# MODELING PERSPECTIVES WITH LIVING SYSTEMS THEORY IN THE DESIGN OF COMPLEX ENGINEERING SYSTEMS

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Complex engineered systems (e.g., aeronautic vehicles and automobiles) consist of many different interfacing subsystems and are subject to numerous requirements and constraints regarding aspects of performance, manufacturability, economics, etc. Their design requires the collaborative teamwork of specialists from a variety of disciplines – each retaining different, but necessary, perspectives of the system under design. These perspectives influence designers, and consequently design, as they are brought to bear on information and knowledge. Here, we define a perspective as a particular context with which a human perceives, thinks, decides, and represents. Successful solutions to design problems depend upon a host of perspectival issues; hence, our conception of perspective plays a crucial role in engineering systems design. In this paper we offer a philosophical foundation for performing design that explicitly incorporates perspective, and we present a method for modeling multiple perspectives of complex engineering systems. Our scope is limited to modeling conceptual systems at a functional level of design abstraction using Living Systems Theory (LST). An example involving the design of a BUG device is provided – a project from our mechanical engineering design courses. In this example we present various knowledge, space, and time perspectives of a conceptual BUG system, modeled with the LST icons.

Keywords engineering design, complex systems, Living Systems Theory (LST), perspectives

## 1. Our Frame of Reference

General methods and tools are needed to better support humans as they design and realize complex engineering systems, such as aeronautic vehicles and automobiles. Complex systems are characterized by the existence of a variety of domains among an extensive hierarchy of interfacing subsystems (Pahl and Beitz, 1996; Simon, 1996). This is particularized to the products of engineering design “in view of the thousands of components involved and the complicated interrelationships between them” (Krick, 1969). These systems are also subject to numerous requirements and constraints

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regarding multidisciplinary aspects of performance, manufacturability, economics, safety, operability, maintainability, etc.

In light of these facts, it is well understood that the design of complex engineering systems requires the collaborative teamwork of specialists from a variety of disciplines and subdisciplines. Endowed with particular expertise and personal mastery, each specialist retains different, yet relevant, perspectives of the system under design. Such perspectives are brought to bear on information and knowledge in order to diminish apparent complexities and create personally meaningful understanding; therefore, perspectives greatly influence and affect design. This serves as impetus to research and develop means enabling product realization teams to employ perspectives efficiently and effectively. Towards that end, in this paper we address the following question, *how can product realization teams explicitly model various perspectives of complex engineering systems?*

Limiting our scope, we answer the preceding question in the context of conceptual design – specifically design at the abstract level of function. In Section 3, we develop a certain clarity of the term perspective and its semantic meaning, presenting a definition that serves us throughout this paper. Further, we offer a taxonomy to classify perspectives within engineering design. In Section 4, we review Living Systems Theory, which we utilize to model various functional perspectives of engineering systems. Our approach is applied to the conceptual design of a BUG device in Section 5. In the next section, we present a precursory motivation for investigating the notion of perspective in engineering design.

## 2. Perspective in Engineering Design: A Motivating Example

The complex products and processes of engineering design are inherently "multifaceted" like a fanciful cut gemstone. As a gemstone is turned, different visions of color, reflection, and brightness are observed from each of its multitude of facets; the subject of engineering design also exhibits this trait in a figurative sense. That is, engineering products and their processes can be viewed, understood, talked about, and represented in a variety of different ways. For example, a coffee bean grinder (also known as a coffee mill) serves a well-defined purpose in a seemingly simple manner. Despite glaring differences in physical form or operation, all coffee grinders achieve the same basic functions as illustrated by the elementary function-block diagram in Figure 1. Coffee beans are input to the device; they are ground into finer pieces; and the coffee grounds are retrieved for making coffee.

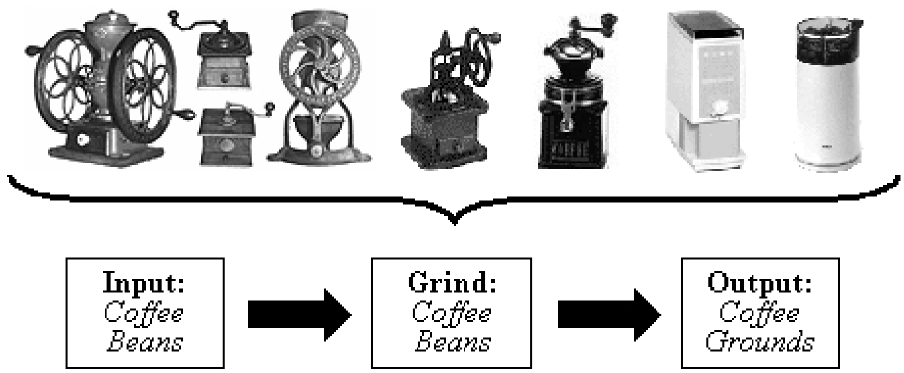


**Figure 1.** Fundamental functions involved in the operation of all coffee grinders

This apparent simplicity of function belies the difficulties involved in the design and realization of a coffee-grinding unit. The artifact and its design are exceedingly more complex owing to many intrinsic facets, a sampling of which we describe here. When viewing the contraption from a marketing facet, the coffee grinder is understood in terms of its ability to satisfy needs and whims of potential customers. From an industrial design facet, the coffee grinder's ergonomic and aesthetically pleasing forms are the primary focus. Viewing the product from a mechanical engineering facet centers upon mechanical apparatus used to grind beans. The coffee grinder seen from an electrical engineering facet is a vast network of electrical componentry. A manufacturing facet reveals simple and standardized parts that are easily assembled. The managerial facet displays coordinated organizations required to realize and sell the coffee grinder as a commercial product.

Many differences exist among these facets, including subject of interest, relevance of subject content, technical detail, vocabulary, and symbology. A mechanical engineering facet focuses upon machine mechanisms that involve a relatively high level of technical detail during the product design stage; words such as "stress and strain" and "torque" are employed. This is strikingly different from other facets. In comparison, a managerial facet focuses upon administering the organization that realizes the coffee grinder. Generally, it consists of less technical detail, but remains active over the entire product life-cycle; a different vocabulary of words is utilized, including "schedule and budget" and "best practices." This diversity further complicates design efforts as designers struggle to collaborate, attempting to communicate their particular interests in dissimilar and often specialized terms.

