..[gesture]"

a relation between what a bird does when it lands and what it means to sit in a plane when it tilts is illustrated by a gesture that indicates a tilting motion. Jones (1981) refers to this as a personal analogy, involving the projection of one's self into a particular situation as a means to better understand a current problem. It was observed that gesturing was inextricably associated with the communication process and its role in analogical decision making is further discussed in the following sections.

The following segment, obtained from transcribed data, illustrates the initiation and termination of analogy episodes:

47: (B) ok why wouldn't they use existing airports?
48: (A) well..uh..thats a good question
49: (B) provided they are here in the 21 first century
50: (A) no..you..you take this ornithopter concept...does it require a convential airport? I..I..my inclination here is that it could land on a roof top or parking lot..I..uh

51: (A) mumbles
52: (B) mumbles
53: (C) mumbles
54: (C) kind of like a helopad on a drilling structure or top of a roof of a executive building
55: (A) yes
56: (C) I..even a marked off space in a parking lot..uh...of a company
57: (A) yes
58: (B) so these things can take off and land just like a helocopter..or..do they need a little bit of runway to get themselves airborne?
59: (A) well...I
60: (C) I...I never...it [ornithopter] flaps if you look at large birds
61: (A) using the bird analogy..uh..if you look at large birds like storks they do have to run and flap to get off...but..uh I..uh you look at other birds they seem to be able to land on a dime...I am not sure..I uh
62: (B) well..it would have to be the thrust to weight ratio I guess you would have to be concerned with
63: (A) yeah..I
64: (B) you got to figure these are going to be alot of different companies making these suckers..so
65: (A) I..uh..well if we go back to looking at airports....

Line 58 of this segment specifically represents a stated comparison (described earlier) between ornithopters and helicopters. As part of the comparison, the subject identified attributes of a helicopter, take off and land, that established the relationship between the two analogues. At line 60, Subject C responded with an comparison between ornithopters and large birds, and at line 61, Subject A stated a similar comparison but instead identified an instance of large birds. Both of these comparative statements attempted to answer the question stated in line 58. At line 62, Subject B made a concluding statement that described why some birds run and flap to take off and others can "land on a dime", again attempting to answer the question stated in line 58. Termination of the episode occurred at line 64 or 65 where the group's attention was focused on another aspect of the design problem. Lines 58 through 63 clearly indicate that the group is engaged in decision making using

comparative statements (analogies and similes) to synthesize the conclusion stated in line 62.

The beginning of an episode is determined by either the intentional redirection of the topic of discussion that leads to analogy discourse or any other recognizable break in the conversational data. For example, line 64 represents a new thought that appears disconnected from the previous discussion. At line 65, the redirection of the group's focus simultaneously marked the end of the episode and potentially the beginning of a new episode. Line 47 represented a recognizable break in the data, it introduced a new topic through a question aimed at determining whether an ornithopter required the use of a conventional airport and was followed by a discussion that attempted to answer the question.

Using key words and phrases and recognized points of initiation and termination, nine episodes of similarity and analogical decision making were identified from the data. Transcriptions for each of these episodes are shown in Appendix C.

Communicative Behaviors Observed in Analogic Episodes

The next step towards developing a descriptive representation of the analogical decision making process is to identify salient communicative behaviors that appear in analogy episodes. Data recorded during the design session were transcribed and then reviewed to identify analogy episodes. All data, transcripts, and notes were reviewed to determine an initial catalogue of communicative behaviors. As this catalogue was applied to conversational data, it was modified to improve consistency in the interpretation and coding of data. The video recordings and transcripts were revisited when there were inconsistencies in the interpretation or coding of data. The development of a

catalogue of communicative behaviors was therefore an iterative process. Final communicative behaviors identified from the data are summarized in Table 2.

This cataloque of communicative behaviors is considered unique to analogy discourse because it specifically identifies behaviors that act on design information. As recorded data, transcripts, and notes were reviewed, communicative acts which appeared to aid the transformation of design information from one state to another were identified as communicative behaviors unique to analogical decision making. It is proposed that the identification and definition of communicative behaviors *which act on information particular to a given task* is essential in deriving a credible coding scheme and description for a communication process. In Neidermeier's study of small group decision making, Neidermier attempted to confirm Scheidel and Crowell's decision making codying scheme by applying the lag sequential analysis method to conversational data (Neidermeier, 1988). It was determine that no statistically significant message patterns existed among the data. It is proposed that Scheidel and Crowell's coding scheme was not sensitive to the task that was administered to the groups in the study. The task used in Scheidel and Crowell's study, and in Neidermeier's, was an evaluation of the Denver Post as a metropolitan newspaper and was given to groups from a computer manufacturing and distribution facility. What should have been done first in the study was the identification of communicative behaviors that were associated with the activity of evaluating a newspaper in a group setting. The analysis of these behaviors, using the lag sequential analysis method, might have then revealed patterns of interaction.

Verbal	*Example:*
1. Requirement Query • functional requirements • design requirements	"..the understanding is that uh a multipassenger ornithopter, right?" "..how much headroom is in an aircraft, about six and a half feet?"
2. Statements of Held/Acquired Knowledge • facts, constraints, conditions • physical and mechanical properties • engineering principles • concepts of physics • factual knowledge gained during session	"..wing size [of a bird] is twice the body length.." "..typical airplanes, 737, is a 120 passenger plane.." "..I don't know if that would be cost effective.."
3. Statements of Control • direct or redirect decision making focus • direct process or procedure	"..well if we go back to looking at airports.." "..go back to the ornithopter mind set.."
4. Statements of Comparison • analogy • analogy attributes • analogy generalizations or conclusions	"..so these things take off and land just like a helicopter" "..it flaps" "..have to be the thrust to weight ratio.."
5. Statements of Proposition • design goals • naming things • proposed solutions	"..use a parachute landing approach to get down in a minimal space.." "..omniornithopter.." "..have a small electric motor..and drive it like a small electric car"
6. Statements of Confirmation • approve • disapprove • questionable application	"yes" "..six feet is fine for me.." "..yeah thats the way a typical bird is designed.." "..I don't know if something like that could be.."
Non-Verbal	***Example:***
7. Gesturing	Subject uses his body to illustrate the condition of tilting in an airplane.
8. Sketching	Subject transforms verbal description into a sketch of the compartment space of an ornithopter.

Table 2: Communicative Behaviors Observed in Episodes of Analogical Decision Making

The strategy used in this study to develop a coding scheme is similar to that of Akin's who sought to describe design behaviors (cognitive) that transform design information from one state to another. Akin referred to these behaviors as primitive processes of design, or state transforms, and include the projection, acquisition, representation, and confirmation of information, and the regulation of flow of control (1986). However, these behaviors were based on protocols of individual designers performing design exercises and were used to describe the cognitive processes of the individual designer. The use of these categories is limited in this study because they represent cognitive processes of individuals, they do not represent communicative behaviors. In some ways, communicative behaviors proposed in this study are similar to Akin's cognitive behaviors. The following describes communicative behaviors identified in analogy episodes and, where appropriate, discusses similarities and differences with Akin's cognitive behaviors.

Requirement Queries

It was observed that questions asked in analogy episodes facilitated the understanding of a particular aspect of the emerging design and the elicitation of analogies to further the decision making process. Data from the observed episodes revealed that query statements initiate the derivation of functional requirements and the synthesis of design solutions. Functional requirements describe what the prototype is to do and design solutions represent physical embodiments that satisfy a particular requirement or set of requirements. Consider the following segment from the Rail System episode (Appendix C, p. 118) that illustrates the derivation of a functional requirement:

Requirement Query:

28: (A) the idea here is that it is not an individual..I,..I..this um..it doesn't say that you..you couldn't have a one passenger ornithopter does it?

29: (C) no

30: (B) but that but that would be..I don't know if it would be cost effective

31: (C) an omniornithopter

32: (A) the understanding here is that uh a multipassenger ornithopter, right?

Implied functional requirement:

33: (B) I would say...I would say it be analogous to our light rail system we have today

34: (A) yeah

The purpose of this segment was to determine whether an ornithopter functions as a multipassenger or single passenger vehicle as indicated by the question in line 28. Subject B responded to the question by making an analogy that proposed that the function of an ornithopter is similar to the function of an existing and familiar rail system (line 33). Subject B's analogy therefore implied that the ornithopter functioned as a multipassenger vehicle which was confirmed by Subject A in line 34.

Requirement queries were also observed to elicit analogies that supported the derivation of design solutions. This is illustrated in the following segment from the Beechcraft episode (Appendix C, p. 121):

Requirement Query:

299: (B) true true this this is just well like I said you've got the outer hull..and then..what I'm thinking you may have a box..where this is eight feet you know the seats are down here as far as head room goes..how much head room is in an aircraft, about six and a half feet...?

Personal Analogy:

300: (C) I crawled onto a Beechcraft up in Providence or Portland

301: (B) thats right you're going to be ducking down..so

302: (A) some of them you don't have a full amount of six foot head room I believe

303: (C) I was doing well to stand on my feet

304: (A) yeah

Design Solution:

305: (B) well thats about six feet

During this episode the attention of the design group was focused on the development of a sketch for the ornithopter compartment space. Subject B identified from the sketch the need to determine the amount of required head room (line 299) and Subject C responded to the question by reflecting on a past experience as a passenger onboard a beechcraft airplane. Jones (1981) refers to this reflection as a personal analogy where the projection of one's self into a situation or condition enables one to "feel" the situation or condition. This form of analogy aided Subject C in expressing the condition of crawling onboard a Beechcraft airplane. What followed were statements that described what it meant to embark onto a beechcraft airplane (lines 301, 302, and 303). Subject B then concluded that the amount of head room is six feet and recorded the decision on the sketch.

The amount of head room required for the ornithopter (six feet) is considered a design solution or embodiment because it satisfied the higher order requirement that the vehicle carry passengers. The analogy acted as a potential solution set and narrowed (constrained) choices available to the decision makers in terms of identifying the required headroom. The purpose of this particular episode, initiated by a query statement (line 299), was to derive a design solution subject to height limitations experienced in another situation (the personal analogy). These two examples illustrate that requirement queries elicit

analogies that aid the derivation of functional requirements and potential design solutions.

The *requirement query* behavior resembles Akin's state transform, *acquisition of information* (1986). Akin proposes that when a subject asks a question, obtains information from external sources, or recollects information, the subject is acquiring information. However, this behavior is purely a result of what was observed in the protocol of an individual, no interaction among multiple designers occurred to support design decision making. The fact that other subjects can act on or modify the information acquired through this behavior distinguishes it as a behavior different than that proposed by Akin. For example, in one protocol reported by Akin, the role of the researcher was simply to show slides of the design problem when asked by the subject (1986, pg. 31, Table 3.5). Such a request was coded by Akin as an attempt to acquire information.

Statements of Held and Acquired Knowledge

The data indicate that statements of held knowledge were made during analogy episodes to evince factual data, information, and concepts to support design decision making. Held knowledge was observed to include information that each interlocutor processed, acquired through previous design or personal experiences and tailored to address relevant questions pursued by the design group. Stated principles of engineering, mathematics, or physics, and other factual or precedential information that described how things are known to exist constituted held knowledge. Akin (1986), Anderson (1981), and Sussman (1973) consider this kind of information as declarative knowledge, represented and conveyed through objects, attributes,

and corresponding relationships. For example, the following utterance made during the design session described how lifting forces are a function of the velocity of air moving around a wing section:

> 433: (A) ....but you have the wing you have the faster moving air over the top giving you a certain pressure based on the velocity of the air and this velocity being greater causes its going a greater distance giving you an effective lift on a wing section and this is true regardless on how you orientate the wing...

This statement of held knowledge was made to describe how a flapping wing enables an ornithopter to fly, it focused attention on the physics of flight that must be considered in the design of an ornithopter wing. Table 3 summarizes several statements of held or acquired knowledge identified in analogy episodes. The data indicate that these statements either: established conditions or constraints that were considered in potential solutions; provided a reference point from which decision making proceeded from; or summarized what had been already determined in previous discussions (acquired knowledge).

Episode	Utterance	Purpose
Rail System	..I don't know if that would be cost effective (30)	drawn from personal experience, established a constraint to be considered in evaluating a design solution
Stork	..provided they [airports] are here in the twenty-first century (49)	established a condition for possible solutions for an ornithopter
Passenger	..typical airplanes, 737, is a 120 passenger plane (65)	established a reference point for possible solutions, led to a 40-50 passenger vehicle.
Jetsons	..keyed in on the larger vehicle and 10 to 20 people (409)	summarized the current state of the design solution, led to the evaluation of an alternative approach
St. Louis Arch	..when a bird flies when it lands the body actually tilts like that [gesture]	identified a condition that must be considered in the design

Table 3. Statements of Held or Acquired Knowledge identified in Analogy Episodes

Statements of Control

Statements of control refer to the intentional redirection of focus during design discourse. Line 65 from the Passenger Episode (Appendix C, p. 120) illustrates redirection of focus during design decision making:

> 64: (B) you've got to figure there are going to be alot of different companies making these suckers..so
> 65: (A) I..uh..well if we go back to looking at airports... the typical airplane uh your 737 is what a 120 passenger plane...

It was also observed that statements of control, in some cases, served two functions concurrently: first, to redirect the group's focus; and second, to provide a point of reference for subsequent dialogues and decision making. This is illustrated in the following utterance from the Parachute episode:

> 329: (A) yeah I huh think..I think if we huh go back to the huh ornithopter sort of mind set the wings are the parachute per se...

This utterance not only redirected the groups attention, but also provided a context ("..ornithopter sort of mind set..") from which the analogy between wings and parachutes evolved. In addition, statements of control played a role in identifying points of initiation and termination of analogy episodes as discussed earlier.

This behavior is similar to Akin's state transform, *regulation of flow of control*. However, what distinguishes the proposed behavior from Akin's state transform is that Akin's behavior represents the subject's control over his or her own thought processes. The control behavior proposed in this study, reflects the exercise of control by an individual on the group's decision making process. They are however similar in that they both attempt to identify new goals or issues to address in the design effort.

Statements of Comparisons

Statements of comparison observed in episodes of analogical decision making consisted of the identification of base and target knowledge domains and corresponding attributes that defined relationships between the two. This is illustrated in the following utterance from the Stork episode (Appendix C, p. 119):

> 58: (B) "...so these things [ornithopters] take off and land just like a helicopter..or do they need a little bit of runway to get themselves airborne?"

Here helicopters and ornithopters represent the base and target domains, respectively. This statement is essentially a proposition supported by attributes, take off and land, "mapped" from the base to the target domain in an attempt to describe capabilities of ornithopters. These attributes qualify the comparison between ornithopters and helicopters, they describe characteristics shared by both domains. The questionable (unmatched) attribute in line 58, “does it require a runway”, evoked further investigation to validate or determine the applicability of the comparative statement.

Even though a single interlocutor constructed this comparative statement, the fact that it was articulated to the group provided opportunity to challenge the appropriateness of attributes that established the similarity of the two domains or to determine whether or not the two domains were the "correct" domains to compare. The second part of the utterance that asked if ornithopters needed a runway represented an attribute that not only checked the validity of the comparison, but also necessitated a subsequent alternative base domain (something other than helicopters) to further decision making.

This is clearly the case as illustrated in Subject's C response (Stork Episode, Appendix C, p. 119):

> 60: (C) I..I never..it flaps if you look at large birds

Subject C introduced a new comparative statement where "large birds" represented the base domain and "it flaps" represented a shared attribute with ornithopters. This alternative comparative statement established a condition of flapping to be considered in answering the original question, do ornithopters need a runway? Subsequent utterances illustrate how these comparisons furthered the decision making process:

> 61: (A) ..using the bird analogy..uh..if you look at large birds like storks they do have to run and flap to get off..but..uh I uh you look at other birds they seem to be able to land on a dime..I am not sure..I uh
> 62: (B) ..well it would have to be the thrust to weight ratio I guess you would have to be consemed with
> 63: (A) ..yeah..I..uh

Subject B's response represents an analogy generalization (line 62), inductively drawn from information provided by previous comparative statements and corresponding attributes. In this example, the generalization represented a design heuristic that was used in the design of the ornithopter and appeared in later segments of design discourse.

Statements of Proposition

Statements of proposition represent design goals or proposed solutions which are generally derived through internal processing of information by an individual designer. The conditions or supporting information of a proposed

solution are not necessarily made available to other group members for evaluation. Consider the following segment from the Stork episode:

Requirement Query:

50: (A) no..you..you take this ornithopter concept..does it require a conventional airport?....

Proposed Solution:

I..I..my inclination here is that it could land on a roof top or parking lot..I..uh

51: 52: 53: all mumble

Proposed Solution:

54: (C) kind of like a helopad on a drilling structure or top of a roof of a executive building

55: (A) yes

Proposed Solution:

56: (C) I..even a marked off space in a parking lot..uh..of a company

57: (A) yes

Comparative Statement:

58: (B) so these things can take off and land just like a helicopter..

Based upon the initial question stated in line 50, both Subject A and C proposed locations where an ornithopter might land, representing potential solutions (lines 50, 54, and 56). Because no information was provided that qualified each proposed solution, acceptance seemed to have been predicated on a mutual understanding of the solution and context. Clearly processing of information internal to each interlocutor had occurred.

In the Jetsons episode (Appendix C, p. 124), a question and proposed solutions led to the acquisition of a design goal. The design goal was to identify a solution that was more personable. In this case, proposed solutions acted as physical embodiments that aided development and confirmation of a concept for a "personable" vehicle:

Design Goal:

409: (C) we've seemed to keyed in on the larger vehicle and 10 to 20 people what about something more personable approach...cars

for instance are personable and go from point A to point B and C and they're also used for intercity

411: (C) could could you dream up a vehicle that would be pilotable by the average person?

Comparison:

412: (A) this is the Jetsons concept

Requirement Query:

415: (A) yeah the thing that made me question that is the huh the ornithopter huh mode of flapping to get you going doesn't seem very personable to me...you know how do you land it in your driveway?

Proposed Solutions:

416: (C) well you you use the streets..most streets are wide enough may maybe there is going to be required a little forward motion and you'll have to move street lights out of the way

417: (B) either that or once you've landed the wings retract and fold up and you'll have a small electric motor and you drive like a small electric car... once you're near your destination you land at a port and drive the rest of the way

Confirmation:

420: (A) yeah

421: (C) yeah

422: (B) go that route to be personable

In response to the question asked in line 415, Subjects B and C proposed potential solutions directly related to the design goal expressed in line 409 and 411. The analogy provided a solution set from which solutions were generated. The Jetsons concept is a children's cartoon where characters travel in airborne compact vehicles, something like present day automobiles but without wheels. Jones (1981) referred to this as a fantasy analogy, characterized by imagining things as they are known not to be.