In this paper, such facets are more formally termed *perspectives*. Adopting this terminology, the design and realization of a coffee grinder, or any other complex engineering system, involves many different perspectives; therefore, it is important to formally incorporate the notion of perspective in engineering design. The individual treatment of these perspectives leads to the establishment of particular product attributes, such as elegance of industrial design, "bells and whistles" from marketing specification, performance of grinding mechanism, or quality of manufacture. For this reason, it is necessary to identify, label, and explicitly model individual design perspectives. But the key to product "wholeness" – and hence, overall success – lies in the seamless integration of product attributes; hence, it is essential that designers account for perspectives in a common language, investigate interrelationships among perspectives, and synthesize multi-perspectival models. Before addressing such issues in this paper, the term perspective is further investigated. In the next section, we develop and explicate a formal definition of the word perspective that is applicable to engineering design.

## 3. Understanding Perspective

*What is this thing called perspective?* In talking about perspectives, we observe that individuals liberally apply words like: domain, discipline, mindset, view, viewpoint, point of view, frame of reference, frame of mind, vantage point, facet, dimension, *n*-dimensional (i.e., 1-, 2-, 3-dimensional, etc.), and prospect. Since perspective is used interchangeably with these other terms in the same sentence or breath, somehow it must be closely related to these words that connote both mind and sight. Regardless, no unifying consensus or single definition currently exists. If perspective is to be a central concept within this paper, then some sense must be created from the confusion.

The etymological birth of the term perspective is traced back to the Latin word *perspicere*, which means "to look through or closely into, view, behold." The word perspective has many definitions, ranging from the action of looking into something to the appearance of visible objects, views, and vistas; from a science of sight to an optical instrument for viewing objects; from an artistic technique to a mental viewpoint (cf. *Oxford English Dictionary*). Observing these many different definitions, the present task of clarifying meaning might seem rather hopeless. Nevertheless, by investigating the context and use of the term in several different areas we are able to garner its broader significance in the realm of design. Therefore, we briefly explore specializations of the term in the domains of art, psychology, philosophy, and science.

### 3.1 Perspectives in Art, Psychology, Philosophy, and Science

The concept of perspective is essential within the visual arts, graphic art, and architecture. Qualifiers precede the term, including linear, non-linear, one-point, parallel, normal, accidental, oblique, aerial, and colour. In the art world, perspective corresponds to a representational style; it describes how geometric volumes are spatially configured and artistically represented. With regards to conventional paintings, drawings, and sketches, perspective is typically manifested as depth representation of three-dimensional geometries on two-dimensional, planar surfaces.

In the domain of psychology, perspective has two meanings: a visual perception and a frame of mind. The former is derived from extensive work involving human perception of visual stimuli. Experimental subjects recognize different perspectives in images, such as an elegant vase or the two opposing faces of the famous Rubin's vase. Perspectives of the latter meaning are analyzed by psychologists to identify the conscious and subconscious thoughts of their subjects. Perspective-taking exercises are popularly known as role-playing – a common fixture in counsel-based therapy. Subjects imagine themselves as someone or something else, consciously forcing change in their own perspectives.

Philosophers ponder questions of perspective as it relates to truth. Tenets such as absolutism, empiricism, pluralism, reductionism, and relativism account for humans lacking objective knowledge of truth. In perspectivism, Friedrich Nietzsche asserts that both experience and knowledge are unavoidably perspectival in nature: "Facts are precisely what there is not, only interpretations." He denies the possibility of complete and objective knowledge as obtained through a "god's-eye-view" of the world that incorporates every possible perspective; but, he concedes that a more complete and objective knowledge is attained in the attempt. Nietzsche encourages individuals to adopt many different perspectives – to look "now through this window, now through that one." An individual locked into one perspective is unable to know and enjoy the different features of reality obtained from other perspectives.

In the domain of general science, formal use of the term perspective is infrequent. Now antiquated, perspective once meant the science of sight and optics. Another archaic definition is that of an optical instrument for looking through, e.g., a lens such as a magnifying-glass. The most current work that incorporates the term involves the unification of sciences. Perspective describes scientific domains and their viewpoints that are arguably compartmentalized and overspecialized; Bertalanffy (1968) writes: "The same table is to the physicist an aggregate of electrons, protons, and neutrons, to the chemist a composition of certain organic compounds, to the biologist a complex of wood cells, to the art historian a baroque object, to the economist a utility of certain money value, etc. All these perspectives are of equal status, and none can claim more absolute value than the other." Borrowing the term from Nietzsche's tenet, perspectivism is advocated as a theory with which some uniformity of conceptual schemes and symbolic constructs in science is sought out (Bertalanffy, 1953); thus, scientific perspectives are integrated to create a unity of sciences. Next, we develop an understanding of perspective in engineering design that builds upon each of the definitions presented here.

## 3.2 Incorporating Perspective in Engineering Design

Understanding perspective in the context of engineering design requires a knowledge of engineering design itself; in the confines of this paper we cannot treat the matter with great detail. Generally, engineering design is the activity through which an idea is transformed into the reality of an engineered artifact. Krick (1969) states that it is "the general process by which the engineer applies his knowledge, skills, and point of view in the creation of devices, structures, and processes." Mistree and coauthors (1990) define design as "the process of converting information that characterizes the needs and requirements of a system into knowledge about the system itself." In this latter definition, the activity of processing information is quintessential. Synthesis, representation, and analysis typify the sort of information-processing fundamental to design; but, decision-making is paramount. The decisions that designers make bring about the transformation of information into knowledge. Therefore, we subscribe to a design paradigm known as Decision-Based Design (DBD) in which "the principal role of an engineer, in the design of an artifact, is to make decisions" (Mistree, et al., 1990).

The large quantities of information that designers collect, generate, and process in complex system design is diverse. From Section 2, recall that the design of a coffee grinder involves information about coffee markets, grinding mechanisms, methods of manufacture, management techniques, etc. Such information varies not only in terms of content, vocabulary, and symbology, but also quality; some information is "soft" (i.e., abstract and experiential) while other information is "hard" (i.e., concrete and scientific). Consequently, the conversion of design information into knowledge is accomplished in successive stages that feature information at the same level of abstraction. Although a standard number and naming convention for levels of abstraction have not been adopted, we generically denote the principal levels as function, behavior, and structure (Clark, et al., 1997). Function describes intended purpose, represented in a nondescript manner with no mention of physical realization. Behavior describes system performance, quantitatively denoted by mathematical equations that relate system variables. Structure describes physical aspects of the entities comprising the system, including assemblies, components, and parts. Designers systematically execute the design of complex systems by negotiating these levels from the abstract to the concrete, i.e., function to behavior to structure.