The data suggests that statements of proposition played several roles in analogy episodes. First, it appeared that statements of proposition established a context for analogy as illustrated in the Stork episode. As a second role, statements of proposition validate or confirm, through physical embodiments,

concepts previously stated through analogy as illustrated in the Jetsons episode.

Statements of proposition resemble Akin's state transform, *projection of information*. Akin described the projection of information as an act of inference making, combining new information to what is known to obtain new or modified information. The difference between the behavior proposed in this study and Akin's projection of information, is that, members of the design group have the opportunity to consider and respond to the information provided through this communicative behavior.

Statements of Confirmation

Simply, statements of confirmation represent utterances that either accept, question, or reject presented information. These statements might also be made to question the appropriateness, applicability, or consistency of presented information. The following table summarizes several statements of confirmation identified from the data and describes the role each played in design decision making. However, the utterances shown in the table are considered exceptional, the most common utterance used to confirm information was "yeah." This behavior is similar to Akin's state transform, confirmation of information in concept, it differs in that group members have the opportunity to agree, disagree, or expand on a statement of confirmation.

Epsiode	Utterance	Purpose
Paradigm	line 8: ..maybe thats a pretty good design technique..	Subject agreed with the idea to use a cam device that would enable wings to flap and rotate
Parachute	line 335: ..yeah thats the way a typical bird is designed..	Confirmed a sketch that was made to determine how ornithoptic wings are like parachutes
Jetsons	line 422: ..go that route to be personable..	A statement made to confirm proposed design solutions that support a stated analogy.
Wing Size	line 446: ..right I mean thats not atypical..	Confirmed the assumption that a bird's wing span is twice its body length

Table 4: Statements of Confirmation in Analogy Episodes

Gesturing and Sketching

In Tang's study of design workspaces, it was observed that gesturing and sketching were nonverbal behaviors that supported design decision making (Tang, 1989). Each acted, at varying degrees, to store information, support the expression of ideas, and mediate interaction within the design group. Akin (1986) considered sketching as a state transform referred to as *representation of information*. Based on data from this study, gesturing and sketching were observed to be inextricably involved in analogic discourse, filling communication roles similar to those identified by Tang. In fact, it was observed that gesturing and sketching were so enmeshed in the communication process that it was often difficult to dissect verbal from nonverbal behaviors without corrupting intended messages. The following utterance from the St. Louis Arch episode (Appendix C, p. 123) illustrates the role of gesturing in analogy discourse:

> "see now when a bird flies when it lands the body actually tilts *like* that ..[gesture] we can't have that I mean I don't know about you if I'm sitting in a plane and all of a sudden the plane did one of these numbers..[gesture]"

The subject first used gesture to convey the tilting action of the bird's body using a hand motion. The rest of the utterance represented a type of analogy that Jones (1981) refers to as a personal analogy where the projection of one's self into a condition provides a means to "feel" the condition. The subject indicated this condition by tilting his body congruent with the condition of a bird's tilting body. It appears that there were two aspects of information conveyed in this utterance. The first is that data conveyed through the utterance identified what a bird does when it lands, that is, it tilts. The second aspect described what it means to tilt and was conveyed through

the personal analogy. Therefore, it appears that gesture aides the interpretation of presented data.

The activity of sketching was observed in three of nine analogy episodes and played an important role in the derivation of analogy generalizations or design solutions. The role of sketching in each of the three episodes is summarized in the following table:

Episode	Sketching Activity
Beechcraft	Developed a sketch of the internal compartment space of an ornithopter, led to a determination of required head room based on a personal analogy.
Parachute	Developed a sketch that described how the wings of an ornithopter are like a parachute, led to a "stubby" wing concept.
St. Louis Arch	Sketch aided visualization of a proposed scheme for a self leveling module resulting from an analogy between the tilting motion of a bird and the St. Louis Arch.

Table 5: Summary of Sketching Activities in Analogy Epsiodes

The Beechcraft episode was initiated by a subject sketching a proposed internal arrangement of an ornithopter and concurrently stating a question concerned with the required headroom for the compartment space. What followed was an analogy that described a personal experience of embarking on a Beechcraft airplane. The analogy led to a headroom requirement of six feet which was recorded on the sketch. Clearly the sketch provided a point of reference from which a requirement was identified and an analogy was evoked to derive a solution. It also acted as a record of the decision made by the group.

The sketching activity observed in the Parachute and St. Louis Arch episodes performed a somewhat different function than observed in the Beechcraft episode. In these episodes an analogy had already been stated, the sketch represented a physical representation that aided the understanding of the analogy through visualization . In the Parachute episode a subject

sketched how ornithopter wings are like parachutes and in the St. Louis Arch episode a subject sketched the self-leveling action of passenger cars as they traveled through the arch, similar to the tilting action of a bird's body. These three episodes suggest that sketching provided a point of reference for subsequent analogy discourse or aided visualization of aspects of an analogy.

The Structure of Similarity and Analogy in Design Discourse

To aid the visualization of a structure for analogical decision making, episodes identified from the transcripts were coded using communicative behaviors defined in Table 2 and graphically portrayed as an *analogy decision making graph* (ADG) as illustrated in Figure 3. The ADG provides a means to graphically represent behaviors, their relationships, and suggestive processes that might support design decision making. The ADG, supplemented by the lag sequential analysis method, is used to determine if the decision making process can be described as a recognizable and reoccurring process. The lag sequential analysis method will be used in the next section to analyze sequential aspects of the ADG.

Analogues, their corresponding attributes, and analogy generalizations or conclusions, as well as other communicative behaviors, are mapped in the order in which they occurred in the episode. As shown in the Figure 3, a horizontal line with arrowheads on each end represents an analogy and identifies the target and base analogues. A target or base analogue may be located to the left or right of the vertical line. Attributes that are perceived or interpreted to establish or maintain a relationship between a target and base analogue, referred to as a *matched* attribute, are recorded to the right of the vertical line. Unmatched attributes are recorded to the left. No sequential order is implied in this illustration, it serves only to clarify the method for

mapping communicative behaviors. Also indicated on the ADG are the subjects associated with a particular utterance, indicated as subject A, B, or C.

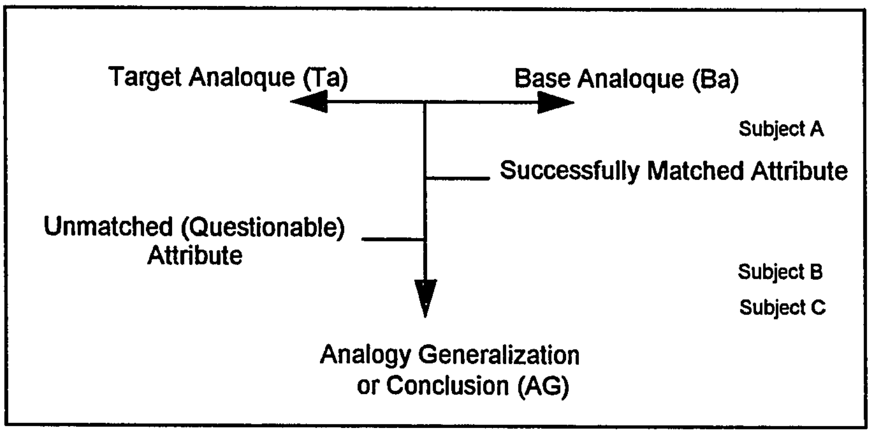

Figure 3: Analogy Decision Making Graph (ADG)

By graphically representing episodes of analogical decision making in this manner, components of an analogy are discernible and their influence on antecedent and subsequent behaviors can be evaluated in the episode. The ADG provides one method to represent analogy discourse, target and base domains, supporting attributes, and the generation of analogy generalizations and conclusions.

Prior to building an ADG the following operationally defined rules of interpretation for communicative behaviors identified in Table 2 are used to code transcribed data:

1. When a subject asks a question concerning the functionality of some aspect of the prototype or specific design requirement, the utterance is coded as a requirement query (RQ).
2. When a subject articulates factual information such as physical and mechanical properties, principles of engineering or physics, or factual

knowledge gained during the design session, the utterance is coded as a statement of held/acquired knowledge (S). Statements of held knowledge do not directly relate to an analogy; instead, they represent information that may be considered during design decision making by acting as a constraint or condition. In addition, when it appears that a subject has acquired information from a sketch or the problem statement provided to the group, the utterance is coded as a statement of held/acquired knowledge.

3. When a subject comments or suggests how to proceed or changes the focus of attention, the utterance is coded as a statement of control (Cn).

4. When a subject makes a statement that can be interpreted as a comparative statement, the utterance is considered an analogy. The base and target analogues of an analogy are each identified and coded as separate analogues (An). If attributes of either analogue are stated, they are identified and coded as an analogue attribute (Aa). For an utterance to be considered an analogue attribute it must directly relate to an analoque and the comparative statement that identified the analogy. Any personal reflections or fantasy references that appear to suggest a comparison are considered to be an analogy.

5. When a subject states a potential design solution, which may represent a design goal, the utterance is coded as a proposed solution (PS). These utterances usually represent the product of internal reasoning of an individual.

6. When a subject confirms or questions the validity, appropriateness, or consistency of a given piece of information, the utterance is coded as a statement of confirmation (Cf).

7. Because of the complex interaction observed in the design session between verbal behaviors and gesturing and sketching, gesturing and sketching are not coded as separate behaviors. As reported by Tang (1989) and observed in this study, these nonverbal behaviors are almost always accompanied by explanations or other verbal behaviors. Therefore, gesturing and sketching are tagged to corresponding verbal behaviors and are identified to enhance interpretation and understanding of utterances. A greater degree of fidelity, more than what is required in this exploratory study, would be required to identify and measure these behaviors.

The following example illustrates the process of mapping communicative behaviors as well as the application of behavior codes to transcribed utterances. The Stork episode is used to illustrate this process because it contains aspects of analogical decision making found in the majority of recorded episodes.

As utterances are coded they are mapped as an ADG while maintaining the sequence in which they occurred. Utterances that do not convey complete information required to achieve some degree of understanding are not coded. The transcript for the stork episode is provided in Appendix C (page 119) and the corresponding ADG is shown in Figure 4.

Referring to Figure 4, the Stork episode was initiated by a requirement query (line 47). Note that even though an analogy statement was not made until line 58, prior utterances that are determined to be relevant to the subsequent analogy are included so that an evaluation of behaviors that trigger or initiate analogy can be made.

As illustrated in the ADG, prior utterances (lines 47 to 57) established the context for the analogy. Each of the proposed solutions, " could land on a roof," " like a helopad on a drilling structure," and "marked off space in a parking lot" established an implied requirement for some degree of vertical ascent and decent capability which led to the analogy in line 58. The analogy in this case (line 58), in a sense, acted as a generalizing statement that identified a familiar knowledge domain (helicopter) that satisfied the requirement. What follows are subsequent communicative behaviors that validate and facilitate a better understanding of this initial analogy. Referring to line 58 in the ADG, the analogy of this episode, as stated by Subject B, is decomposed into elements that are considered to constitute analogy. The reference made to ornithopters, "these things," represented the

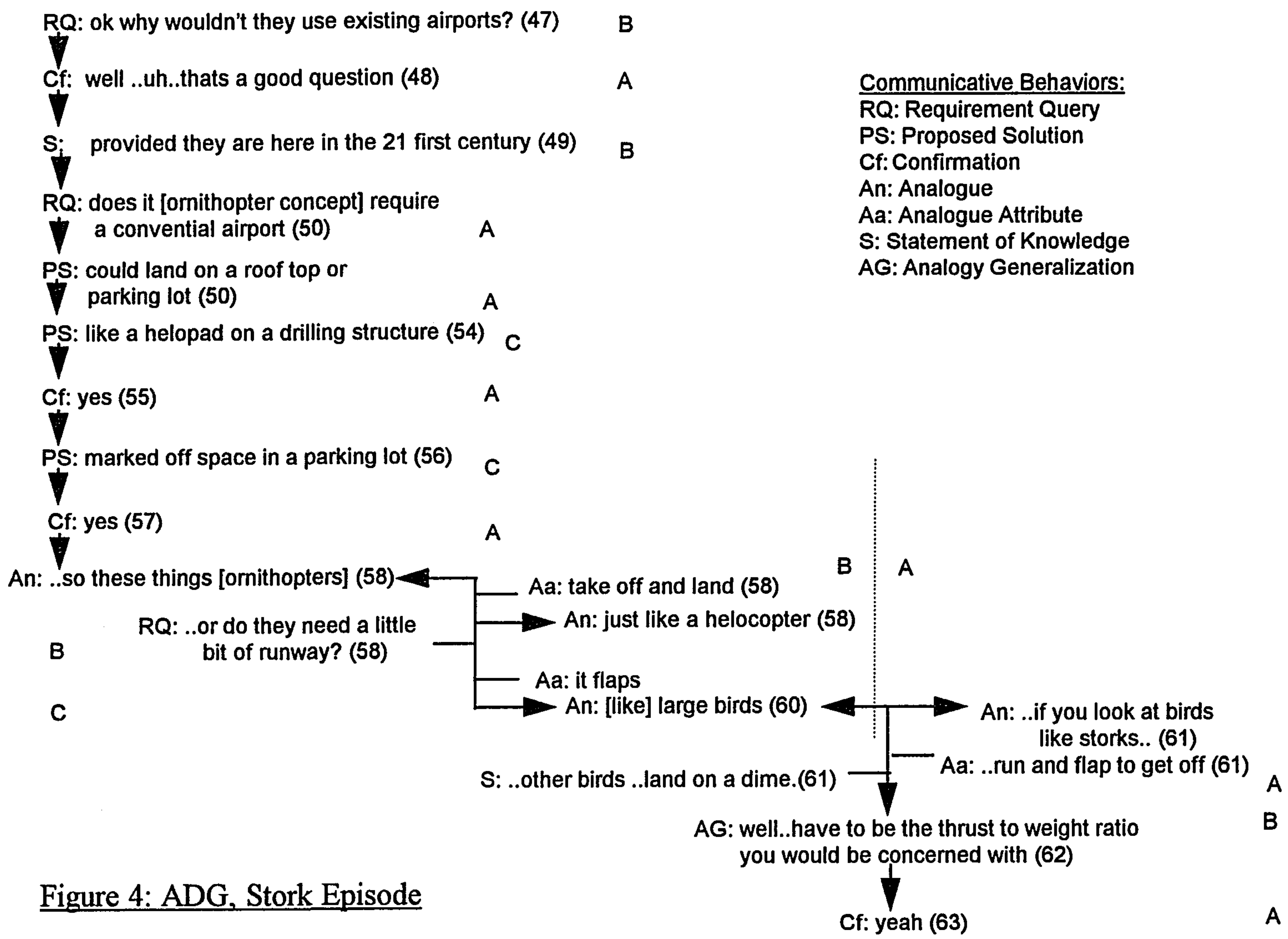

Figure 4: ADG, Stork Episode

target analogue or item to be explained. The explanation occurred through a comparison to a known and familiar body of knowledge, helicopters, which represented the base analogue. The relationship that described how ornithopters are like helicopters is established by the attribute "take off and land." Note that the order of the analogy components as they are stated is maintained.

As recorded on the ADG, Subject B then posed a question that represented an unmatched attribute (line 58), unmatched because requiring a runway is not what a helicopter necessarily requires for taking off and landing, but may be required for an onithopter. In response to Subject B's question, Subject C builds upon the previous analogy by stating another analogy (line 60) between ornithopters and large birds. The relationship is established by the matched attribute "it flaps." Subject A then identified an instance of large birds, storks, and stated a matched attribute that described how storks are like birds, they have to run and flap to take off (line 61). However, Subject A also identified a condition that doesn't necessarily support the relationship that defines how storks are like large birds, that is, "..other birds...land on a dime." This utterance represents an exception to the previous comparison and analogic relationship, it represents a new or alternative condition that exists in the domain of birds. This utterance is considered as a statement of held knowledge because it is recollected from a body of knowledge held by the subject and acts to constrain subsequent design soluitons. To reconcile the relational difference, that is, why some birds have to run and flap and others can land on a dime, Subject B stated an abstract schema that generalized the two conditions in line 62. This abstract schema is a design heuristic that can be used to determine the degree of vertical ascent and decent of an ornithopter based upon its weight and

generated thrust. Subject A confirmed this analogy generalization as indicated by line 63.

It is important to note that the analogy generalization may not necessarily represent a true "synthesis" of the stated analogy and attributes, the subject might have been already aware of the design heuristic stated in line 62. Instead, it might be said that it was through analogy discourse that an "appropriate" heuristic may have been evoked from the subject's memory to satisfy conditions established by the analogy.

The coding of utterances is not as straight forward as it might appear, sometimes judgment must be used where utterances appear to serve more than one function. For example, the initial utterance in the stork episode (Figure 4, line 47) can be interpreted as a statement of control as well as a requirement query. To reconcile the dual purpose of the utterance, judgment is applied in regards to the role of the utterance in the episode.

Each of the nine episodes identified from the data are mapped as an ADG. Corresponding transcriptions and ADGs for each episode are shown in Appendix C and D respectively. An examination of ADGs revealed several key aspects of similarity and analogical decision making as observed in analogic episodes. The following discusses these aspects.

Table 5 summarizes each of the observed episodes, their goals, analogy attributes, and resulting generalizations and conclusions. Analogical decision making involved comparisons among conceptual domains and instances. These comparisons were accompanied by matched or unmatched attributes. In the Rail Episode, for example, first a comparative statement was made between an ornithopter and a light rail system. Then a second comparison was made between the same target analogue and Pentran (a local bus system).