Clearly, the activity of design is not only complicated, but also intensely cerebral owing to the emphasis upon cognitive information-processes. To manage such large quantities of diverse information, design is implemented among a team of specialists, each retaining different expertise and personal mastery relevant to the system under design. But, to make sense of that information, designers employ perspectives – including those specialized by artists, psychologists, philosophers, and scientists, as discussed in the previous section. For instance, designers utilize artistic perspectives to represent information, perspectives of perceptual psychology to perceive information, perspectives of social psychology to exchange information, philosophical perspectives to reason about information, and scientific perspectives to analyze information, among many others. The commonality that exists among such perspectives, particularly in engineering design, is that they frame human cognition and give meaning to information. Designers bring perspectives to bear on information and knowledge in order to create personally meaningful understanding; therefore, perspectives dictate how, what, and why designers perceive, think, decide, and represent. It is for this reason that perspectives play a crucial role in engineering design. In this paper, we formally define perspective as a particular context – specifically, a context that is perceived, a context with which a human goes about thinking and deciding, or, a context that is represented.

Given this important role that perspective plays in engineering design, it is interesting to note that similar notions of perspective are underdeveloped or nonexistent. At best, established frameworks, procedures, and tools for design unwittingly incorporate perspective. For example, Concurrent Engineering (CE), Integrated Product and Process Design (IPPD), Design for *X* (DF*X*), Quality Function Deployment (QFD), and Multidisciplinary Optimization (MDO) offer schemes to negotiate one or more perspectives tacitly; however, they are severely limited since they are not built upon formal conceptions of perspective.

Acknowledging the significant influence of perspectives, we view design as a process in which a whole and complete system is created, developed, and realized by negotiating a multitude of perspectives. We strive to gain a better understanding of and improve upon the ways in which designers utilize such perspectives to their advantage. This can only be achieved by making them explicit within engineering design. Consequently, we offer a philosophical foundation for performing design predicated on the idea that successful solutions to design problems depend upon a host of perspectival issues. That is, perspectives of complex engineering systems must be identified, labeled, and explicitly represented; they must be accounted for in a common language; they must be analyzed, particularly their interrelationships; and, they must be synthesized into multi-perspectival models. Only by considering all perspectives is a greater holistic understanding of a system attained such that more informed, better design decisions are made. In the next section, we introduce a taxonomy of principal perspectives that are employed in engineering design.

### 3.3 A Taxonomy of Principal Perspectives

Work that explicitly incorporates perspective within engineering design is new and embryonic. To develop further a new idea of this sort, classification schemes are often created. A simple taxonomy of principal perspectives that humans apply to design information is presented here. In proposing this scheme, our goal is to identify and label the types of perspective that are typically encountered in engineering design.

The perspectives that humans employ when designing complex systems may be classified among three principal headings: knowledge, space, and time. Traditional disciplines, databases, archives, knowledge-based domains, and similar repositories of learning are included within the principal perspective of knowledge. Therefore, the scientific principles embodied within various fields of science and engineering constitute examples of knowledge perspectives. Spatial perspectives, i.e., the contexts a human utilizes to process spatial information, include issues of dimension, scale, location, configuration, and arrangement. Perspectives of time, i.e., the contexts that give meaning to temporal information, include duration, rate, chronology, and process. An illustration of these perspectives that comprise our taxonomy is shown in Figure 2.

With our taxonomy, designers are able to easily identify perspectives under principal headings, or decompose complex perspectives into simpler components. In this manner, designers are afforded the opportunity to take stock of and better manage perspectives relevant in the design of complex engineering systems. This is exemplified by revisiting our coffee grinder example from Section 2. The design of a coffee grinder requires different knowledge perspectives, including but not limited to knowledge of: coffee and beans; structural housings and enclosures, electrical circuits, and mechanical grinding mechanisms. Further, time-based perspectives play an important role in the design of a coffee grinder. Examples of such temporal perspectives include: considerations of life-cycle and product realization processes; time-based performance aspects of the product; and operational sequences. Finally, spatial perspectives are of fundamental importance in the design of any physical product. The different spatial perspectives of a coffee grinder and its various components include: interrelationships among physical forms; component shapes and dimensions; and arrangements of different parts.

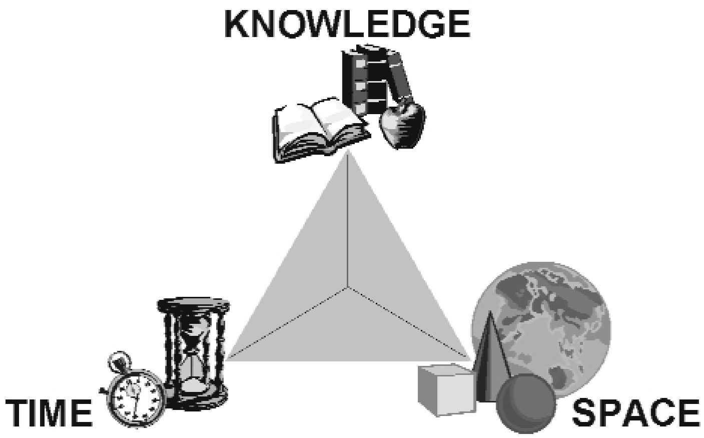


**Figure 2.** A taxonomy of principal perspectives in engineering design

Throughout Section 3, we develop an understanding of perspective, particularly as it relates to engineering design. We discuss the integral role that perspective retains in design and, consequently, advocate a design philosophy in which perspectives are made explicit. Our proposed taxonomy is utilized to identify, label, and manage the variety of perspectives encountered in design. What we have yet to establish is an overtly generic way to represent and model perspectives. This is a vital part of engineering design since designers work extensively with representational models. In the next section, we address the issue of functional representation with Living Systems Theory.

## 4. Living Systems Theory: A Foundation for Engineering Design

Living Systems Theory (LST) is the conceptual framework developed to integrate the findings of system theorists and scientists in biology, physiology, neurology, the social sciences, economics, and management. LST serves as a unified theory of science that deals with the hierarchical structure of living systems (Miller, 1995; Miller 1990). As a general system theory, LST is also applicable to nonliving entities since there are comparable analogies between both living and nonliving systems.

In LST, twenty critical subsystems are identified; they perform basic functions that are essential life processes in living systems. These subsystems are classified into three categories and identified as follows: two subsystems that process both *matter-energy* and *information* (namely, the *reproducer* and *boundary*); eight subsystems that process *matter-energy* (namely, the *ingestor*, *distributor*, *converter*, *producer*, *storage*, *extruder*, *motor*, and *supporter*); and ten subsystems that process *information* (namely, the *input transducer*, *internal transducer*, *channel and net*, *decoder*, *associator*, *memory*, *decider*, *timer*, *encoder*, and *output transducer*). The symbolic representation scheme for these twenty LST subsystems is presented in Figure 3. We refer the reader to (Miller, 1995) for definitions and detailed explanations of the LST subsystems.

Both the Systems Design Laboratory at the University of Houston and the Systems Realization Laboratory at Georgia Tech have a rich and fruitful history of applying LST to engineering design. Shupe (1988) first explored the applicability of LST to decision-based engineering design. He developed heuristics and rules that established it as a paradigm for partitioning design systems. Koch, et al., (1996) demonstrated that LST is a powerful asset for designers with which functional requirements are represented and different conceptual systems created. A computer tool called the Partitioner was created to help designers generate models featuring the LST icons (Koch, 1994). Peplinksi, et al., (1996) devised the Flame software that extracts specifications from Partitioner-created models and addresses product manufacture issues. Clark, et al., (1996; 1997) proposed a catalog that links LST functions to engineering components. Mumpower (1998) demonstrated the use of LST in modeling manufacturing systems. Throughout this wealth of work, LST has been successfully employed as a functional modeling scheme in the design of nonliving systems that include a lawn mower (Mistree, et al., 1995), lubricant cooling system (Koch, et al., 1995), and aircraft evacuation system (Koch, et al., 1994).

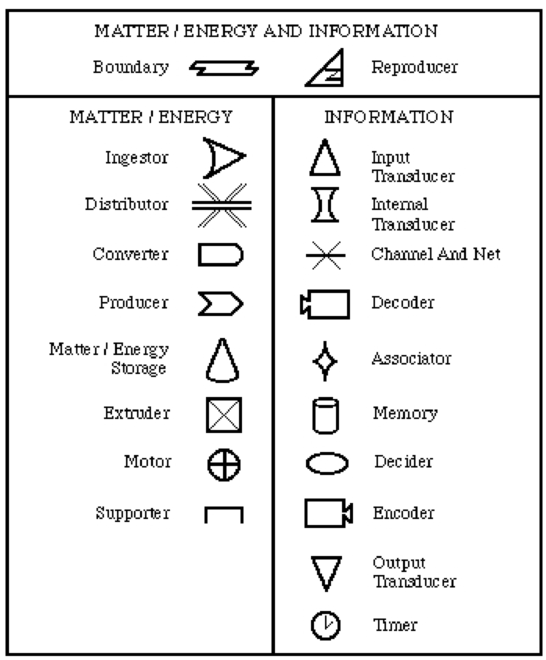


**Figure 3.** Symbolic representation of LST subsystems, from (Koch, et al., 1995)

Regarding our work with perspectives, two particular strengths of LST stand out among all others. First, LST serves as an appropriate functional modeling scheme in engineering design, exemplified by the pioneering work of both the Systems Design and Systems Realization Laboratories. Functional modeling is a well-established initial step in the conceptual design of engineering systems (e.g., Pahl and Beitz, 1996). With LST, designers can model adequately the various technical perspectives of nonliving systems at the abstract level of function; for guidelines on modeling engineering systems with LST see, e.g., (Koch, et al., 1994). Second, LST proves useful in modeling a broad spectrum of living systems. LST is the only general system theory of its kind that has been successfully utilized to model systems in biology, psychology, sociology, management, and economics (Miller and Miller, 1992). In contrast, other functional modeling schemes are overspecialized, too generalized, or unproven in terms of their breadth. This generic applicability suggests to us that designers can model with LST the relevant complex system perspectives that are neither technical nor strictly engineering-related.

We capitalize upon these strengths and employ LST in modeling the diverse functional perspectives of complex engineering systems. In our approach, LST is the core lexicon and representation scheme utilized by all members of a product realization team. Individual designers, endowed with different but necessary perspectives, create the variety of functional models characterizing all aspects of the system under design. These models are composed of the same language and symbology, thereby facilitating communication among the design team. This particular feature of our scheme allows for unique collaborations; designers aggregate their individual perspectives to generate more complete system models. Therefore, our approach reflects the holistic thinking necessary for the development of seamlessly integrated products and processes. The explicit representation of perspectival models with LST constitutes our foundation for incorporating perspective in engineering design. In the next section, we demonstrate our approach by modeling perspectives of a BUG system, the subject of an engineering class design project.

## 5. Illustrative Example: Project BUG

To demonstrate our approach involving the explicit incorporation of perspective in conceptual engineering design, we present an example problem termed Project BUG. It is a problem of appropriate complexity that has been utilized as a class project in the mechanical engineering design curriculum at the Georgia Institute of Technology. The complete problem story and other pertinent details are given in (Shupe, 1988). To establish a creative atmosphere, the problem itself is set in the virtual reality of the fictitious Planet Vayu, sometime in the far future.

### 5.1 Project BUG Story

In Project BUG, the evil Phoenix came to Planet Vayu in a huge, black, ovoid spaceship. To deny access by the Vayuns, he hung mesh from the sides of his ship. He was able to start a fire between the net and the ship, which only consumed animate matter. The Phoenix then announced that he was taking over Planet Vayu and controlling the Confederation of Worlds. This surely meant the enslavement of Vayuns and other terrible inhumanities. To save their planet, the Vayuns called upon the technical skills of its inhabitants to construct a mechanism, known as the BUG, which would be capable of climbing the fiery mesh and extinguishing the blaze. This would allow Vayuns to board the ship, incapacitate the Phoenix, and turn him over to Confederation Police. Thus, designers assume the roles of Vayun engineers in their time of peril, and are confronted with the following task.