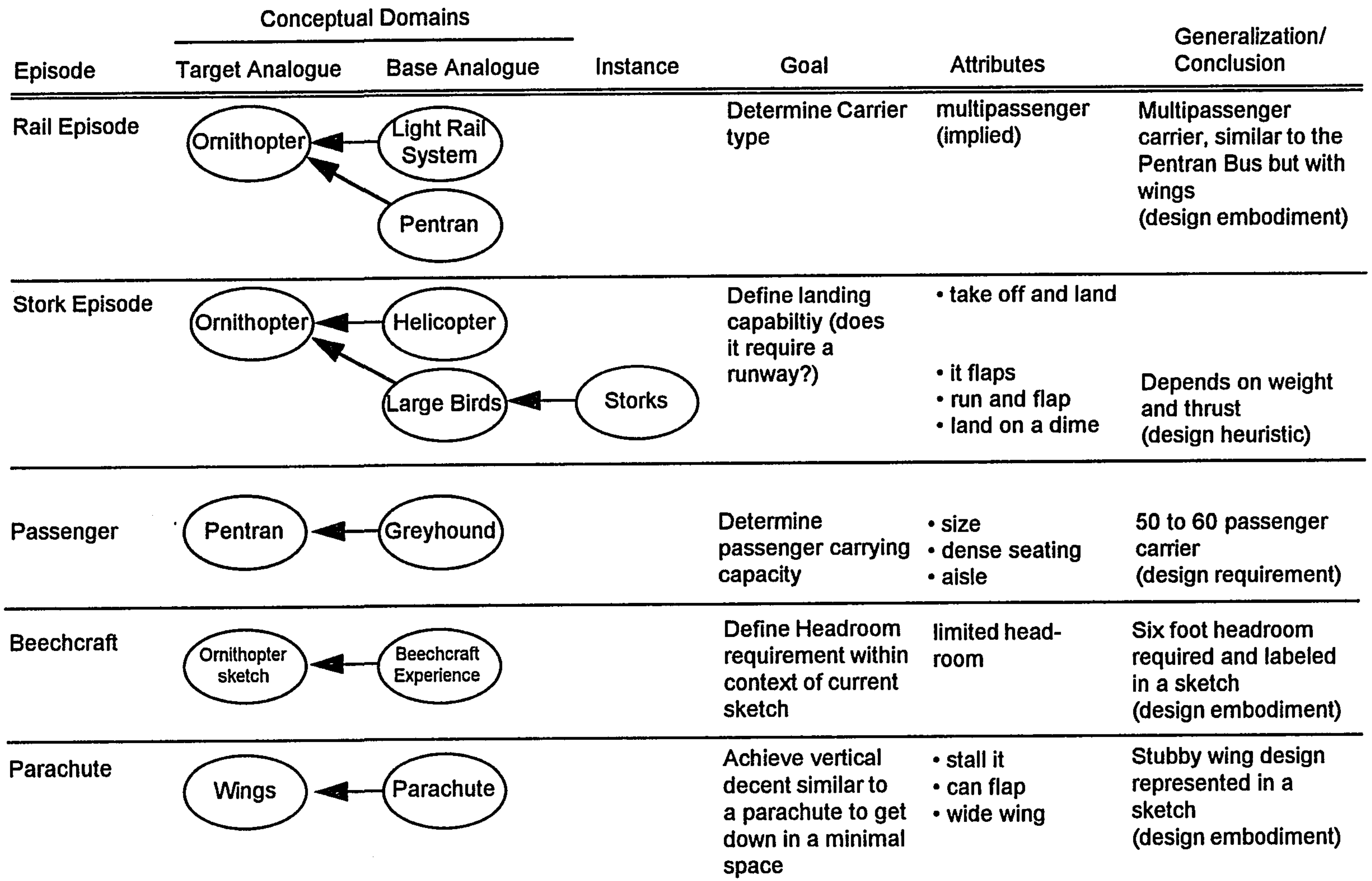

Figure 5: Summary of Similarity and Analogy Episodes

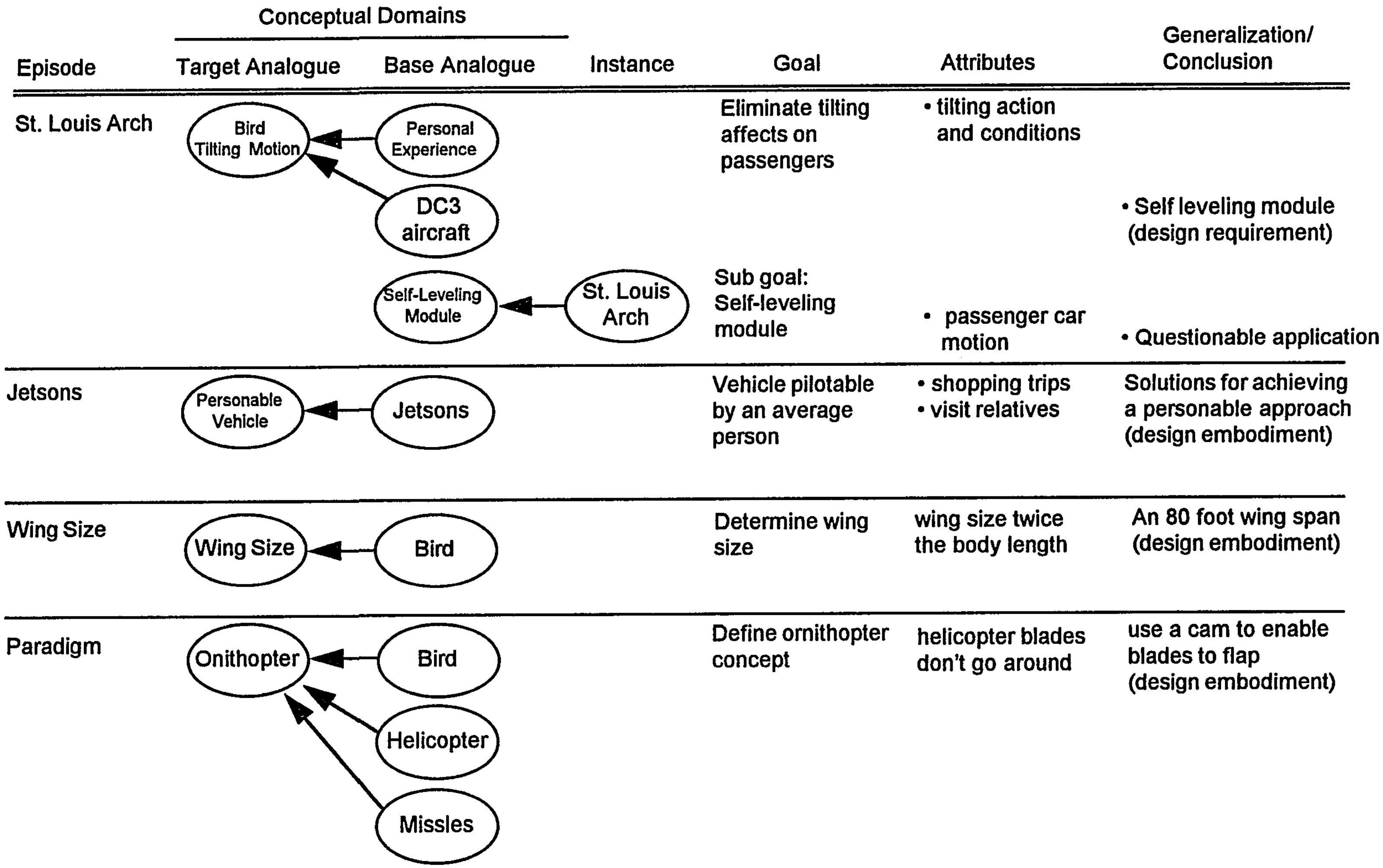

Figure 5 (con't): Summary of Similarity and Analogy Episodes

What is important to note in each of these episodes is that attributes facilitated an understanding of a target domain. Attributes of each of the stated archetypes or exemplars were selectively mapped to a target domain in an attempt to explain or describe the target domain.

In the Stork Episode comparisons between conceptual domains (ornithopter, helicopters, and large birds) appeared inadequate, further explication through a known and familar instance was required to achieve the goal of the episode, i.e., determine if an ornithopter requires a runway. Comparative statements about how ornithopters are like helicopters and large birds represent comparisons between conceptually different domains. This differs from the comparative statement made between large birds and storks. Here the comparison occurred within the same knowledge domain, because storks represent an instance or subset of large birds. Because the concept of an ornithopter is what is being defined by the design team, it can't yet be said to exist within the knowledge domain of helicopters. All that is known is that ornithopters are vehicles for human transport that fly by flapping appendages. The question remains, how are ornithopters like helicopters? What can and can not be considered to exist within a common knowledge domain therefore depends upon the current state of held knowledge. We know that storks are a type of large birds, but we do not know (yet) if an ornithopter is a type of helicopter or if a helicopter is a type of ornithopter.

For each of the identified episodes an implied or explicitly stated goal can be identified. For example, in the Parachute episode the initial utterance identified a goal to land in a minimal space. What resulted through analogy discourse was a "stubby" wing concept that catches enough air to allow an ornithopter to land in a minimal space. The importance of a goal in each of the episodes was to constrain or tailor solutions that can be proposed by the

subjects. Essentially design goals support the development of a context in which solutions can be proposed.

The data suggests that there were four approaches used in analogy discourse to converge toward an analogy generalization or conclusion. As illustrated in the Passenger, Beechcraft, Parachute, Jetsons, and Wing Size episodes, single comparisons between base and target domains led to analogy generalizations. Where single comparisons were inadequate, additional base analogues were identified to further understanding of a target analogue. This is illustrated in the Rail and Paradigm episodes.

The Stork episode illustrates a third method where properties of analogies and attributes appear to have been cascaded down to a more familiar instance in an attempt to further define or understand an initial analogy. Attributes, acting as constraints, influenced the selection of subsequent analogues until some conclusion was reached.

The St. Louis arch episode also illustrates a cascading of requirements and constraints to subsequent comparisons. However, in this episode the initial analogy generalization, the concept of a self-leveling module, represented a subgoal that led to further comparative discourse. An exemplar that employed the self-leveling concept was used to explicate the concept , the St. Louis Arch. The comparison made was between the operational concept of passengers cars within the arch and that of the self-leveling module concept as defined by previous analogies between the tilting action of a bird, a DC3 aircraft, and the personal reflection of embarking on a beechcraft airplane.

It was also observed in the Stork episode that analoques switched roles as either the base or target analogue. In the stork episode the analoque, "large birds", represented the familiar or base domain used in the comparison

to ornithopters. This analoque then became the target domain when Subject A made a comparison to storks and supported the comparison by stating matched attributes. The role switching of analoques appears to support the decomposition and further understanding of a previously stated analogy.

As shown in Figure 5 episodes of similarity and analogical decision making result in either design requirements, heuristics, or design embodiments. The role of design requirements was to act as a constraint, narrowing the range of alternative solutions available to the designer. For example, in the passenger episode it was determined that fifty or sixty passengers would be carried by an ornithopter. This requirement clearly established a lower limit on the volume to be afforded by the ornithopter's compartment space. In fact, this requirement later guided the development of a sketch for the compartment space. The Stork episode was the only episode that resulted in a design heuristic. Even so, it was used later in the design session to sketch dimensions of the prototype.

The data suggest that design embodiment directly captures implications of design requirements in physical representations, which are often conveyed through sketches. It appears that design embodiment was used purposely to validate or assess the appropriateness of a requirement derived through previous comparative discourse. This can be thought of as a means to gain a more indepth understanding of a particular requirement or sets of requirements. Design embodiment occurred in six of the nine episodes as indicated in Figure 5. A design embodiment is a physical representation derived through analogy discourse that was either stated or conveyed in a sketch. The Rail, Jetsons, Wing Size, and Paradigm episodes illustrate derived and stated design embodiments that represent physical solutions that satisfy particular design goals. The Beechcraft, Parachute, and St. Louis

Arch episodes resulted in design embodiments that were reflected in sketches.

The activity of deriving design embodiments can be thought of as a *synthesis* of design solutions, and, in accordance with Suh's proposition, occurs through the mapping of functional spaces to physical spaces (1990). Based on the data, design synthesis can be described as the transformation of requirements, aided by similarity and analogy, into a physical embodiment that depicts the current state of a design solution:

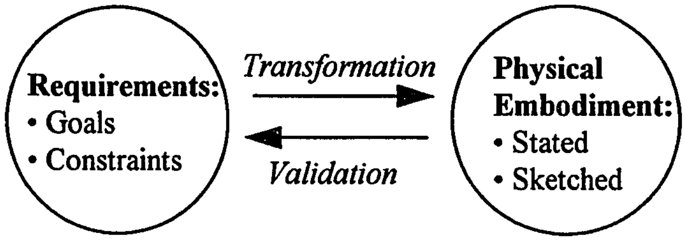

Figure 6: Design Synthesis

A key activity of all observed analogy episodes is the elicitation of requirements and the evaluation of requirements against goals and constraints defined in an initial problem statement. In some episodes the evaluation of requirements, in terms of assessing validity or appropriateness, occurred through a synthesis process that resulted in a physical representation or description. More specifically, the synthesis process was initiated by the mapping (or allocation) of requirements to analogues of an analogy. Relationships established by the analogy and its attributes were then used to develop a physical representation that satisfied goals and constraints of the requirement. Physical representations were conveyed in sketches and drawings developed by members of the design group. The Parachute Episode illustrates the synthesis process:

Requirement Identified:

328: (C) maybe we can use a parachute landing approach..to get down in a minimal space

Requirement allocation and Analogy:

329: (A) yeah I huh think..I think if we huh go back to the huh ornithopter sort of mind set the wings are the parachute per se I think if you stall it huh

330: (B) you can you can flap the wings

Synthesis:

331: (C) well in plan view then your vehicle..just drawing half of it..is going to have to have sizable length you're talking about wings probably..two times..the aspect of of normal wings cause if your're coming down you're going to come down gently enough you'll have to catch a fair amount of air

332: (B) yeah

333: (A) yeah

334: (C) and you've got to do it in length

335: (A) yeah thats the way a typical bird is designed I believe

Physical Embodiment:

336: (C) kind of a stubby wing

The episode began when Subject C proposed that a parachute landing approach would enable an ornithopter to land in a minimal amount of space. This proposition represented a design goal and invoked the requirement to land in a minimal amount of space (line 328). Subject A then made an analogy between ornithopter wings and parachutes and qualified the comparison by stating a matched attribute, i.e., "if you stall it" (line 329). At that point in time, not only had the requirement been identified and defined, but it also had been allocated to the wings of the ornithopter. Note that Subject C identified the design goal (requirement) in line 328 and Subject A allocated the requirement to the ornithopter's wings through the analogy in line 329. In this episode the allocation of the requirement initiated the synthesis process through its association with a physical aspect (wings) of an

ornithopter. Subject C then began to sketch a plan view of the vehicle using current information known about the design of an ornithopter (line 331). This sketch is shown in Figure 7. Subject C then sketched the wings and Subject A confirmed the sketch by stating how it matched the known physical configuration of a bird (lines 334 and 335). What is important is Subject C's concluding remark that designated the design solution as a "stubby wing." This design solution represented a generalization of the analogy, drawn from the relationship created by the analogy and conveyed in the sketch. This episode clearly illustrates the design synthesis process that effectuates the transformation of requirements, aided by analogy, into a physical representation or description.

It was also observed that even though the synthesis process resulted in physical representations, physical representations and/or requirements were sometimes determined to be inappropriate and, thus, not accepted and assimilated into the current concept of an ornithopter. This suggests that the synthesis process facilitated visualization of the meaning of a requirement as a means to assess the appropriateness or validate either the requirement or physical representation. The St. Louis Arch Episode (Appendix C, p. 123) illustrates how sketching aided the determination that an initial requirement was inappropriate for the current concept of an ornithopter. The episode began when Subject B made an analogy between the tilting motion of a bird when it lands and the personal experience of sitting in a plane that also tilts when it lands (line 337). To support the conveyance of what it meant to tilt while landing, Subject B gestured the action with his hands and body. What followed was the sketching of the tilting motion of passenger cars as they traveled through the St. Louis Arch. In addition, based on the sketch, the subject gestured to emphasis the shifting and tilting of the cars. What

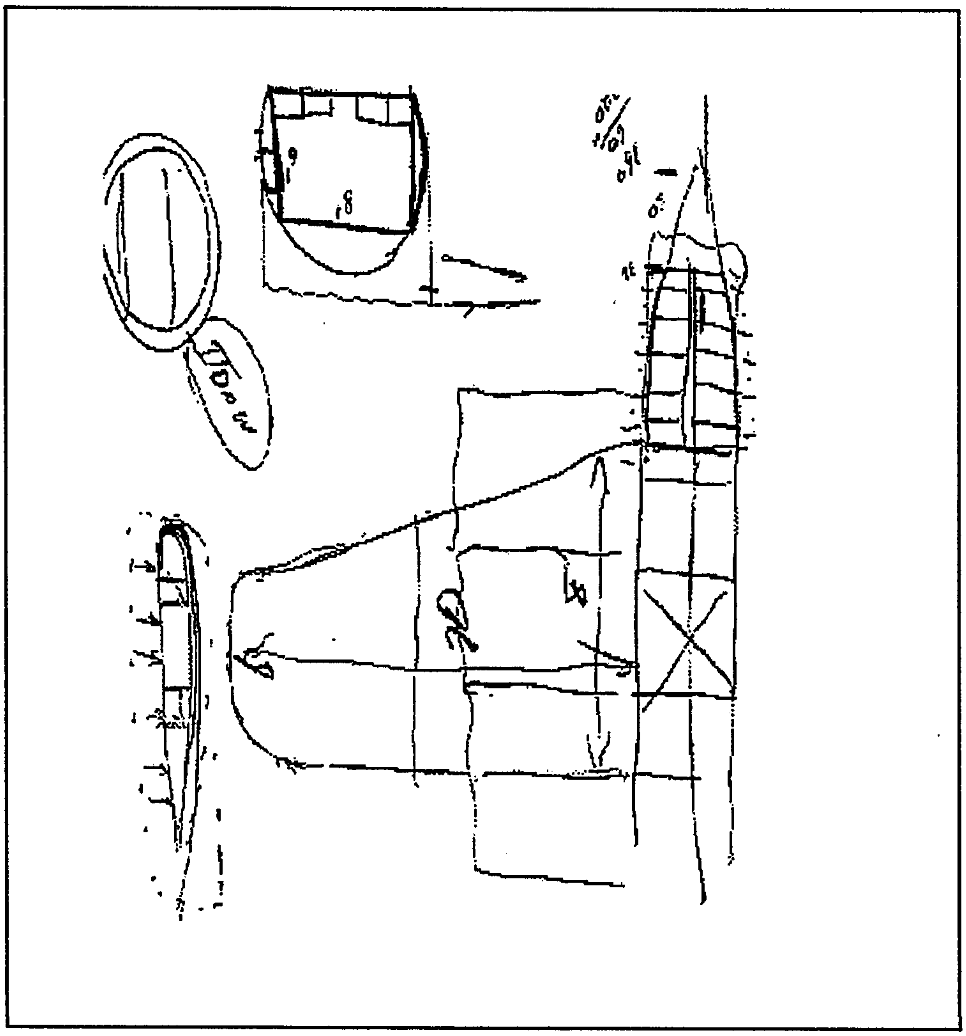

Figure 7: Stubby Wing Sketch, Parachute Episode

resulted, however, was that the subject questioned the applicability of the tilting concept in the current design of the ornithopter. In fact, the concept was never considered again during the design session.

The Process of Analogical Decision Making in Collaborative Design

To develop a descriptive representation of analogical decision making, communicative behaviors coded in analogy decision making graphs (ADGs) are evaluated for possible patterns of reoccurring interaction. In Chapter Two it was hypothesized that humans influence a communication system through communicative behaviors. If the punctuation of these behaviors can be determined to be cyclic, then it becomes possible to describe a communication process.