*Design, build, and test a BUG mechanism capable of climbing a mesh track and, upon reaching the top of its climb, releasing a fire-extinguishing powder. The BUG device must perform within required specifications and be autonomous, self-contained, and appropriately dimensioned.*

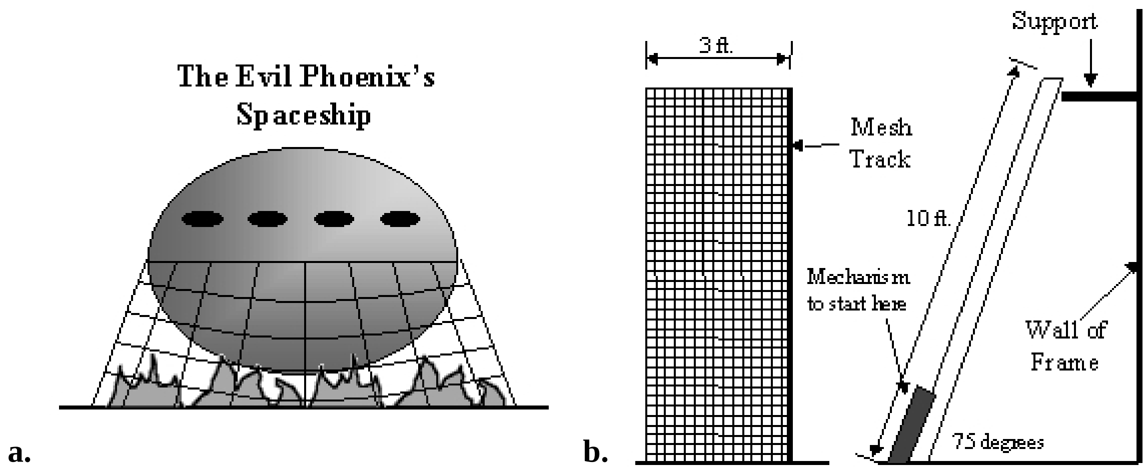


**Figure 4.** An illustrated view of (a.) the Phoenix's ship, and (b.) a configuration of the BUG track

A possible configuration of the BUG track is illustrated in Figure 4. Detailed restrictions and requirements are given in the original problem description (cf. Shupe, 1988). Project BUG is a problem for which there is no clear-cut, easily determined, unique solution. Rather, there exist numerous and vastly different ways and means to successfully solve the problem. From our experience, the common aspect in all engineered solutions to Project BUG is that they consist of many different interfacing parts. Furthermore, the parts are representative of a variety of different domains. In light of these facts, we assert that a BUG device is generally illustrative of complex engineering systems.

### 5.2 Perspectival BUG Models at a Functional Level of Abstraction

Consider the multiplicity of perspectives involved in the design of a BUG device. Expertise and personal mastery generally dictate the perspectives taken, which in turn shape how designers perceive, think, decide, and represent. As a result, various aspects of the BUG system are the primary focus of different individuals. To one designer, the BUG is merely a device that traverses a track; for another designer, the BUG is simply a contraption that stores and releases a payload of powder. Other designers view the BUG as a mechanism that operates through the conversion of energy; a structural frame that supports components; an artifact that is manufactured; a project that is managed; a system that ends conflict and produces peace of mind. Each perspective of the BUG is not only valid, but also equally necessary for its design. These individual perspectives define in part the complex BUG; collectively, they constitute a more complete system picture.

To develop, design, and realize a solution requires the negotiation of such assorted perspectives. We offer a design approach in which the notion of perspective is formally incorporated and explicitly featured. In this section we demonstrate our technique with which different system perspectives of a BUG are modeled with the LST icons. These perspectival models, derived from our taxonomy, are organized and presented according to the principal perspectives of knowledge, time, and space.

*5.2.1 Perspectives of Knowledge in the Design of a BUG*

From our taxonomy in Section 3.3, knowledge perspectives include the principles within disciplines, databases, archives, and similar repositories. In the conceptual design of a BUG, knowledge perspectives involving the engineering disciplines are particularly relevant; they are prominently featured in this paper. Examples of such perspectives include mechanical engineering (principles governing common machine mechanisms) and electrical engineering (principles governing electrical mechanisms) among others.

In Figure 5, mechanical and electrical engineering perspectival models of the BUG propulsion subsystem are shown. In the electrical engineering perspective of Figure 5a, electrical energy is stored and released in a discretionary manner; the electrical energy is distributed and converted it into a more appropriate form. In the mechanical engineering perspective of Figure 5b, mechanical energy for moving the BUG is provided and distributed. It is converted into a more useful form and further distributed through the system; finally, it is transmitted out of the system where it is utilized in the propulsion process.

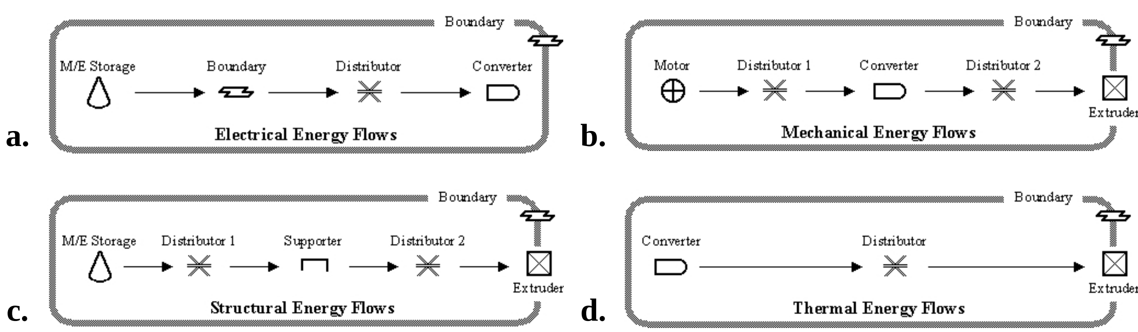


**Figure 5.** Engineering knowledge perspectives: (a.) electrical, (b.) mechanical, (c.) structural, (d.) thermal

Other knowledge perspectives are equally significant and must be addressed during design; focusing on engineering knowledge, structural and thermal perspectives of the BUG propulsion subsystem are considered. In the structural perspective of Figure 5c, elements from different perspectives are represented by the LST storage icon. Here, the functions depicted in other perspectives are of little interest to the structural designer; rather, the designer is keenly aware that those functions are performed by physical entities having mass and weight. Structural forces and energy are transmitted through the connections of the entities to a body frame; ultimately, they are transmitted out of the system to the track. In the thermal perspective of Figure 5d, thermal energy is generated and distributed within the system. The thermal designer focuses on these flows of thermal energy; with regards to other perspectives, the designer is interested only in the fact that heat is a product of energy conversion and transmission owing to frictional effects. If the thermal energy is not captured and put to useful work then it is emitted from the BUG.

*5.2.2 Perspectives of Time in the Design of a BUG*

Following the taxonomy presented in Section 3.3, another important principal perspective is that involving time. Temporal perspectives, essential in the creation of conceptual designs, include duration, chronology, process, and other time-related aspects. Here, it is appropriate to model with the LST icons time-based perspectives such as product realization and operational processes of the BUG system.

A particular temporal perspective of the BUG is the entire process through which the device is developed, designed, and realized. This is a small part of what is termed the product realization process. It is generally constituted by a complex series of sub-processes that occur over the passage of time. In Figure 6a, an abridged product realization process for the BUG device is modeled. The process begins with a problem recognition phase, where information about the problems and needs of the Vayuns are identified. The output is newly developed knowledge about those problems and needs, which becomes the input to the next phase – the feasibility study. Utilizing repositories of information and knowledge, preliminary design concepts that satisfy the problems and needs are synthesized. Information about the solution system is created, which is then input to the design phase. Here, designers utilize repositories of information and knowledge to make decisions that transform information about the product into knowledge of the product. This product knowledge is input to the manufacturing phase. An operational BUG device is the physical product that results from the manufacturing process supplemented with materials and energy.

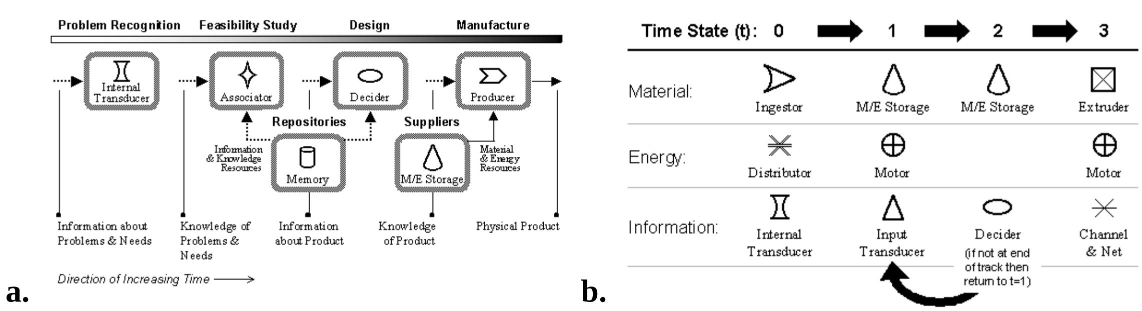


**Figure 6.** Temporal perspectives of BUG: (a.) product realization process, and (b.) operational sequences

Another significant temporal perspective involves the operational processes of the BUG. In Figure 6b, time-based sequences of BUG operations are modeled in terms of material, energy, and information processes. At t=0, the BUG system is initialized for operation: powdery material is loaded into the payload; the system is energized; and the internal status of the device is determined. Next, t=1 follows where the material in the payload is stored, energy is utilized to move the device up the track, and information regarding the device's position is sensed. At t=2, the payload material is still stored; however, the motion of the BUG ceases while the system processes position information determined from the previous time state. Here, an operational loop is modeled with the LST decider icon and the following rule: if the BUG is not at the end of the track then return to t=1. Should the device be at the top of the track then t=3 follows, where an information signal that activates the dispenser subsystem is transmitted. Consequently, energy is utilized to appropriately dispense the payload of powder onto the fire.

#### *5.2.3 Perspectives of Space in the Design of a BUG*

The final principal perspective from our taxonomy in Section 3.3 is that of a spatial nature. Spatial perspectives include dimension, scale, location, configuration, and arrangement. These aspects play an important part in conceptual design, particularly as the functions are instantiated by physical components and structured to give form to the product.

An example spatial perspective is illustrated in Figure 7a. The path of the device's movement from bottom to top of the track is modeled spatially with respect to a coordinate system. In this perspective, a LST motor represents the BUG, as the designer is only concerned with the fact that the device moves along the track; a LST supporter appropriately represents the track itself. Two separate two-dimensional views from different vantage planes are depicted in the figure, and fundamental parameters of the track are indicated. This type of spatial modeling scheme may be logically extended from two to three-dimensions, demonstrated later in Section 5.3.2.

Different spatial conceptions of the device's dispenser subsystem are also relevant perspectives requiring investigation. Three such different models are illustrated in Figure 7b. In each, the subsystem contains the same three elements: a LST motor that provides energy for movement, a LST storage that retains the payload of powder, and a LST extruder that allows powder to exit the system. Boundaries and flows are also represented, grouping and configuring the subsystem, respectively. Employing different spatial perspectives, designers create alternative conceptual subsystems by varying boundary arrangements and process flows. For example, Figure 7b-i includes a payload component retaining both storage and extruder capability, e.g., an open bucket. The process flow configuration corresponds to a dispenser subsystem where energy moves the entire payload component, e.g., by tipping, which in turn emits the powder. The same icons in Figure 7b-ii constitute an entirely different dispenser subsystem. Here, energy is applied directly to the extruder, which then releases powder from storage. In this alternative the extruder might be physically instantiated by a sliding or trap door. A third alternative is represented in the conceptual model of Figure 7b-iii, where energy is applied to the stored powder, perhaps through a process of pressurization. The energized powder then escapes the storage payload through the extruder.