To investigate the occurrence of possible patterns of interaction, sequences of communicative behaviors shown in ADGs are analyzed using the lag sequential analysis method. The frequency of two event sequences (behavior A followed by behavior B) and transitional probabilities for all episodes are determined using the calculation method described in Chapter Three. These calculations are provided in Appendix E and are summarized in Appendix F.

Using ADGs presented in Appendix D, frequencies determined for coded communicative behaviors are summarized in Figure 8. The behaviors *confirmation* (Cf), *analogy attribute* (Aa), and *analogue* (An) each approximately represent 20% of the total communicative acts observed during episodes of analogical decision making, combined they represent 60% of all observed behaviors. *Proposed solution* (PS) and *statements of held/acquired knowledge* (S) represent only 24% of the total communicative behaviors. This distribution suggests that a significant effort by the design group is

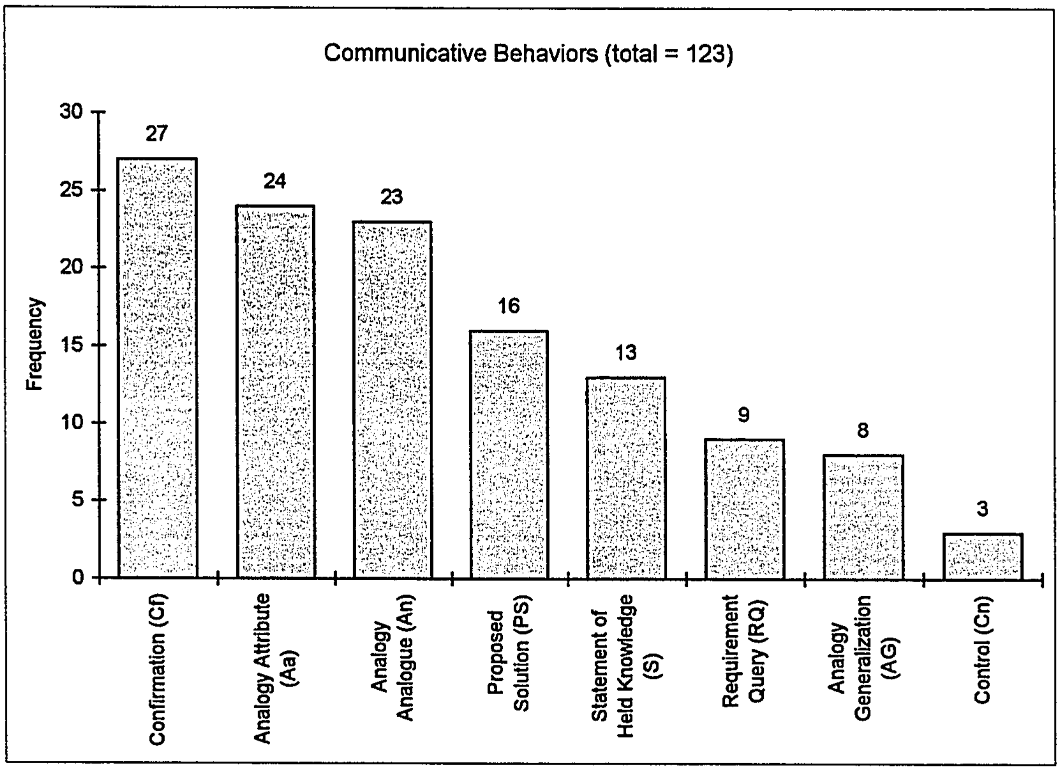

Figure 8: Frequency of Communicative Behaviors Observed in Episodes of Analogical Decision Making

placed on the proposition of analogues, the identification of corresponding attributes to support analogy, and confirmation of the appropriateness of analogy and attributes for a predefined context or goal. On average approximately four communicative behaviors proceeded the articulation of an analogy, and included, requirement query (RQ), proposed solution (PS), and statements of control (Cn) and confirmation (Cf). As shown in the following distribution these prior behaviors appear to establish a context for analogy discourse, limiting the use of known analogues available to the designer and effectuating the tailoring of those that are articulated toward the achievement of a stated or implied goal:

Behavior	Occurrence prior to analogy	Total Observed	% of Total
RQ	7	9	78
Cn	2	3	67
PS	9	16	56
S	6	13	46
Cf	7	27	26

These data indicate that the occurrences of RQ, Cn, and PS prior to analogy is greater than 50% of each of their total observed occurrences. Subsequent analogues can therefore be considered as solutions sets that are selected internally by a designer based upon an established context or goal. Even though the behavior *control* (Cn) represented only 2% of the total observed behaviors, it was important in influencing possible paths that analogy discourse may follow. This was observed in three of the nine episodes. For example, in the Parachute episode (Appendix C, page 122, line 329) the control statement (Cn) "..go back to [the] ornithopter mind set" established a frame of reference for subsequent discourse, it implicitly constrained potential

solution sets available for analogy discourse. The control statement identified in the Passenger episode (Appendix C, p. 120) also provided a context for subsequent discussion and redirected the group's focus:

line 65: ....well if we go back to looking at airports..

Based on the summary of transitional probabilities provided in Appendix F, two event sequences that suggest patterns of interaction are described in the following discussions. Figure 9 illustrates a general pattern of analogical decision making behaviors for two event sequences while holding the behavior analogue (An) as the criterion behavior. The criterion profile indicates that An inhibited analogy generalization (AG) and proposed solution (PS) while exciting analogy attribute (Aa) and An at a lag one condition. As analogy discourse continued, Aa became increasingly inhibited and AG and PS increasingly excited by the criterion behavior. It also appears that An was inhibited after lag one. At lag six, the conditional probability of AG exceeded that of Aa. This profile suggests that after the articulation of analogy analogues, decision making was primarily focused on analogy attributes followed by either analogy generalizations or proposed design solutions. This suggests a communicative behavioral pattern of An-Aa-AG or PS. It appears that after the An behavior, attention was focused on substantiating the analogy through corresponding attributes which was then followed by analogy generalization (AG) or proposed solution (PS).

In order to gain confidence in the An-Aa-AG or PS pattern, this chain of behaviors must be evaluated while holding each behavior, in turn, as the criterion (Sackett, 1987). For example, holding Aa as the criterion behavior, conditional probabilities for subsequent behaviors are evaluated to determine which is more likely to follow Aa. If AG is determined to most likely follow

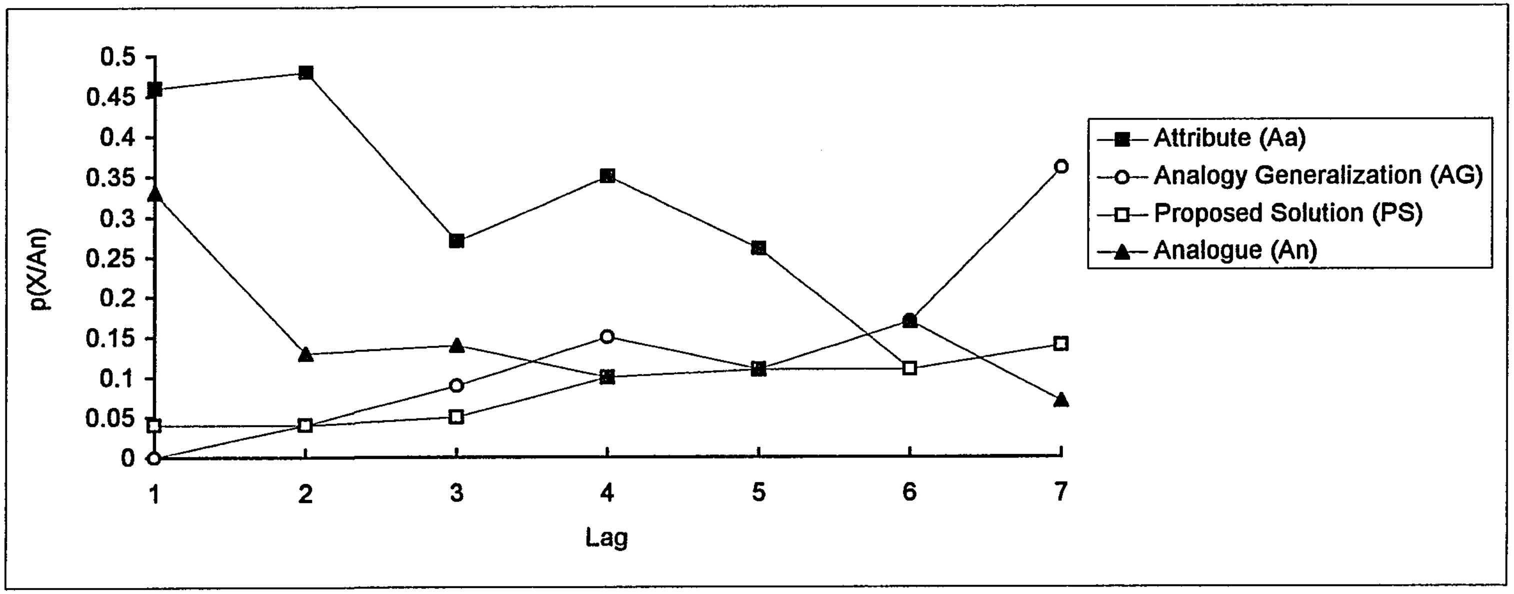

Figure 9: Criterion Profile and Conditional Propabilities for the Criterion Behavior Analogue (An)

Aa, then AG becomes the criterion and subsequent behaviors are evaluated again for the most likely to follow AG.

In the case of Aa as the criterion, the resulting profile is shown in Figure 10. With Aa as the criterion, the probability of additional Aa behaviors following the criterion is greater than An. The profile indicates that, to at least lag three, Aa behaviors occur in support of a previously stated analogy. At lags four and five the occurrence of An exceeds that of Aa. This profile also indicates that the periods of Aa and An are approximately similar except that they are out of phase. This suggests that during analogical decision making, if Aa is "on" then An must be "off" and vice versa. It also appears that Aa and An are cyclically related to the criterion Aa with periods of about six lags for Aa and about five lags for An.

Figure 11 shows the criterion profile for Aa as the criterion again, but with AG and PS as subsequent behaviors. This profile also indicates that additional Aa behaviors are more likely to follow the criterion Aa for lags one, two and three. At lag four and five, PS and AG are more likely to follow Aa. At lags six and seven, AG is completely inhibited while Aa is excited by Aa, which suggests that the process has return somewhat to a lag one condition. The criterion profile indicates some degree of cyclic dependency between the criterion Aa and AG with a period of two to three lags. There also appears to be some degree of cyclic dependency between PS and the criterion Aa with a period of about every seven lags. However, the occurrence of PS is at a maximum at lag four and returns to a minimum value at lag seven. This profile would have to extend beyond lag seven to verify the dependency between Aa and PS.

A similar cycle of inhibition and excitation of An and Aa behaviors occurs with *requirement query* (RQ) as the criterion behavior (Figure 12). At

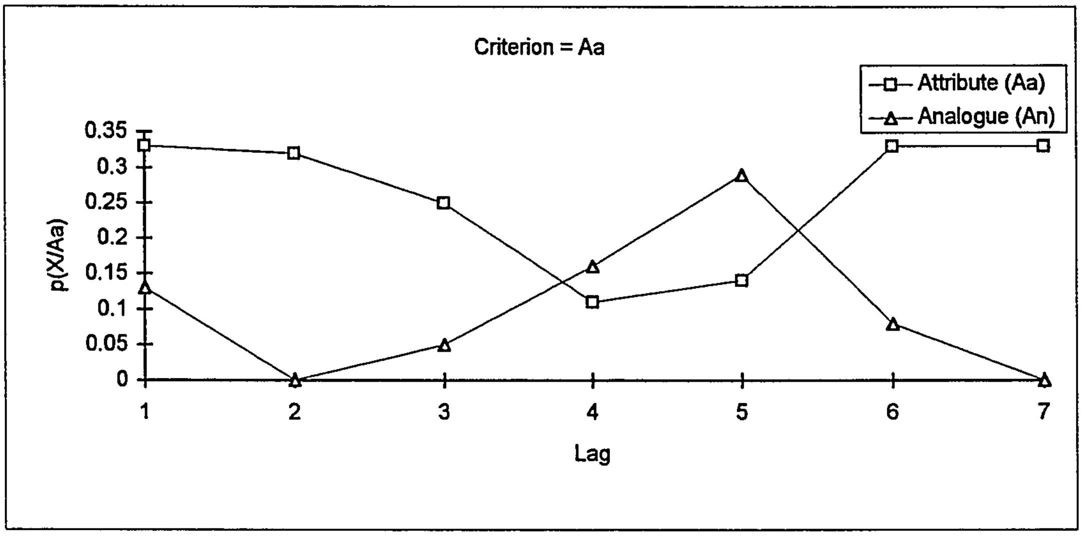

Figure 10: Criterion Profile for the Criterion Behavior Attribute (Aa) with Analogue (An) and Attribute (Aa) as Subsequent Behaviors

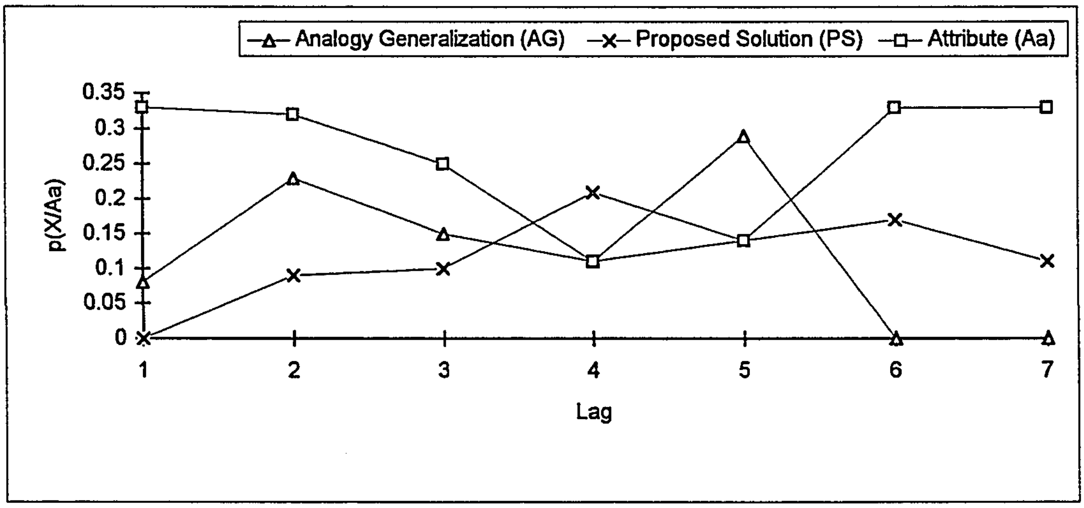

Figure 11: Criterion Profile for the Criterion Behavior Attribute (Aa) with Analogy Generalization (AG), Proposed Solution (PS), and Attribute (Aa) as Subsequent Behaviors

lag one and two An is clearly excited, more so than Aa, after the criterion behavior RQ. At lags three and four Aa is somewhat more excited than An. The cycle repeats at lags six and seven except the periods appear shorter and dampened. This profile suggests again the cyclic occurrence of An and Aa (one is "on" while the other is "off") as well as their cyclic dependency with the criterion RQ. It appears that RQ acts an impetus for analogy, suggesting that prior behaviors establish a context for the selection of analogues and corresponding attributes.

Pursuing this point further, Figure 13 shows the criterion profile for held knowledge (S) and proposed solution (PS) with An as the subsequent behavior. After lag one, An becomes excited at lags two and three with PS as the criterion. At lags three and four, An also becomes excited with S as the criterion. These profiles clearly suggest cyclic dependencies between PS, S and the subsequent behavior An. These profiles also suggest that information conveyed by RQ, PS, and S behaviors is important in establishing a context for analogic discourse.

Summary of Results

Chapter Two identified several perspectives that established a basis for this study. First, the activity of designing is considered to be a social process where communication plays a supporting and organizing role. It was proposed that similarity and analogy enable multiple perspectives, language systems, and technical domains to be combined, aiding the development of physical systems. Reflecting on the results of this study it is evident that a plethora of design knowledge and worldly experiences are brought to bear on perceived needs. Technical aspects of helicopters, parachutes, and flight in

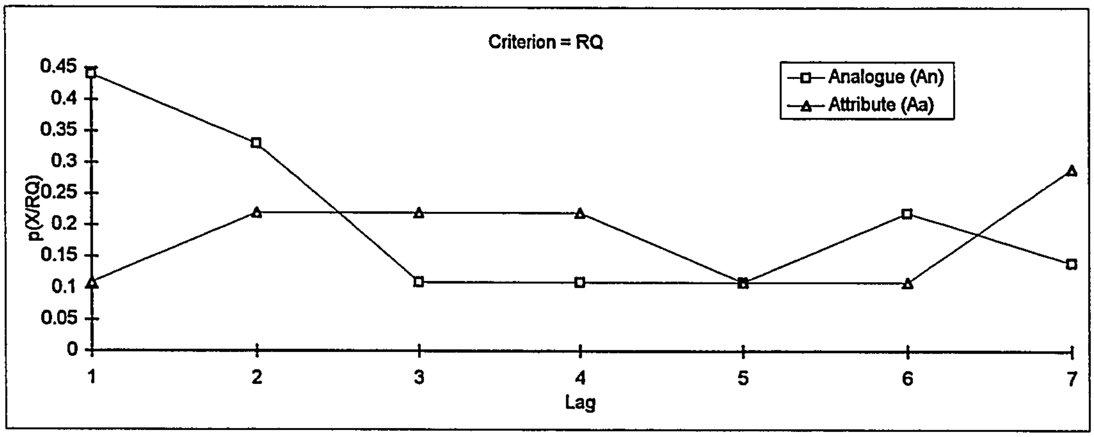

Figure 12: Criterion Profile for the Criterion Behavior Requirement Query (RQ) with Analogue (An) and Attribute (Aa) as Subsequent Behaviors

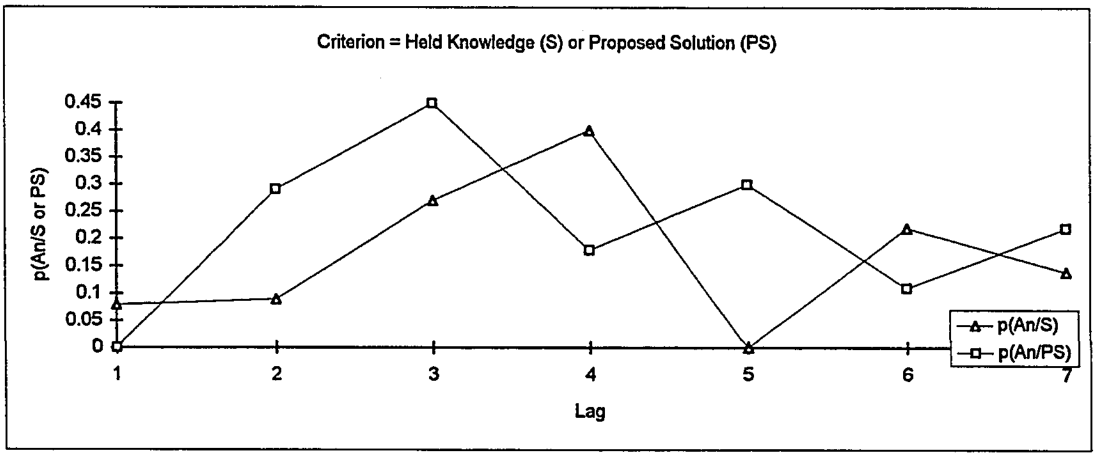

Figure 13: Criterion Profile for the Criterion Behaviors Held Knowledge (S) and Proposed Solution (PS) with Analogue (An) as the Subsequent Behavior

general, knowledge gained through personal experiences, and fantastical projections (e.g., the Jetsons Episode) all played a part in the definition of an ornithopter (see Figure 5 for a summary of similarity and analogical episodes).

Analogical decision making was observed to involve comparisons between conceptual domains, archetypes, and known instances. In addition, personal experiences and projections, acting as base domains, facilitated the understanding and explanation of target domains. Not only were attributes that define relationships between two analoques (referred to as matched attributes) but also unmatched attributes were observed to be important in the decision making process. For example, in the Paradigm episode (Appendix C, p. 117) the unmatched attribute, “helicopter blades don't flap but go around,” led to a design solution that would enable helicopters blades to flap. Neither Gentner or Holyoak's Theories of Analogy address the efficacy of unmatched attributes in analogy decision making. Their efforts however were focused on describing the analogical reasoning processes of individuals, not on the process of communication.

Sketching and gesturing were observed to be inextricably associated with the activity of designing and with communication. In fact, because these nonverbal behaviors often replaced verbal behaviors, and their participation in communication was observed to be complex, differentiation from other process variables was sometimes difficult. However, an interesting aspect of the sketching behavior observed in this study was the reluctance of participants to initiate the sketching activity. Thinking about this observation in the context of this study, this reluctance may be due to not knowing how to start and may be attributable to the activity of sketching itself. When a sketch becomes the target domain, requiring a transformation of thought (the base

domain) to graphic and symbolic representations, an issue that emerges in the mind of the designer might be concerned with how best to begin the sketch. Once a single line is drawn it acts to constrain what can be drawn next. Often during the sketching activity statements like "..no it looks like this" led to revised sketches that attempted to represent a better match with verbal descriptions or representations held internal to the designer. What was observed was the appearance of subjects "tippy-toeing" around the drawing area in an attempt to avoid unnecessarily constraining or limiting the emergence of sketched solutions. Therefore, there appears to be two factors that designers must mediate prior to the sketching activity: (1) the identification and presentation of appropriate attributes of the sketch that match verbal expression and thought (2) while minimizing the constraining effects of a sketch on emerging solutions. As proposed by Van Sommers (1984), because the strategy of sketching is determined by the semantics of what is being drawn, the difficulty that the group had in initiating a sketch could have been due to a lack of a semantic description for an ornithopter.

A second perspective of this study discussed in Chapter Two presented the idea that communication systems can be described by the punctuation of communicative behaviors which act to guide the communication process. It was proposed that communicative behaviors facilitate the construction, manipulation, and convergence of design information, which is presented in the form of design experiences and expectations. Based upon the results of this study, it is proposed that *requirement queries* and *statements of held knowledge, control, comparison, proposition, and confirmation* represent communicative behaviors that enable a merger of knowledge domains and a convergence toward common descriptions for artifacts. These behaviors, represented as coded events in analogy decision making graphs (ADGs),

marked the initiation, execution, and termination of analogy discourse. The ADGs showed that a major part of the decision making effort was focused on the identification of target and base domains, corresponding attributes that either describe how the two domains were similar or dissimilar, and the assessment of an analogy in terms of satisfying a stated or implied goal. An important observation from the data is that analogy, in the context of design, is purpose-driven which is congruent with Holyoak's Pragmatic Theory of Analogy.

Data from this study suggests that these communicative behaviors occur in reoccurring and sequential patterns. It was determined that cyclic dependencies exist between the antecedent behaviors *requirement query*, *proposed solution*, and *statements of held knowledge* and the initial identification of analogues which suggests that a context must first be established prior to analogy. A cyclic dependency was also observed between stated analogues and corresponding attributes, suggesting that as part of the decision making process the degree to which target and base analoques are similar is evaluated.

From these cyclic dependencies a general process of analogical decision making, as observed in design discourse, can be summarized as shown in Figure 14. It was observed that the majority of analogy episodes began with the establishment of a design context which implicitly or explicitly defined requirements, goals, or constraints that influenced the selection of analogues and corresponding attributes, all of which are referred to as solution sets. The identification of analogues and corresponding attributes led to the acquisition of either new requirements, heuristics, or physical

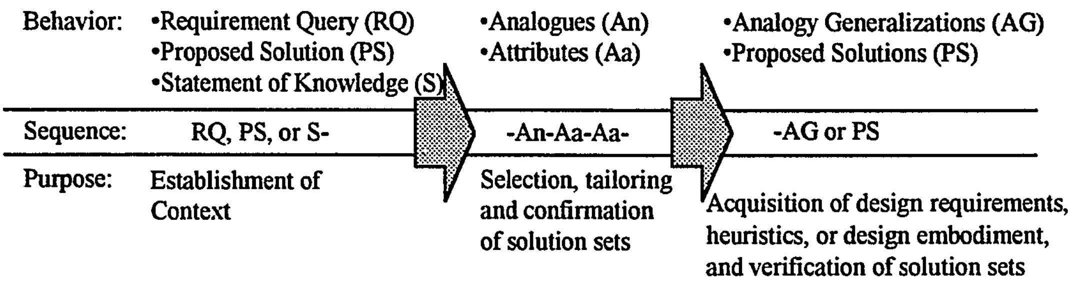

Figure 14: A General Analogical Decision Making Process for Collaborative Design

descriptions that were captured in sketches. In several episodes, analogy discourse led to a determination of basic requirements, such as whether an ornithopter is a multi- or single passenger aircraft. In one episode, analogical decision making led to a design heuristic that was later used to approximate the size of the passenger compartment space. In other episodes analogy discourse led to physical embodiments conveyed in sketches. The process of transforming requirements through analogy discourse into physical embodiments is described as a synthesis process. It is proposed, based upon the ADGs, that this process is initiated by the allocation of requirements to some aspect of an ornithopter. Relationships established by an analogy and corresponding attributes are used to develop a physical representation to satisfy goals and constraints of a requirement. It is concluded that the synthesis process visually aides the understanding of requirements as well as the validation of requirements.

As indicated in Chapter Three, a survey was administered to each participant after the design session to determine:

1. If the research setting in any way hindered efforts of the participants.

2. Each participant's familiarity with the design task.

3. The degree to which the task was structured.

All participants indicated that the research setting in no way hindered their efforts during the design session. This included the camera locations, seating arrangement, and use of large sheets of paper and colored markers. In regards to the familiarity of the task, all participants indicated that they had no familiarity with the task and each perceived that the group as a whole was unfamiliar with the task. In addition, all participants indicated that the design problem was not well defined. Results of this survey indicate that the strategy described in Chapter Three for developing the design task was successful.

CHAPTER FIVE
CONCLUSIONS

The purpose of this study was to explore and describe the role of similarity and analogy in design decision making. The use of analogy in design has been recognized by other researchers, but no operational definition or description of analogical decision making as a communication process had been made prior to this study. This study described analogical decision making as a communication process, influenced by communicative behaviors that appear to elicit and act on design information. It is proposed that communicative behaviors identified from recorded data represent process variables of analogical decision making that occur in design discourse. In addition, results from this study suggest that the communication process of analogical decision making, as observed in a group setting, can be viewed as a system of behaviors that is recognizable and predictable. This conclusion is based upon cyclic dependencies among communicative behaviors that were determined from the lag sequential analysis.

A key objective of this study was to demonstrate that if communicative behaviors are defined as acts that transform design information from one state to another, they can be analyzed stochastically to reveal patterns of communication and interaction. As an additional proviso, communicative behaviors that are used to develop a description of a communication process must be unique for a given task environment. As ostensibly demonstrated in Neidermeier's study, a generalized coding scheme which is insensitive to the

task environment will not yield patterns of communications when the lag sequential analysis method is applied to conversational data (Neidermeier, 1988). Therefore, in this study, an observational approach was first used to qualitatively identify and describe communicative behaviors which appeared to act on design information and were therefore considered unique to the activity of collaborative design.

The focus of this study was therefore on the qualitative assessment of an observed design activity, the lag sequential analysis was used only to demonstrate an alternative means to present data. For this exploratory effort, transcriptions and analogy decision making graphs alone supported a description of analogy discourse, the lag sequential analysis method provided a visual representation of the communication process. It was through an observational approach that an in-depth examination and qualitative assessment could be performed of the observed design activity. As Patton points out, this approach provides a means for in-depth examinations, particularly where "information-richness" is of greater concern than statistical analysis:

> "The validity, meaningfulness, and insights generated from qualitative inquiry have more to do with the information-richness of the cases selected and the observational/analytical capabilities of the researcher than with sample size." (Patton, 1990, p. 185)

Because this study was an exploratory examination of a particular decision making process, it was necessary to qualitatively assess all aspects of the observed activity. This was accomplished by: observing and recording design activities of a group of experienced engineers; transcribing conversational data and physical actions that occurred within a shared work space; and, the interpretation and assessment of communication behaviors by a experienced

engineer with a similar technical background to that of the subjects. This effort provided the basis for a descriptive representation of the analogical decision making process. Communicative behaviors (verbal and nonverbal) were then applied as a coding scheme to conversational data and analyzed using the lag sequential analysis method to investigate cyclic dependencies among communicative behaviors. It was determined that cyclic dependencies exist between these behaviors, suggesting that analogical decision making can be viewed as a communication system.

Based upon observed episodes of analogical decision making, it is proposed that *requirement queries* and statements of *held/acquired knowledge, proposition, confirmation, control* and *comparison* are key communicative behaviors that facilitate the elicitation, promulgation, and synthesis of design information. It was determined from the data that the role of requirement queries was to initiate the derivation of functional requirements and the synthesis of design solutions. Functional requirements described functions a system or particular components of a system were to perform. Design solutions represented physical embodiments that satisfied a predefined requirement or design goal. It was observed that requirement queries were also important in establishing a context for the articulation of analogies and analogy analogues and attributes.

Statements of held and acquired knowledge were observed to evince factual information, such as principles of physics or engineering, and represented knowledge acquired through previous design or personal experiences or acquired during design decision making. The data indicate that these statements: established conditions for proposed solutions; provided a reference point for subsequent discourse; or summarized information from

previous discussions. Statements of held and acquired knowledge were also observed to be important in establishing a context for analogy.

Statements of proposition represented proposed design solutions that were observed to be generally derived through internal processing of information by an individual. These statements appeared to play two roles in analogy discourse. First, statements of proposition that occurred prior to analogy appeared to be important in the establishment of a context for subsequent analogy discourse. Secondly, statements of proposition that occurred after analogy validated or confirmed concepts previously stated and supported by analogy.

Statements of confirmation represented utterances that functioned to either accept, question, or reject presented information. They were observed to question the appropriateness, applicability, or consistency of design information.

Even though statements of control represented only 2% of the total observed behaviors, they were observed to be important in redirecting the group's focus of decision making and in providing a point of reference for subsequent discourse and decision making. In addition, statements of control played a role in the initiation and termination of analogy episodes.

Statements of comparisons consisted of elements of analogy. These statements involved the articulation of base domains (knowledge domains familiar to the interlocutor) and target domains (domains to be explained) and corresponding attributes that defined the relationship between the two domains. The data indicate that there were four approaches used to compare analogues (knowledge domains) in analogy discourse. The first and simplest approach was the comparison of a single base and target domain. This approach was observed in five of the nine analogy episodes identified in the

data. Where additional information or clarification was required, additional base domains were identified to further design decision making. The impetus for identifying additional base domains may be due to a need to improve comparisons with a target domain where previously stated base domains may have been deficient in some relational aspect. Another approach appeared to cascade requirements and constraints of previous information to subsequent lower levels of comparisons, particularly to levels where instances of a particular knowledge domain were identified to support the derivation of conclusions. Alternatively, the cascading of requirements and constraints to lower levels of comparison may result in subgoals from which further analogic discourse would follow.

It was determined from the data that statements of comparisons led to either design requirements, design heuristics, or design embodiments. Design requirements acted as constraints to be considered during subsequent design decision making. In one case, a design heuristic, derived through analogy, was used in later discussions about the evolving design. Design embodiments were observed to directly capture implications of design requirements in physical representations conveyed in sketches. Design embodiments were used to validate or assess the appropriateness of requirements derived through analogic discourse.

The nonverbal behaviors, gesturing and sketching, were observed to be important in conveying design information. Gestures appeared to provided an additional way to express conditions of analogies that influenced design decisions. Sketching was observed to facilitate better understanding of requirements and analogies through physical representations conveyed in sketches. Sketching was also observed to be important in the synthesis of design solutions which is described as the transformation of requirements,

aided by analogy, into physical embodiments depicted in sketches. Sketching also provided a means to validate or assess implications of requirements or design goals through physical representations.

Important to the process of analogical decision making proposed in this study is the establishment of a pre-defined context or goal. It was observed that context, defined primarily by the communicative behaviors *requirement query, statement of held/acquired knowledge*, and *proposed solutions,* appeared to influence the selection of analogies, analogues and corresponding attributes, thus making analogical decision making a purpose-driven process. It is proposed that a pre-defined context acts to limit and constrain the selection of design solutions sets, articulated as analoques and analogue attributes and evaluated against implied or explicitly stated goals. And finally, the process was observed to generate either new requirements, design heuristics, or physical embodiments that supported further analysis and design decision making.

Limitations and Issues of the Results

Conclusions drawn from the lag sequential analysis are limited by the sample size. No significance testing was performed on results of the lag sequential analysis because the sample size did not meet the criteria proposed by Bakeman and Gottman (1986). Based upon conditional probabilities determined for 123 coded behaviors, approximately 800 to 1000 coded behaviors would be required for significance testing. However, what has been accomplished in this study is not denigrated by this limitation. The goal of this study was to explore and explain the role of analogy in design decision making, seeking "information-richness" of the observed design activity in lieu of statistical significance. What resulted from this study was the

identification of salient communicative behaviors observed during analogy episodes that appear to facilitate the elicitation of design information and its transformation into design solutions. Criterion profiles developed from the lag sequential analysis, in some cases, suggest a sequential nature of the analogical decision making process, providing a degree of confidence in the proposed communicative behaviors. However, an increased sample size and significance testing are required to fully verify the proposed behaviors and analogical decision making process.

A question remains with respect to how well the designer's world was accessed by the researcher. Did the research approach allow sufficient entry into the activity of designing to allow description of the communication and decision making process and what aspects of the methodology limited what was possible to observe? These issues were addressed and considered in the planning of the study as described in Chapter Three. For example, engineers selected for the study had similar technical and experiential backgrounds as that of the researcher. The strategy for this selection criterion is based on the assumption that sharing a similar language system would enhance the tractability of design discourse. As discussed in Chapter One, Bucciarelli suggests that names of things evoke "...visions of form and function..". In order to detect the subtle articulation of comparisons between different knowledge and technical domains some degree of a shared language system might be required. For example, consider the following utterance recorded during the design session:

> ...but huh...it was a fatigue cycle problem but huh..I don't know what fraction of the hull strength is used for huh...you know longitudinal strength of the girder and what fraction is used for pressurization...

This utterance was made to support the determination of failure modes for the passenger cabin of jet airliners. The utterances "hull strength" and "longitudinal strength of the girder" evoked in the mind of the researcher images of loading and deflection of a ship's hull as it travels over and is supported by waves of specific height and period. In fact this phrase is commonly used by naval engineers to refer to the analysis of this loading condition which leads to a definition of the primary longitudinal structure for a ship's hull. The question that each member of the design team must answer pertains to the appropriateness of the knowledge evoked by this phrase in the context of jet airliners. Recognizing that other team members were also naval engineers, the phrase was legal because it appeared to be understood and it summarily described the condition of the passenger cabin that the subject wanted to convey. Phrases such as these are considered to be culturally based, conveying information to only a selected group of people with similar backgrounds and understanding. Imagery, meaning, and intent conveyed in this phrase might elude one outside the domain of naval engineering. The point being made here is that key words and phrases can act as cultural cues, evoking specific knowledge and experiences which are subject to evaluation against predefined contexts. Without prior knowledge or awareness of these cultural cues, the recognition of analogy may be limited to the prepositional cues, *like* and *as*. A more profound analysis of the role of these cultural cues in their more subtle occurrence remains to be determined.

An additional limitation that became evident from the data was the duration of the design session. Because the session lasted for only an hour, only nine episodes of analogy discourse were identified from the data. Clearly a longer period of observation or an increase in the number of observed groups is required to increase the sample size. In addition, the

observation period should be increased to obtain a more complete understanding of the role of analogy in the development of an artifact. This would allow, for example, an analogy to be traced to the final configuration of the design.

The development of a coding scheme and the coding of utterances was an iterative task because of the need to build consistency in the interpretation and coding of utterances. As discussed earlier, the coding of utterances sometimes required judgment where single utterances served multiple purposes. Supplemented by findings from other studies, the language system of the researcher was used in the construction of the coding scheme. Even though participants with the same engineering background as that of the researcher were selected for this study, how each viewed and participated in the process might result in different interpretations of utterances and perhaps even a different coding scheme. The results of this study are therefore limited to how the researcher viewed the observed activity. Given the perspective of an external observer, an inter observer reliability assessment of coded utterances should be performed to gain confidence in the proposed coding scheme. However, if the interest is in assessing the perspective of the participants, the proposed coding scheme should be reevaluated.

Implications of the Study

It appears that analogy discourse is not as an efficient mechanism of design decision making as this study might suggest. This short coming may be attributable to the task of designing where multiple goals, constraints, and potential solutions are weighed and compared concurrently to arrive at some optimum design. The inability of a group of designers to evaluate these multiple aspects might be facilitated through prescribed methods where all

possible paths made available through analogy are evaluated against some selection criterion or criteria. The data suggests that the group does not lack the ability to identify analogies, but rather the ability to identify and evaluate all possible solution paths made available through analogy. As a future goal, prescribed methods and training should be developed to improve the process of analogical decision making in collaborative design.