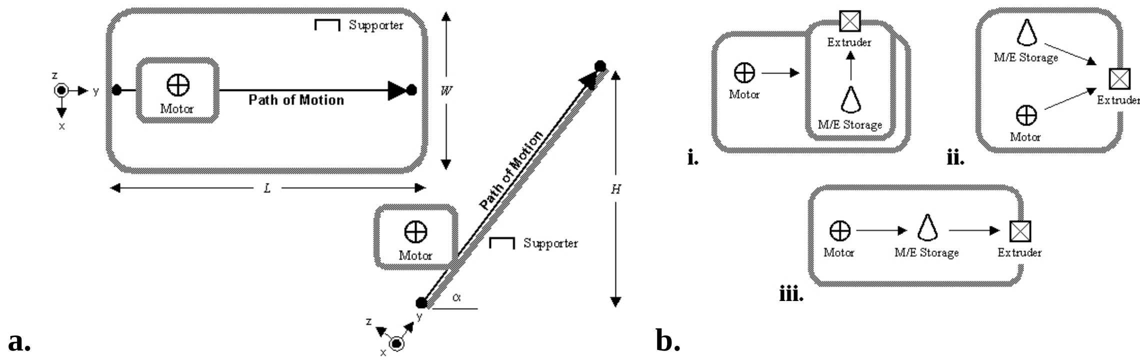


**Figure 7.** Spatial perspectives of BUG: (a.) path of motion, and (b.) dispenser subsystem variants

As demonstrated in this section, various perspectives of knowledge, time, and space that are important in the conceptual design of a BUG system are modeled adequately with LST. Perspectives are made explicit in this common language that can be understood by all, despite complexities or specializations. But the real benefit of our perspectival technique lies in aggregating individual perspectives after identifying interrelationships that emerge. An interconnected network of perspectives results as interfaces are created and subsequently captured in multi-perspectival models. This is the topic of the next section.

## 5.3 Aggregating Perspectival Models in Project BUG

The individual perspectives modeled throughout the previous section are but small pieces of the larger BUG system as a whole. Taken separately, they are highly disjointed and limited in both scope and applicability; they cannot be utilized individually to design the entire BUG device. Therefore, we desire to synthesize many perspectival models, thereby creating representations of the system that are more comprehensive. But given the different and diverse perspectival models from the previous section, *how can system models be represented through aggregation?* In the following section, we develop a suitable scheme to represent function sharing, after which we present examples of aggregated perspectival models in Section 5.3.2.

### *5.3.1 Representing Function Sharing*

In complex engineering systems, physical entities typically perform more than one function. For example, the housing of a modern coffee grinder serves multiple purposes including protective enclosure, structural support, ergonomic handling, and aesthetics among others. Therefore, perspectival models of the type presented in Section 5.2 often feature different functions that are executed by a singular entity. This is termed function sharing, and is formally defined in mechanical design as "the simultaneous implementation of several functions by a single structural element" (Ulrich and Seering, 1988). Since function sharing is frequently encountered in engineering systems, a method is required to represent such instances. Ultimately, this allows for the synthesis of system models from multiple perspectives in which functions are shared.

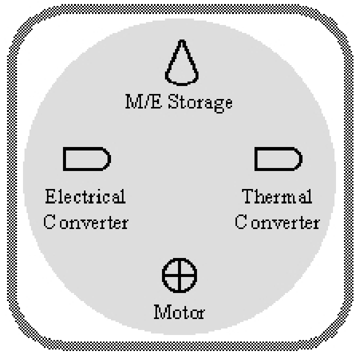


**Figure 8.** Representing function sharing in the BUG propulsion subsystem

To further illustrate the concept of function sharing, we revisit the perspectival knowledge models of the BUG propulsion subsystem discussed in Section 5.2.1. In Figure 5a, the electrical engineering perspective contains a LST converter that transforms electrical energy into a more useful form. In Figure 5b, the mechanical engineering perspective contains a LST motor that provides the mechanical energy necessary for propulsion. Designers recognize that a single entity might simultaneously perform both functions – e.g., an electrical motor converts an input of electrical energy and provides an output of mechanical energy. In the structural perspective of Figure 5c, LST storage represents the matter and weight of such an entity. Additionally, a LST converter represents heat generated by that entity due to frictional effects (e.g., electrical and mechanical) as captured in the thermal perspective of Figure 5d. We illustrate our convention for representing such function sharing in Figure 8. The LST icons shared by the singular propulsion subsystem entity are extracted from their separate perspectival models and united on a bounded circular matte. In this manner, we denote that a singular entity shares all of these LST functions despite their occurrence among four different and separate perspectives.

*5.3.2 Aggregating Multiple Perspectives to Create System Models*

Two or more individual perspectival models of the type developed in Section 5.2 may be aggregated into larger, more complete system models. Clearly, there are numerous possible combinations of the various perspectival models. In theory, any set of perspectives may be aggregated with the resulting model offering unique insights into the product and process. In this section, we illustrate two particular aggregations of perspectives employed in the conceptual design of a BUG: a synthesis of two different knowledge perspectives, and the combination of a knowledge and spatial perspective.

The fundamental procedure for aggregating perspectival models includes: identifying multiple perspectives to be aggregated, establishing instances of function sharing, deciding issues that arise from aggregation (e.g., process flows, arrangement, etc.), and representing aggregated perspectives in a system model. Designers must work collaboratively to synthesize their individual perspectives as compatibility, consistency, and connectivity issues are negotiated. This indicates that the process of aggregation has a significant social component. In this paper we do not address the topic of collaborative strategies; rather, we assert that a design team acting under the principles of a learning organization will have great success with aggregation (cf. Senge, 1990).

Electrical and mechanical engineering knowledge perspectives are employed to create perspectival models of the BUG's propulsion subsystem in Figure 5. Identifying these two models as prime candidates for aggregation, we wish to synthesize a system picture. We limit ourselves to these perspectives in this example; therefore, issues associated with temporal, spatial, and other knowledge perspectives are neglected here. It is determined that the functions represented by the LST converter in the electrical perspective and the LST motor in the mechanical perspective are shared. In Figure 9, we represent a system model featuring the aggregated perspectives. Both perspectives are represented simultaneously, producing a more complete model of the propulsion subsystem. Designers clearly see that an interface exists between the two engineering perspectives as assembled in the model; particular mechanical and electrical properties of the functions now emerge. Such discoveries and newfound cognizance are extremely significant in the conceptual design of complex engineering systems.