Future Research

It is recommended that this study be expanded to obtain a more complete application of the lag sequential analysis method. This would allow significance testing of conditional probabilities required for the validation of communicative behaviors and the analogical decision making process proposed in this study. In addition, multiple coders should be used so that an assessment of inter observer reliability can be made. This would provide greater confidence in the proposed communicative behaviors by testing the consistency of the coding process.

As an alternative approach, it is recommended that perspectives of the participants be explored as means of validating the coding scheme as well as the process proposed in this study. The duration of the design session should also be increased so that a more complete understanding of the role of analogy in later phases of a design process can be determined. This might enable analogies to be traced to a final configuration of the design as means of evaluating the efficacy of analogy. And finally, the fidelity for identifying and measuring the occurrence of verbal and nonverbal behaviors should be increased so that the role of nonverbal behaviors in analogy discourse can be more thoroughly described.

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Appendix A: Design Problem Statement

Design Problem Statement

The Federal Office of Transportation is funding research to identify modes of public transportation for the 21st century. Emphasis has been on identifying vehicles to support commuter transportation in some of the largest and fastest growing cities in the U.S. The government wishes to explore and identify vehicle prototypes based on the concept of an ornithopter, which is defined as an airborne craft that is propelled by flapping appendages. Preliminary studies indicate that aircraft derived from the ornithopter concept may be a cost effective approach to providing inter as well as intra-city transportation.

You and your design team are to develop a conceptual prototype based on the ornithopter concept. In addition to using your technical knowledge and design experience, you are encourage to explore, as a team, other sources that may provide potential design solutions. Your prototype will be evaluated on the novelty of the design approach and solution.

Appendix B: Post Session Questionnaire

Post Session Questionnaire

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1. Did the setting (cameras, seating arrangement, use of paper or markers, etc) in any way inhibit your efforts during this design exercise? (explain if yes)

2. Did the setting (cameras, seating arrangement, use of paper or markers, etc) in any way inhibit the team's efforts? (explain if yes)

3. How familiar were you with the subject matter presented in the design problem?

   a. not familiar
   b. somewhat familiar
   c. familiar
   d. very familiar

4. How familiar was the team with the subject matter at the beginning of the design session?

   a. not familiar
   b. somewhat familiar
   c. familiar
   d. very familiar

5. How well was the design problem defined?

   a. not well defined
   b. was somewhat defined
   c. was adequately defined
   d. was highly defined

Appendix C: Transcriptions of Analogy Discourse

Paradigm Episode

1: (B) I can't envision this thing..you know I'm stuck in the traditional bird paradigm its got wings that flap and is going to look like a bird
2: (C) that isn't the way the airplane got built
3: (B) I know
4: (C) well think of helicopters...think of missles
5: (B) yeah but helicopter blades don't flap
6: (C) not yet..they don't flap yet..they go around but we can make them flap we could we could have some sort of cam to make them flap rather than go around
7: (B) yeah thats good
8: (C) maybe thats a pretty good design technique
9: (A) maybe we can use lighter than air technology

Rail System Episode

28: (A) the idea here is that it is not an individual...I..I..this..um..it doesn't say that you..you couldn't have a one passenger ornithopter..does it?
29: (C) no
30: (B) but that but that would be..I don't know if it would be cost effective
31: (C) an omniornithopter
32: (A) the understanding here is that uh a multipasssenger ornithopter, right? is that given?
33: (B) I would say... I would say it be analogous to our light rail system we have today
34: (B) yeah
35: (B) I..they want it..and uh..the Pentran system we have in our city
36: (A) you think this is a replacement for Pentran?
37: (B) it might be...they just might slap wings on Pentran
38: (C) well
39: (A) that could be it, um

Stork Episode

47: (B) ok why wouldn't they use existing airports?
48: (A) well..uh..thats a good question
49: (B) provided they are here in the 21 first century
50: (A) no..you..you take this ornithopter concept..does it require a convential airport? I..I..my inclination here is that it could land on a roof top or parking lot..I..uh
51: 52: 53: all mumble
54: (C) kind of like a helopad on a drilling structure or top of a roof of a executive building
55: (A) yes
56: (C) I..even a marked off space in a parking lot..uh..of a company
57: (A) yes
58: (B) so these things can take off and land just like a helocopter..or..do they need a little bit of runway to get themselves airborne?
59: (A) well..I
60: (C) I..I never..it flaps if you look at large birds
61: (A) using the bird analogy..uh..if you look at large birds like storks they do have to run and flap to get off..but..uh I uh you look at other birds they seem to be able to land on a dime.. I am not sure..I uh
62: (B) well..it would have to be the thrust to weight ratio I guess you would have to be concerned with
63: (A) yeah..I..uh

Passenger Episode

65: (A) I..uh..well if we go back to looking at airports..the typical airplane uh your 737 is what a 120 passenger plane..something in that order..uh..so you know you not only need something for your inter..intracity of..of..of at least be able to carry that kind of passenger load..uh..and your talking about something that may or may not require some particular..uh..infrastructure..it may just be a concrete padded parking lot
66: (B) uh..how many people can a bus take?..like a pentran bus
67: (A) well, uh Greyhound is about 40
68: (B) 40?
69: (A) Pentran is about the same size but they're more dense seating and have a aisle for standing so..uh..50 or 60
70: (B) I was going to say
71: (A) never seen a Pentran with 40 people on it

Beechcraft Episode

299: (B) true true this this is just well like I said you've got the outer hull..and then..what I'm thinking you may have a box..where this is eight feet you know the seats are down here..as far as head room goes..how much head room is in an aircraft, about six and a half feet? Then you wouldn't even need that in the seating area
300: (C) I..I..I crawled onto a Beechcraft up in Providence or Portland
301: (B) that's right you're going to be ducking down..so
302: (A) some of them you don't have a full amount of six foot head room I believe
303: (C) I was doing well to stand on my feet
304: (A) yeah
305: (B) well that's about six feet
306: (A) all of us are at least six feet

Parachute Episode

328: (C) maybe we can use a parachute landing approach..to get down in a minimal space
329: (A) yeah I huh think..I think if we huh go back to the huh ornithopter sort of mind set the wings are the parachute per se I think if you stall it huh
330: (B) you can you can flap the wings
331: (C) well in plan view then your vehicle..just drawing half of it..is going to have to have sizable length you're talking about wings probably..two times..the aspect of of normal wings cause if your're coming down you're going to come down gently enough you'll have to catch a fair amount of air
332: (B) yeah
333: (A) yeah
334: (C) and you've got to do it in length
335: (A) yeah thats the way a typical bird is designed I believe
336: (C) knid of a stubby wing
337: (B) see now when a bird flies

St.Louis Arch Episode

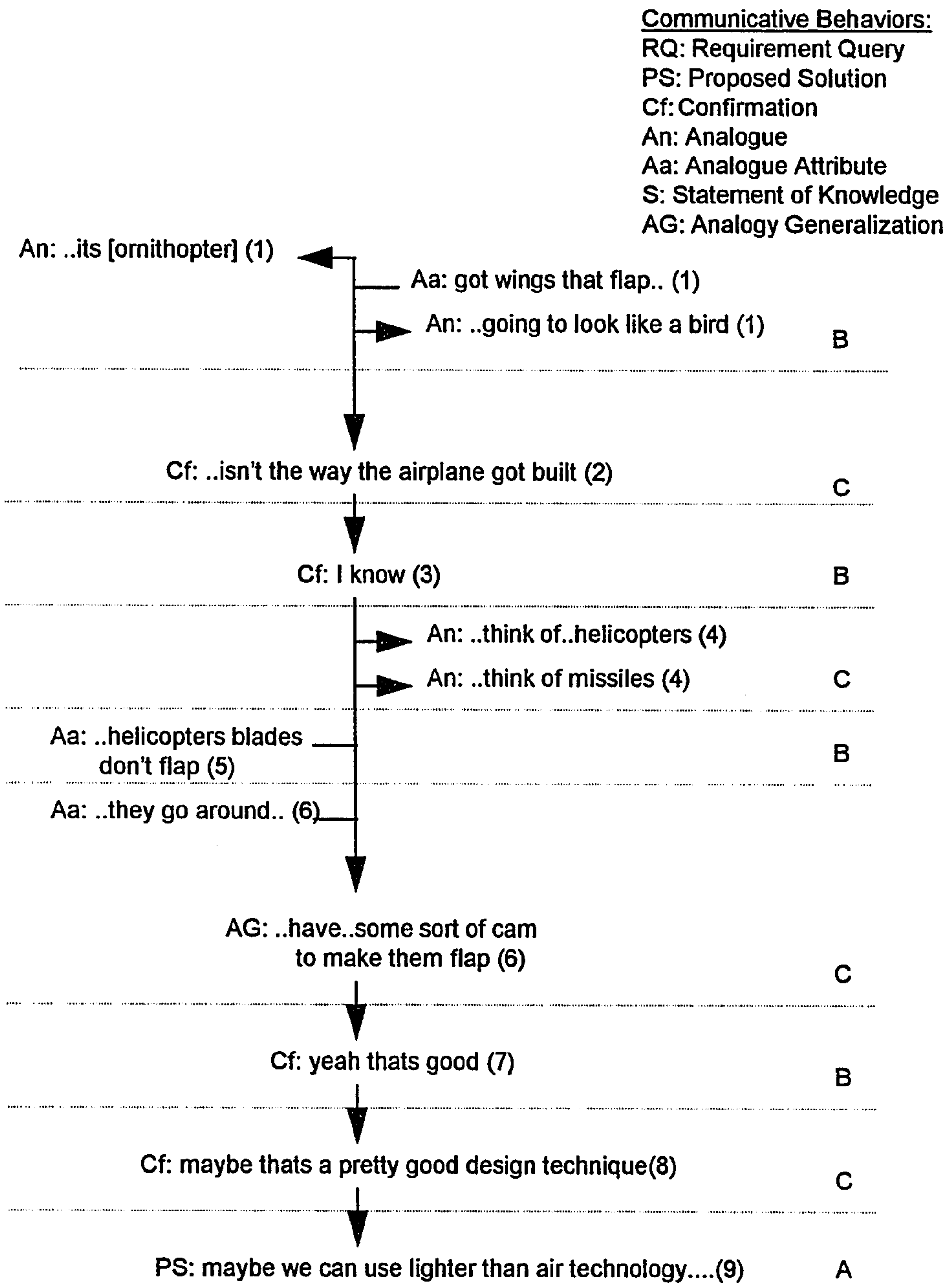
337: (B) see now when a bird flies when it lands the body actually tilts like that [gesture]..we can't have that I mean I don't know about you if I'm sitting in a plane and all of a sudden the plane did one of these numbers
338: (C) well they used to when for instance the old DC3's it was at a fairly steep angle
339: (A) when you got in it
340: (C) when you got in it landed it came in level but then the tail set down
341: (A) quickly and you were looking up hill
342: (C) yeah
343: (B) well what would be ideal would to be to have a passenger compartment contained within its own module and have the module and have the module self leveling
344: (A) hmm..
345: (B) like the I don't know if you've ever been
346: (C) St. Louis
347: (B) yeah the arch in St. Louis yeah you go
348: (A) the elevator keeps tilting as you go up
349: (B) yeah you go like this
350: (A) yeah
351: (B) and...when they reach a certain point
352: (A) the elevator tilts
353: (B) I don't know if something like that could be well that could be that would be

409: (C) we've seem to keyed in on the larger vehicle and 10 to 20 people what about something more personable approach...cars for instance are personable and go from point A to point B and C and they're also used for intercity
410: (A) yeah
411: (C) could could you dream up a vehicle that would be pilotable by the average person?
412: (A) this is the Jetsons concept
413: (C) yeah...that huh you could either go to the grocery store across town or visit Aunt Mable's 200 miles away
414: (B) umm
415: (A) yeah the thing that made me question that is the huh the urnithopter huh mode of flapping to get you going doesn't seem very personable to me...you know how do you land it in your driveway?
416: (C) well you you use the streets...most streets are wide enough may maybe there is going to be required a little forward motion and you'll have to move street lights out of the way
417: (B) you'll have to build them small enough to fit into a normal lane
418: (C) yeah
419: (B) either that or once you've landed the wings retract and fold up and you'll have a small electric motor and you drive like a small electric car...once your're near your destination you land at a port and drive the rest of the way
420: (A) yeah
421: (C) yeah
422: (B) go that route to be personable

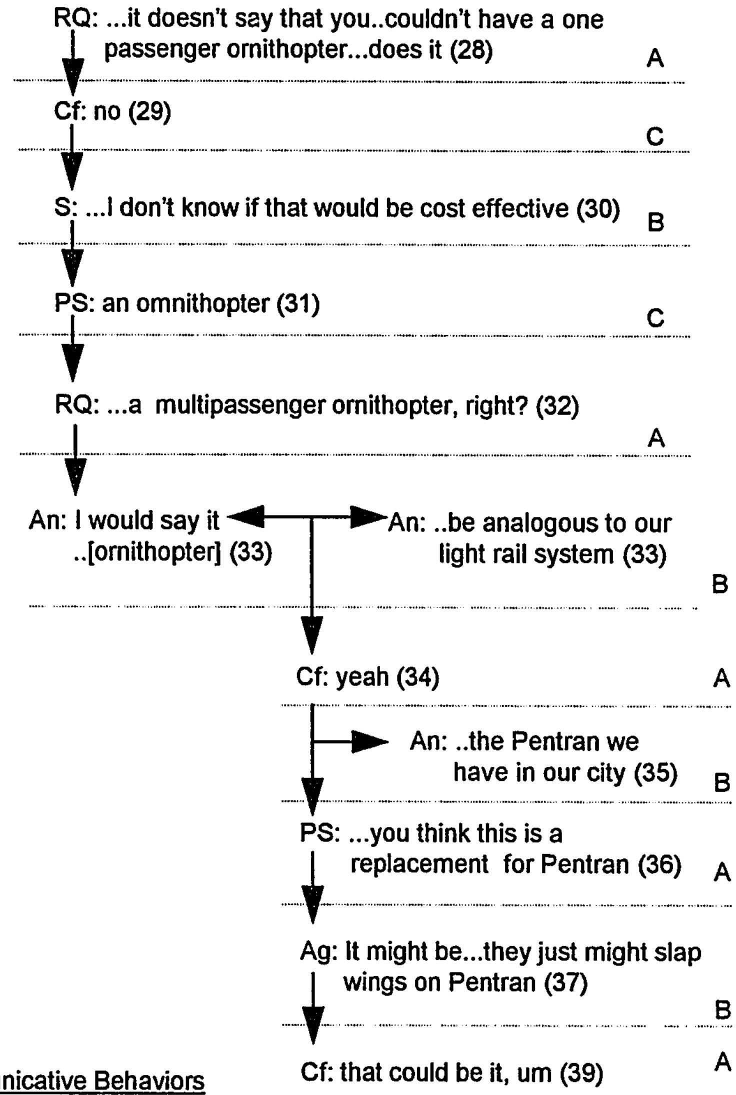
Wing Size Episode

442: (A) it the the wing size is something we had a little better background in aerodynamics...we could determine...it seems like portioning it like a bird...is is not a bad guess if you don't have any science I you know
443: (B) well well if you work at the size of a bird pretty much the wing span is twicw the body length
444: (A) right
445: (B) as as a minimum
446: (A) right I mean thats not atypical you huh
447: (B) so maybe the huh forty passenger jobee is kind of out of the question
448: (A) well thats going to make you an 80 foot wing span
449: (B) yeah and how many buildings well you could actually
450: (A) the wings could hang over the building I suppose

Appendix D: Analogy Decision Making Graphs (ADGs)

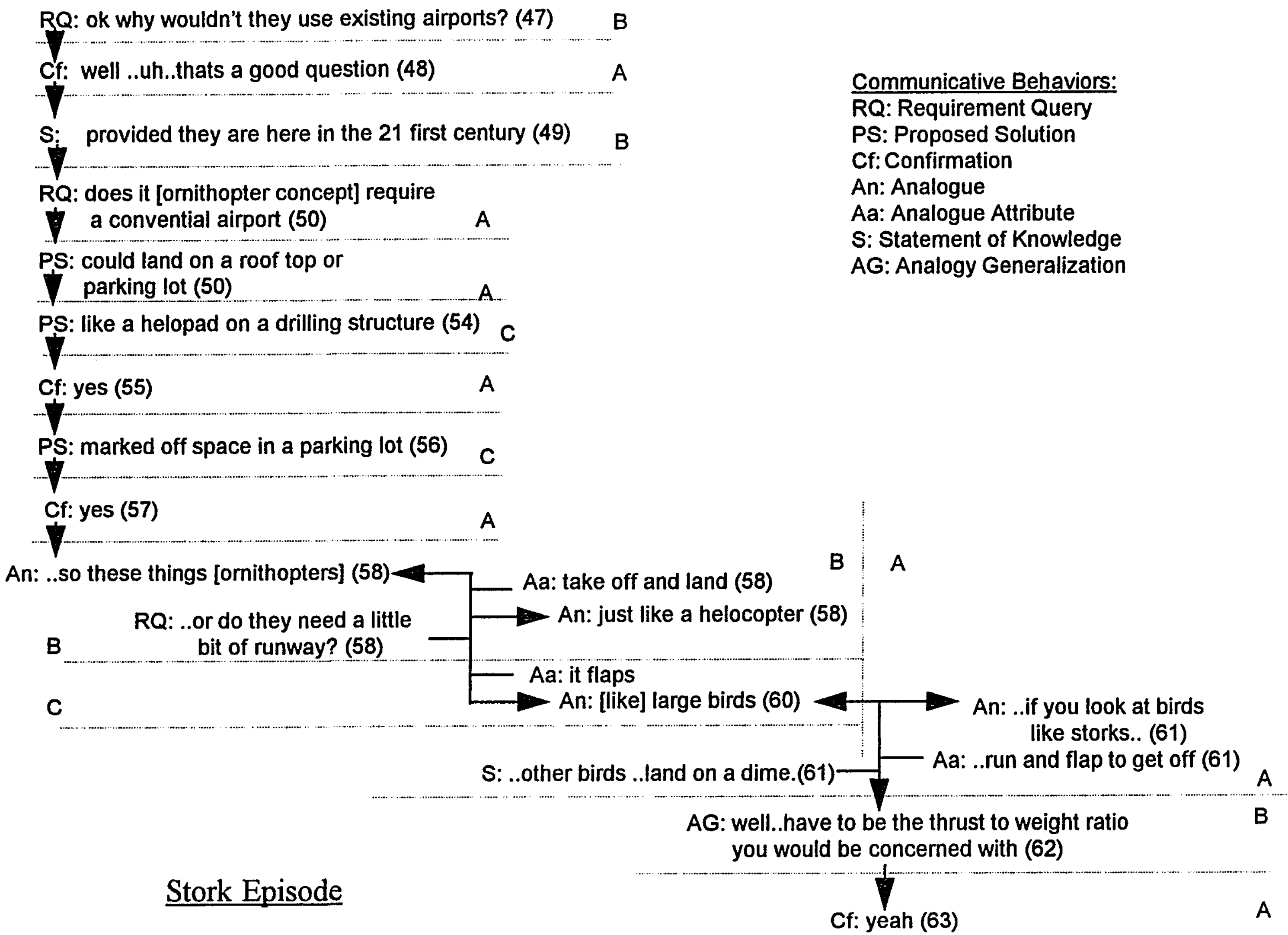


Paradigm Episode

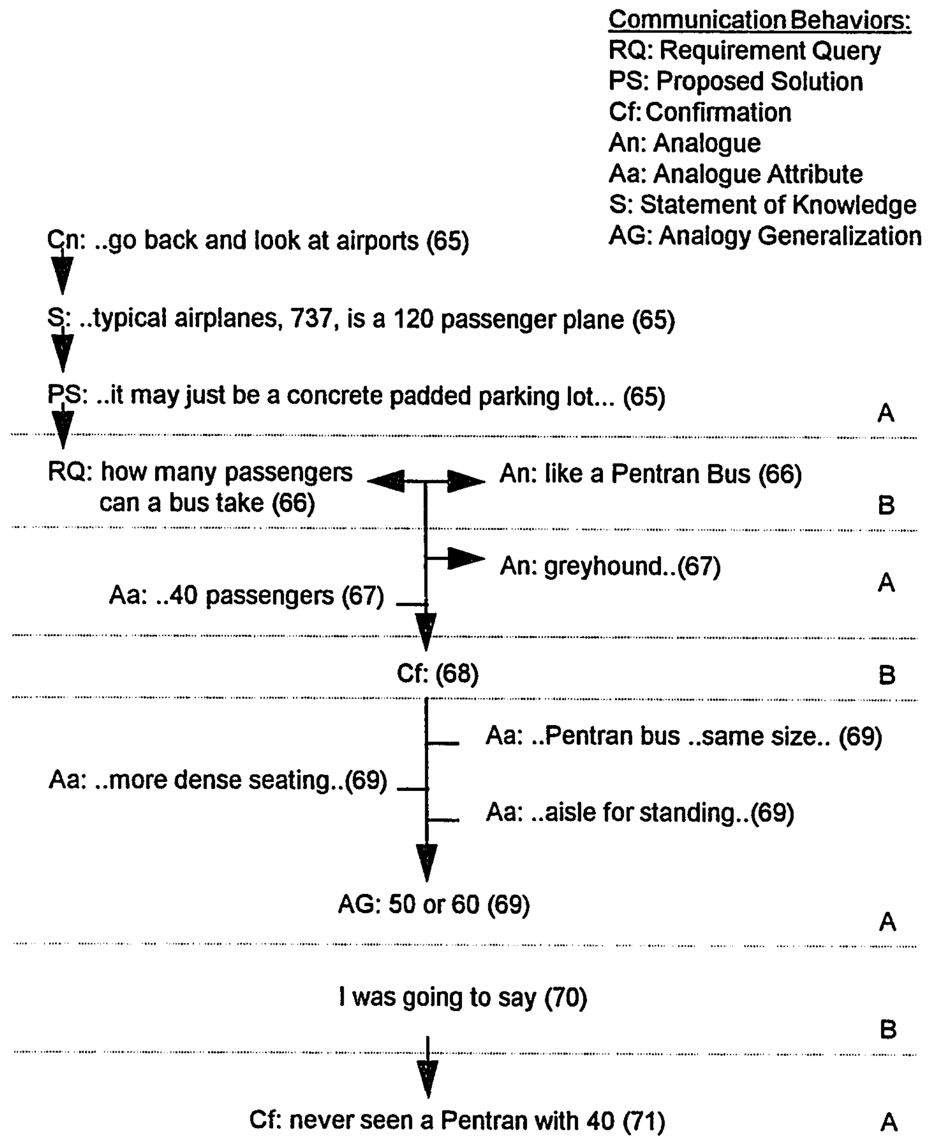


Communicative Behaviors
RQ: Requirement Query
Cf: Confirmation
S: Statement of Held Knowledge
PS: Proposed Solution
An: Analogue
AG: Analogy Generalization

Rail System Episode



Stork Episode



Passenger Episode

Communicative Behaviors:
RQ: Requirement Query
PS: Proposed Solution
Cf: Confirmation
An: Analogue
Aa: Analogue Attribute
S: Statement of Knowledge
AG: Analogy Generalization

S: okay what we have from that sheet of paper..(295) A

PS: ..you have an 18 inch aisle down the middle? [subject points to the sketch] (295) A

Cf: yeah, I don"t know that (296) B

PS: you got an eight foot breadth..[subject point to the sketch] (297) A

Cf: ..that's kind of a goal..after you factor other things..(298) C

RQ: ..how much head room is in an aircraft [subject is sketching internal arrangement and space of an ornithopter] (299) B

An: ..I crawled onto a Beechcraft ..(300) C

Aa: ..that's right you're ducking down (301) B

S: some don't have 6 foot headroom (302) A

Aa: doing well to stand on my feet (303) C

Cf: yeah (304) A

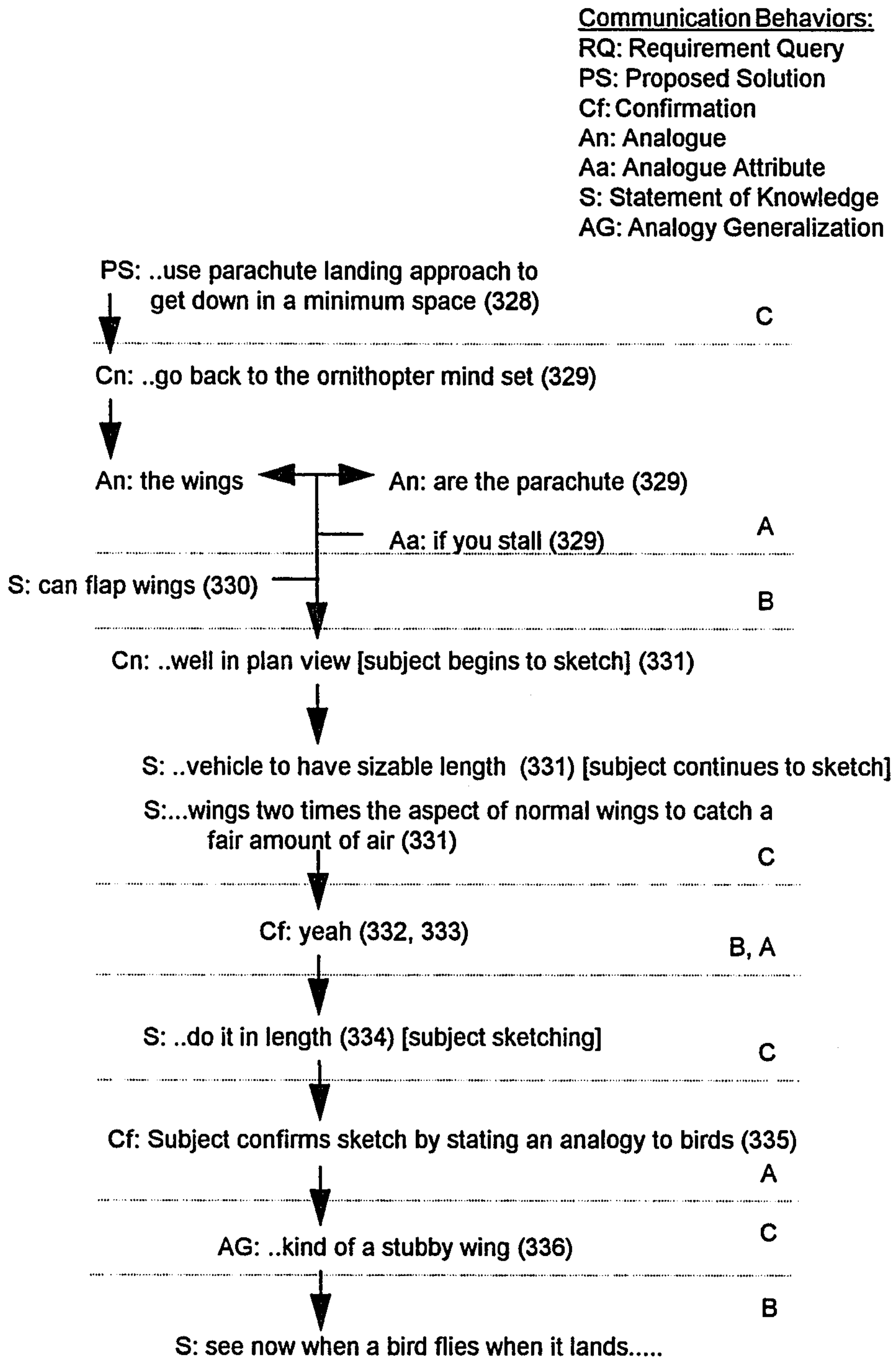
AG: well that's about 6 feet [subject points to sketch and writes 6 foot] (305) B

An: all of us are at least 6 feet (306) A

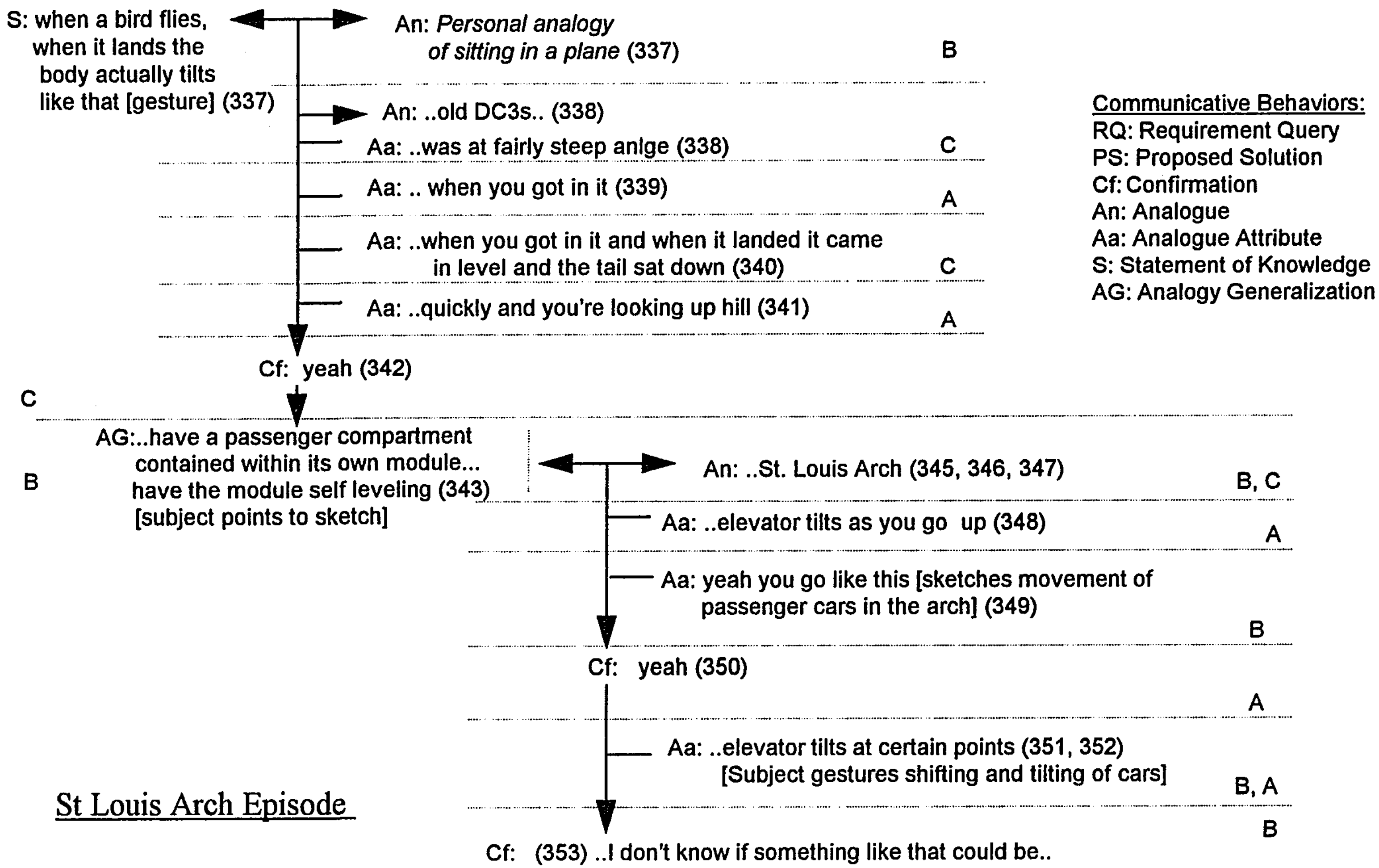
Cf: 6 feet is fine for me (307) B

PS: start with 6 feet you'll end up with 5 feet because.. (308) C

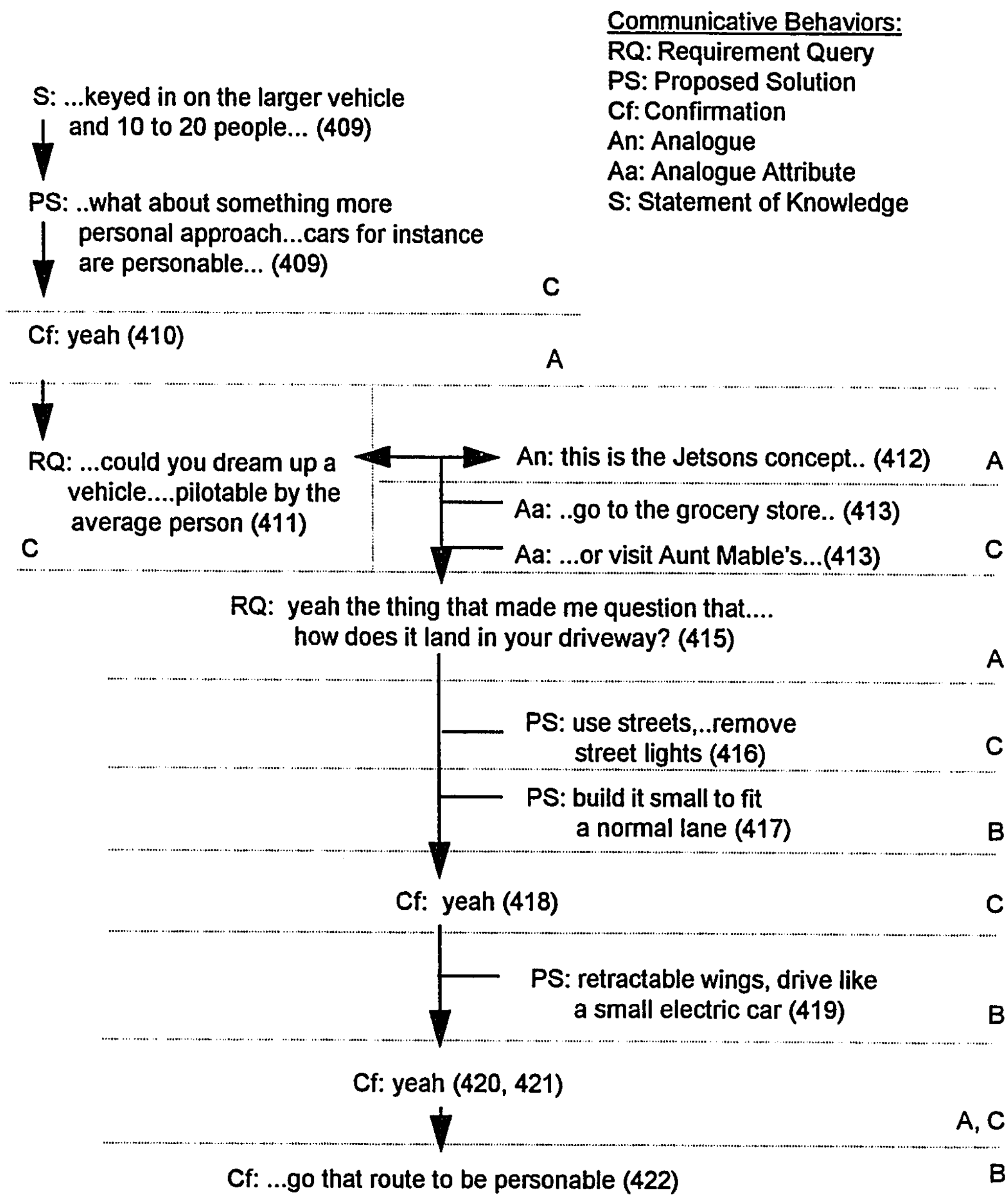
Beechcraft Episode



Parachute Episode

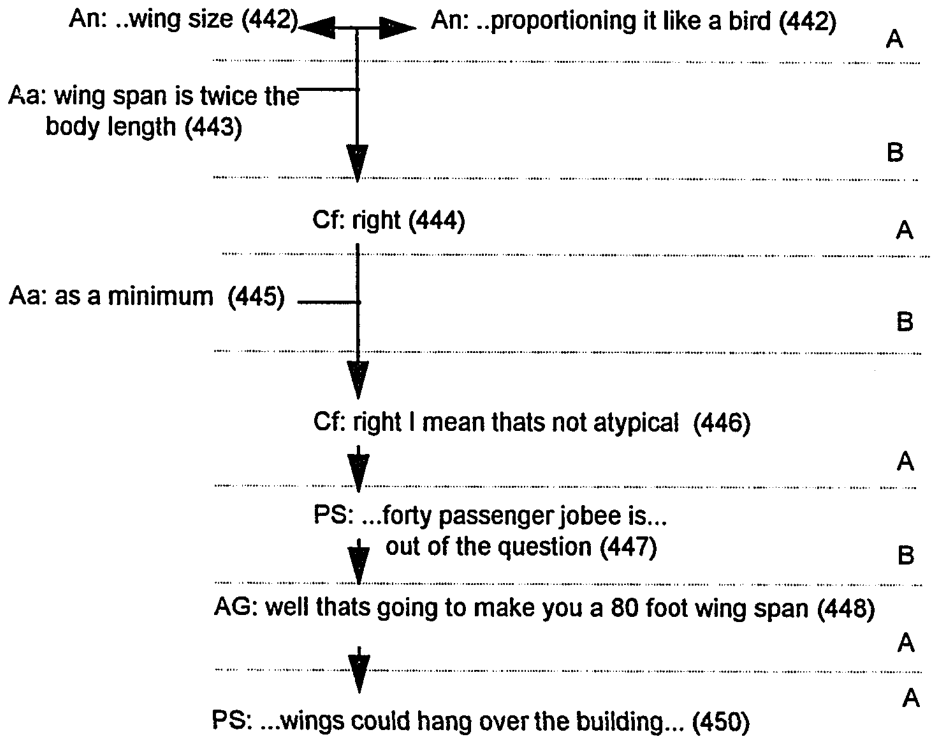


St Louis Arch Episode



Jetsons Episode

Communicative Behaviors:
PS: Proposed Solution
Cf: Confirmation
An: Analogue
Aa: Analogue Attribute
AG: Analogy Generalization