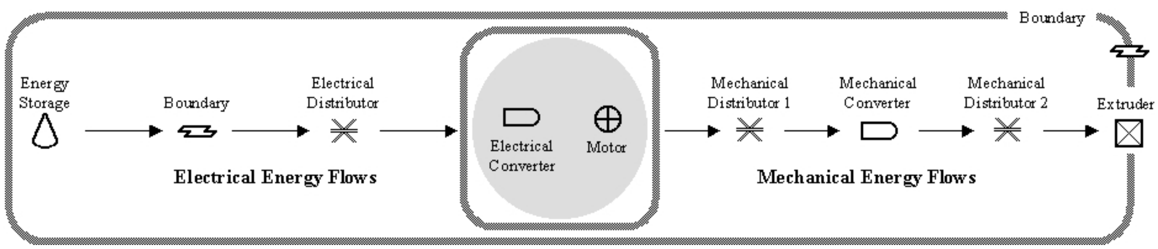


**Figure 9.** Aggregated BUG propulsion model featuring two knowledge perspectives

Combining perspectival models of knowledge and space generates another example of aggregation. In particular, great value arises from combining the mechanical engineering perspective of Figure 5b with a spatial perspective emphasizing three-dimensional form and arrangement. Instead of creating two-dimensional function diagrams of the sort exemplified in Figure 5, we utilize three-dimensional shapes that give form to the functions; this technique is illustrated in Figure 10a. As early as conceptual design, we may not know the specifics of the structure that is later chosen to implement the intended function; however, we can often represent generally candidate entities' structures with coarse accuracy. This is accomplished by selecting a solid primitive (e.g., parallelepiped, cylinder, or sphere) with rough dimensions (e.g., length, width, and height) that denote the structural entity's volume. The preliminary form associated with the function is merely a placeholder for the actual physical structure later chosen to instantiate that function.

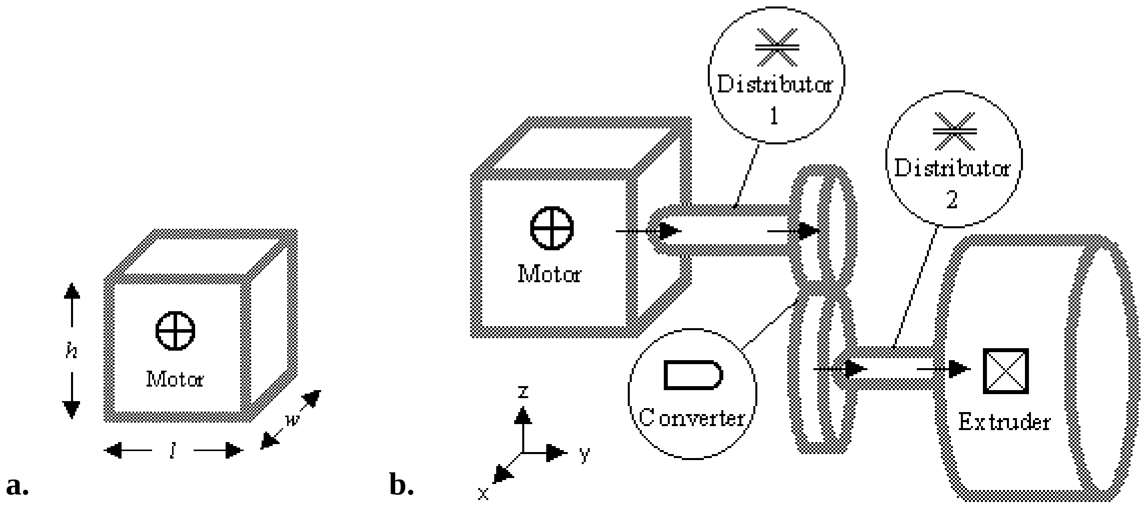


**Figure 10.** Aggregated knowledge and spatial perspectives: (a.) 3-dimensional functional icon,
and (b.) 3-dimensional functional model of BUG propulsion subsystem

Upon assigning forms to functions, a three-dimensional function model is constructed by spatially arranging the forms according to known or assumed specifications. These models may be sketched by hand, created using drawing software on a computer, or even developed with commercial CAD packages. A sample model of the BUG's propulsion subsystem from a mechanical engineering perspective is depicted in Figure 10b. Here, a cube conceptually houses the LST motor; similarly, the LST distributors, converter, and extruder are bound by cylinders of varying dimensions. All volumes are spatially located with respect to a coordinate system. Even though specific physical structures instantiating these functions have not yet been chosen, it is clear that the LST motor, distributors, converter, and extruder may be embodied later with components like an electric motor, rotary shafts, a gear train, and a wheel, respectively. The system model of Figure 10b constitutes a picture that is more complete than the knowledge or spatial perspective alone. A particular strength of this model is that emergent geometrical properties are captured early in conceptual design; significant features like shape, orientation, configuration, and layout are represented.

Aggregated models such as those presented here constitute a more complete picture of a complex BUG system. They assist designers in assuring the compatibility, consistency, and connectivity of individual subsystem solutions, and are critical in synthesizing the entire system. Once the abstract functional models are established, design proceeds at increasingly concrete levels of behavior and structure. But let us not underestimate the significance of the abstract level of function; it is well known that the early decisions made by designers regarding such things as functions determine significant aspects of final products and processes. Therefore, it is our perspective that function is the foundation of complex system design.

## 6. Closing Remarks

Our approach to engineering design as described in this paper incorporates a formal conception of perspective. Perspectives, the contexts surrounding perception, thinking, representation, and decision-making, shape human cognition and significantly affect design. They are responsible for the one-sidedness and narrow-mindedness which plague designers, causing difficulties and setbacks of various degrees in their design efforts. We seek a systematic methodology that allows designers to negotiate efficiently and effectively the multitude of relevant perspectives that influence the design of complex systems. This requires a foundation built on systems-thinking and holism. Towards that end, the notion of perspective explored in Section 3 creates an understanding with which we anchor the term to engineering design. Living Systems Theory, introduced in Section 4, provides the language and symbology for explicitly modeling perspectives at a functional level of abstraction.

With this method we can clearly model a variety of important functional perspectives encountered in the conceptual design of engineering systems, illustrated in Section 5. Employing the simple lexicon of LST, designers represent perspectives that are not only scientific and engineering-related, but also non-technical and humanities-based; as added benefit, the models lack jargon and technical detail thereby facilitating communication. Such perspectival models are extremely useful for designers creating conceptual systems; they provide design teams with a unique collaborative opportunity to aggregate different perspectives. By making perspectives explicit, otherwise hidden or unspoken assumptions, aspirations, knowledge, understanding, and values are surfaced.

In our approach, perspectives are featured such that they are recognized easily, focused upon deliberately, shared effortlessly, and understood completely. The significant value in this scheme is that of forcing conscious change in perspective. Approaching problems from different perspectives leads to new insights, ideas, innovations, and interpretations, which are essential for the successful design of complex engineering systems.

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