Wing Size Episode

Appendix E: Frequencies and Transitional Probabilities for Lags One through Seven

		Lag 1								
		An	Aa	AG	Cf	Cn	PS	RQ	S	totals
Lag 0	An	8	11	0	3	0	1	1	0	24
	Aa	3	8	2	7	0	0	1	3	24
	AG	2	0	0	3	0	1	0	1	7
	Cf	3	1	4	3	0	6	2	3	22
	Cn	1	0	0	0	0	0	0	2	3
	PS	0	0	2	7	1	2	2	0	14
	RQ	4	1	0	2	0	2	0	0	9
	S	1	1	1	2	1	4	1	1	12
									TOTAL:	115

Observed Frequencies for Two event Sequences

		Lag 1								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Sum
Lag 0	An	0.33	0.46	0.00	0.13	0.00	0.04	0.04	0.00	1.00
	Aa	0.13	0.33	0.08	0.29	0.00	0.00	0.04	0.13	1.00
	AG	0.29	0.00	0.00	0.43	0.00	0.14	0.00	0.14	1.00
	Cf	0.14	0.05	0.18	0.14	0.00	0.27	0.09	0.14	1.00
	Cn	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.67	1.00
	PS	0.00	0.00	0.14	0.50	0.07	0.14	0.14	0.00	1.00
	RQ	0.44	0.11	0.00	0.22	0.00	0.22	0.00	0.00	1.00
	S	0.08	0.08	0.08	0.17	0.08	0.33	0.08	0.08	1.00

Transitional Probabilities for Two Event Sequences

An= Analog
Aa= Analog Attribute
AG= Analogy Generalization
Cf= Confirmation
Cn= Control
PS= Proposed Solution
S= Statement

Table E-1: Frequencies and Transitional Probabilities for Lag One

		Lag 2								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Totals
Lag 0	An	3	11	1	4	0	1	0	3	23
	Aa	0	7	5	5	1	2	2	0	22
	AG	0	1	0	2	0	0	0	0	3
	Cf	6	2	1	6	0	3	1	1	20
	Cn	1	0	0	0	0	1	0	1	3
	PS	4	0	0	4	0	4	2	0	14
	RQ	3	2	0	0	0	2	0	2	9
	S	1	0	1	4	0	1	2	2	11
									TOTAL:	105

Observed Frequencies for Two event Sequences

		Lag 2								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Sum
Lag 0	An	0.13	0.48	0.04	0.17	0.00	0.04	0.00	0.13	1.00
	Aa	0.00	0.32	0.23	0.23	0.05	0.09	0.09	0.00	1.00
	AG	0.00	0.33	0.00	0.67	0.00	0.00	0.00	0.00	1.00
	Cf	0.30	0.10	0.05	0.30	0.00	0.15	0.05	0.05	1.00
	Cn	0.33	0.00	0.00	0.00	0.00	0.33	0.00	0.33	1.00
	PS	0.29	0.00	0.00	0.29	0.00	0.29	0.14	0.00	1.00
	RQ	0.33	0.22	0.00	0.00	0.00	0.22	0.00	0.22	1.00
	S	0.09	0.00	0.09	0.36	0.00	0.09	0.18	0.18	1.00

Transitional Probabilities for Two Event Sequences

An= Analog
Aa= Analog Attribute
AG= Analogy Generalization
Cf= Confirmation

Cn= Control
PS= Proposed Solution
S= Statement

Table E-2: Frequencies and Transitional Probabilities for Lag Two

		Lag 3								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Totals
Lag 0	An	3	6	2	5	1	1	2	2	22
	Aa	1	5	3	8	0	2	0	1	20
	AG	0	1	0	0	0	1	0	0	2
	Cf	3	5	2	1	0	3	2	0	16
	Cn	0	1	0	1	0	0	1	0	3
	PS	5	1	0	3	0	2	0	0	11
	RQ	1	2	0	3	0	1	1	1	9
	S	3	0	1	1	0	2	1	3	11
									TOTAL:	94

Observed Frequencies for Two event Sequences

		Lag 3								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Sum
Lag 0	An	0.14	0.27	0.09	0.23	0.05	0.05	0.09	0.09	1.00
	Aa	0.05	0.25	0.15	0.40	0.00	0.10	0.00	0.05	1.00
	AG	0.00	0.50	0.00	0.00	0.00	0.50	0.00	0.00	1.00
	Cf	0.19	0.31	0.13	0.06	0.00	0.19	0.13	0.00	1.00
	Cn	0.00	0.33	0.00	0.33	0.00	0.00	0.33	0.00	1.00
	PS	0.45	0.09	0.00	0.27	0.00	0.18	0.00	0.00	1.00
	RQ	0.11	0.22	0.00	0.33	0.00	0.11	0.11	0.11	1.00
	S	0.27	0.00	0.09	0.09	0.00	0.18	0.09	0.27	1.00

Transitional Probabilities for Two Event Sequences

An= Analog
Aa= Analog Attribute
AG= Analogy Generalization
Cf= Confirmation

Cn= Control
PS= Proposed Solution
S= Statement

Table E-3: Frequencies and Transitional Probabilities for Lag Three

		Lag 4								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Totals
Lag 0	An	2	7	3	4	1	2	0	1	20
	Aa	3	2	2	6	0	4	0	2	19
	AG	0	0	0	1	0	0	0	0	1
	Cf	2	5	2	1	0	2	1	2	15
	Cn	1	0	0	0	0	0	0	2	3
	PS	2	4	0	4	0	0	1	0	11
	RQ	1	2	0	1	0	3	2	0	9
	S	4	1	1	3	1	0	0	0	10
									TOTAL:	88

Observed Frequencies for Two event Sequences

		Lag 4								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Sum
Lag 0	An	0.10	0.35	0.15	0.20	0.05	0.10	0.00	0.05	1.00
	Aa	0.16	0.11	0.11	0.32	0.00	0.21	0.00	0.11	1.00
	AG	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	1.00
	Cf	0.13	0.33	0.13	0.07	0.00	0.13	0.07	0.13	1.00
	Cn	0.33	0.00	0.00	0.00	0.00	0.00	0.00	0.67	1.00
	PS	0.18	0.36	0.00	0.36	0.00	0.00	0.09	0.00	1.00
	RQ	0.11	0.22	0.00	0.11	0.00	0.33	0.22	0.00	1.00
	S	0.40	0.10	0.10	0.30	0.10	0.00	0.00	0.00	1.00

Transitional Probabilities for Two Event Sequences

An= Analog
Aa= Analog Attribute
AG= Analogy Generalization
Cf= Confirmation
Cn= Control
PS= Proposed Solution
S= Statement

Table E-4: Frequencies and Transitional Probabilities for Lag Four

		Lag 5								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Totals
Lag 0	An	2	5	2	6	0	2	0	2	19
	Aa	4	2	4	2	0	2	0	0	14
	AG	0	1	0	0	0	0	0	0	1
	Cf	2	4	1	4	0	1	1	0	13
	Cn	1	0	0	0	1	0	0	0	2
	PS	3	2	0	2	0	0	1	2	10
	RQ	1	1	0	3	0	3	0	1	9
	S	0	3	1	2	0	1	1	2	10
									TOTAL:	78

Observed Frequencies for Two event Sequences

		Lag 5								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Sum
Lag 0	An	0.11	0.26	0.11	0.32	0.00	0.11	0.00	0.11	1.00
	Aa	0.29	0.14	0.29	0.14	0.00	0.14	0.00	0.00	1.00
	AG	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00
	Cf	0.15	0.31	0.08	0.31	0.00	0.08	0.08	0.00	1.00
	Cn	0.50	0.00	0.00	0.00	0.50	0.00	0.00	0.00	1.00
	PS	0.30	0.20	0.00	0.20	0.00	0.00	0.10	0.20	1.00
	RQ	0.11	0.11	0.00	0.33	0.00	0.33	0.00	0.11	1.00
	S	0.00	0.30	0.10	0.20	0.00	0.10	0.10	0.20	1.00

Transitional Probabilities for Two Event Sequences

An= Analog
Aa= Analog Attribute
AG= Analogy Generalization
Cf= Confirmation
Cn= Control
PS= Proposed Solution
S= Statement

Table E-5: Frequencies and Transitional Probabilities for Lag Five

		Lag 6								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Totals
Lag 0	An	3	2	3	6	0	2	0	2	18
	Aa	1	4	0	4	0	2	0	1	12
	AG	0	1	0	1	0	0	0	0	2
	Cf	1	1	1	3	0	2	1	1	10
	Cn	0	1	1	0	0	0	0	1	3
	PS	1	5	0	0	1	1	1	0	9
	RQ	2	1	3	2	0	1	0	0	9
	S	2	2	0	3	0	1	0	1	9
									TOTAL:	72

Observed Frequencies for Two event Sequences

		Lag 6								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Sum
Lag 0	An	0.17	0.11	0.17	0.33	0.00	0.11	0.00	0.11	1.00
	Aa	0.08	0.33	0.00	0.33	0.00	0.17	0.00	0.08	1.00
	AG	0.00	0.50	0.00	0.50	0.00	0.00	0.00	0.00	1.00
	Cf	0.10	0.10	0.10	0.30	0.00	0.20	0.10	0.10	1.00
	Cn	0.00	0.33	0.33	0.00	0.00	0.00	0.00	0.33	1.00
	PS	0.11	0.56	0.00	0.00	0.11	0.11	0.11	0.00	1.00
	RQ	0.22	0.11	0.33	0.22	0.00	0.11	0.00	0.00	1.00
	S	0.22	0.22	0.00	0.33	0.00	0.11	0.00	0.11	1.00

Transitional Probabilities for Two Event Sequences

An= Analog
Aa= Analog Attribute
AG= Analogy Generalization
Cf= Confirmation
Cn= Control
PS= Proposed Solution
S= Statement

Table E-6: Frequencies and Transitional Probabilities for Lag Six

		Lag 7								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Totals
Lag 0	An	1	2	5	3	0	2	0	1	14
	Aa	0	3	0	4	0	1	0	1	9
	AG	0	0	0	0	0	0	0	0	0
	Cf	2	2	1	4	0	1	0	0	10
	Cn	0	0	0	1	0	0	0	2	3
	PS	2	1	1	1	0	1	1	2	9
	RQ	1	2	0	3	0	1	0	0	7
	S	1	2	1	1	0	1	1	0	7
									TOTAL:	59

Observed Frequencies for Two event Sequences

		Lag 7								
		An	Aa	AG	Cf	Cn	PS	RQ	S	Sum
Lag 0	An	0.07	0.14	0.36	0.21	0.00	0.14	0.00	0.07	1.00
	Aa	0.00	0.33	0.00	0.44	0.00	0.11	0.00	0.11	1.00
	AG	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Cf	0.20	0.20	0.10	0.40	0.00	0.10	0.00	0.00	1.00
	Cn	0.00	0.00	0.00	0.33	0.00	0.00	0.00	0.67	1.00
	PS	0.22	0.11	0.11	0.11	0.00	0.11	0.11	0.22	1.00
	RQ	0.14	0.29	0.00	0.43	0.00	0.14	0.00	0.00	1.00
	S	0.14	0.29	0.14	0.14	0.00	0.14	0.14	0.00	1.00

Transitional Probabilities for Two Event Sequences

An= Analog
Aa= Analog Attribute
AG= Analogy Generalization
Cf= Confirmation
Cn= Control
PS= Proposed Solution
S= Statement

Table E-7: Frequencies and Transitional Probabilities for Lag Seven

Appendix F: Summary Table of Transitional Probabilities

Criterion Behavior		Lag						
	Subsequent Behavior	1	2	3	4	5	6	7
An	Analog (An)	0.33	0.13	0.14	0.1	0.11	0.17	0.07
	Analog Attribute (Aa)	0.46	0.48	0.27	0.35	0.26	0.11	0.14
	Analogy Generalization (AG)	0	0.04	0.09	0.15	0.11	0.17	0.36
	Confirmation (Cf)	0.13	0.17	0.23	0.2	0.32	0.33	0.21
	Control (Cn)	0	0	0.05	0.05	0	0	0
	Proposed Solution (PS)	0.04	0.04	0.05	0.1	0.11	0.11	0.14
	Requirement Query (RQ)	0.04	0	0.09	0	0	0	0
	Statement (S)	0	0.13	0.09	0.05	0.11	0.11	0.07
Aa	Analog (An)	0.13	0	0.05	0.16	0.29	0.08	0
	Analog Attribute (Aa)	0.33	0.32	0.25	0.11	0.14	0.33	0.33
	Analogy Generalization (AG)	0.08	0.23	0.15	0.11	0.29	0	0
	Confirmation (Cf)	0.29	0.23	0.4	0.32	0.14	0.33	0.44
	Control (Cn)	0	0.05	0	0	0	0	0
	Proposed Solution (PS)	0	0.09	0.1	0.21	0.14	0.17	0.11
	Requirement Query (RQ)	0.04	0.09	0	0	0	0	0
	Statement (S)	0.13	0	0.05	0.11	0	0.08	0.11
AG	Analog (An)	0.29	0	0	0	0	0	0
	Analog Attribute (Aa)	0	0.33	0.5	0	1	0.5	0
	Analogy Generalization (AG)	0	0	0	0	0	0	0
	Confirmation (Cf)	0.43	0.67	0	0	0	0.5	0
	Control (Cn)	0	0	0	0	0	0	0
	Proposed Solution (PS)	0.14	0	0.5	0	0	0	0
	Requirement Query (RQ)	0	0	0	0	0	0	0
	Statement (S)	0.14	0	0	0	0	0	0
Cf	Analog (An)	0.14	0.3	0.19	0.13	0.15	0.1	0.2
	Analog Attribute (Aa)	0.05	0.1	0.31	0.33	0.31	0.1	0.2
	Analogy Generalization (AG)	0.18	0.05	0.13	0.13	0.08	0.1	0.1
	Confirmation (Cf)	0.14	0.3	0.06	0.07	0.31	0.3	0.4
	Control (Cn)	0	0	0	0	0	0	0
	Proposed Solution (PS)	0.27	0.15	0.19	0.13	0.08	0.2	0.1
	Requirement Query (RQ)	0.09	0.05	0.13	0.07	0.08	0.1	0
	Statement (S)	0.14	0.05	0	0.13	0	0.1	0
Cn	Analog (An)	0.33	0.33	0	0.33	0.5	0	0
	Analog Attribute (Aa)	0	0	0.33	0	0	0.33	0
	Analogy Generalization (AG)	0	0	0	0	0	0.33	0
	Confirmation (Cf)	0	0	0.33	0	0	0	0.33
	Control (Cn)	0	0	0	0	0.5	0	0
	Proposed Solution (PS)	0	0.33	0	0	0	0	0
	Requirement Query (RQ)	0	0	0.33	0	0	0	0
	Statement (S)	0.67	0.33	0	0.67	0	0.33	0.67

Table F-1. Summary of Transitional Probabilities

Criterion Behavior	Subsequent Behavior	Lag 1	2	3	4	5	6	7
PS	Analog (An)	0	0.29	0.45	0.18	0.3	0.11	0.22
	Analog Attribute (Aa)	0	0	0.09	0.36	0.2	0.56	0.11
	Analogy Generalization (AG)	0.14	0	0	0	0	0	0.11
	Confirmation (Cf)	0.5	0.29	0.27	0.36	0.2	0	0.11
	Control (Cn)	0.07	0	0	0	0	0.11	0
	Proposed Solution (PS)	0.14	0.29	0.18	0	0	0.11	0.11
	Requirement Query (RQ)	0.14	0.14	0	0.09	0.1	0.11	0.11
	Statement (S)	0	0	0	0	0.2	0	0.22
RQ	Analog (An)	0.44	0.33	0.11	0.11	0.11	0.22	0.14
	Analog Attribute (Aa)	0.11	0.22	0.22	0.22	0.11	0.11	0.29
	Analogy Generalization (AG)	0	0	0	0	0	0.33	0
	Confirmation (Cf)	0.22	0	0.33	0.11	0.33	0.22	0.43
	Control (Cn)	0	0	0	0	0	0	0
	Proposed Solution (PS)	0.22	0.22	0.11	0.33	0.33	0.11	0.14
	Requirement Query (RQ)	0	0	0.11	0.22	0	0	0
	Statement (S)	0	0.22	0.11	0	0.11	0	0
S	Analog (An)	0.08	0.09	0.27	0.4	0	0.22	0.14
	Analog Attribute (Aa)	0.08	0	0	0.1	0.3	0.22	0.29
	Analogy Generalization (AG)	0.08	0.09	0.09	0.1	0.1	0	0.14
	Confirmation (Cf)	0.17	0.36	0.09	0.3	0.2	0.33	0.14
	Control (Cn)	0.08	0	0	0.1	0	0	0
	Proposed Solution (PS)	0.33	0.09	0.18	0	0.1	0.11	0.14
	Requirement Query (RQ)	0.08	0.18	0.09	0	0.1	0	0.14
	Statement (S)	0.08	0.18	0.27	0	0.2	0.11	0

Table F-1 (con't). Summary of Transitional Probabilities

AUTOBIOGRAPHY

Christopher E. Weeks was born in Chapel Hill, North Carolina in 1957. He received his bachelor's degree in Ocean Engineering from the Florida Institute of Technology, Melbourne, Florida in 1981. After graduation, Mr. Weeks was employed by Ingalls Shipbuilding in Pascagoula, Mississippi as a naval engineer where he participated in the conceptual, preliminary, and detailed design of naval vessels. In 1985 he left Ingalls to participate in the preliminary and detailed design of the SSN SEAWOLF Attack Submarine at Newport News Shipbuilding in Newport News, Virginia. While employed by Newport News Shipbuilding, Mr. Weeks obtained his master's degree in Engineering Management from the George Washington University, Washington, D.C. in 1989. At the time of this writing, Mr. Weeks was the Program Systems Engineer for the Advanced SEAL Delivery System (ASDS) Program where he was responsible for defining, executing, and managing a systems engineering process for the preliminary and detailed design phases of the program. Mr. Weeks is a member of the National Council on Systems Engineering (NCOSE) and Chapter Organizer for the Tidewater Area.