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Attribute Substitution in Systems Engineering

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ABSTRACT

Cognitive biases affect decision making in systems engineering (SE). Daniel Kahneman, 2002 Nobel laureate for his pioneering studies of cognitive biases in economic decision making, describes many disparate cognitive biases as abstractly belonging to one higher-level bias, that of attribute substitution. Attribute substitution occurs when an answer about a target attribute is unconscientiously provided by referring to a sublevel heuristic attribute that is simpler or more easily accessible, while other subattributes are ignored. The essence of this biasing process is generalized with real examples at all phases of the systems engineering process. Willful awareness of attribute substitution, however, can help prevent erroneous reduction in focus, and ensure that valid systems are being built to satisfy customer needs.
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Key words: attribute substitution; systems engineering; cognitive biases; abstraction; generalization; tradeoff studies; mental mistakes

1. INTRODUCTION

Everyone uses attribute substitution. For example, if you own an old car and you want to know the amount of wear on the engine, then you could measure the thickness of the piston rings. But this is difficult. Therefore, most people substitute a simpler attribute, such as gas mileage. Attribute substitution can cause mental mistakes, but is nonetheless often used for efficiency. This paper postulates that substituting attributes is good, if the decision maker is consciously aware of doing it, and bad if the decision maker is unaware of doing it.

First, we define attributes as complex, subjective, qualitative value characteristics inherent in situations or objects, with the distinction that "characteristics" is a more concrete word than "attributes." Attributes in mathematical treatment are often described as fuzzy, uncertain, or as opinion- and desire-driven characteristics [Ullah, 2005]. Attributes are necessarily tailored to specific situations, so Generic Attributes (GA) have gained acceptance for general process performance appraisal [EIA/IS-731, 2002]. (The present paper does not follow the software engineering definition of "attributes" as variables within classes.) Historically, attributes were discussed by Aristotle as "causes" that implied properties and purposes [Rasmussen, Pejtersen, and Goodstein, 1994: 54].

This paper, for the purpose of illustrating the general usability of the attribute substitution model, begins by reviewing attribute substitution as introduced by Kahneman and Frederick [Kahneman and Frederick, 2002; Kahneman, 2003], who mostly use the word "attribute" to refer to characteristics of an object. This paper then goes on to give examples that generalize the meaning of the word "attribute," and apply the meaning of attribute in an *ad hoc* manner, to refer to needs, requirements, functions, subsystems, components, and management approaches, among other systems engineering and decision making elements. This paper does not attempt to review utility theory as developed by Keeney and Raiffa [1976], but only to present a present a simple, memorable model that is widely applicable and easily remembered in dynamic decision making situations.

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The general phenomenon being illustrated by the attribute substitution model is severe attention restriction that goes significantly beyond innate human short-term memory limitations. Miller [1956] showed the humans have a short-term memory capacity of 7 ± 2 bits or units of information.

Attribute substitution is a common human decision making mechanism. Kahneman [Kahneman and Frederick, 2002; Kahneman, 2003] discusses attribute substitution as a mistake that occurs when attribute and subattribute choices are made unconsciously. Systems engineers, however, can consider attribute substitution as a highly useful model of the natural mechanism of mental focus. As such, attribute substitution errors should be studied as a necessity, and attribute substitution as an abstract model of decision making should be applied consciously and willfully as an appropriate strategy to manage the mental decision making process and to reduce errors.

Attribute substitution as a mistake occurs when an attribute, criterion, or parameter of interest is too complex to be measured, and humans substitute a simpler element. For example, many people regularly monitor their blood pressure. Although they were not originally interested specifically in their blood pressure, they were led to monitor blood pressure as an indicator of cardiovascular health. The substitution of a simpler attribute is common when knowledge of the truly desired attribute is too complicated to be obtained. In this paper, we show how systems engineers can deliberately and beneficially use attribute substitution within a range of examples where attribute substitution, without awareness that this mental mechanism is being used, could cause mental mistakes.

The fundamentals of decision making are taught to today's systems engineering students. However, the use of good decision making practices can never be guaranteed in practice. Engineers, when not required to provide documented analyses, sometimes prefer to make undocumented, and often fallible, mental judgments. For example, Bahill [1999] found that systems engineers in industry generally do not perform or document tradeoff studies. Other analytic models of decision making in dynamic environments are often complicated, context-specific, and not easily remembered or applied. "Creating a model flexible enough to represent the diverse population of human decision-makers is difficult; decision makers have different styles, training and temperament [Sworder and Clapp, 1998: 229]. This paper seeks to illustrate a model that is both memorable and broadly applicable.

Substantial documentation about experts making judgments unsupported by rational analysis exists in the field of medical decision making. Redelmeier and Shafir [1995] (while noting that much medical decision making is seemingly simple and supported by a confirmatory environment of medical colleagues) noted that, in decisions with multiple alternatives:

> [Physicians] do not always resolve medical decisions by analyzing benefits and harms in a reliable manner. Instead, people may resort to intuitive judgments that render them prone to cognitive biases. Psychological theory predicts that these cognitive biases will appear when people have difficulty deciding between conflicting alternatives, face situations of substantial uncertainty, or consider outcomes that have long-term consequences. …

Thinking harder will not eliminate a cognitive bias any more than staring intently will make a visual illusion disappear. Instead, physicians need to recognize specific biases and consider possible corrective procedures [Redelmeier and Shafir, 1995: 302].

Redelmeier and Shafir go on to describe how a technique such as considering each alternative in relation to the status quo is more effective than considering all alternatives at once and only in relation to themselves. More biases that result from the consideration of alternatives exist, and are presented below. We encourage pairwise comparisons, as in the Analytic Hierarchy Process (AHP) [Saaty, 1980] (although intransitivity can sometimes result). Also, alternatives should always be compared to the status quo.

Specific de-biasing techniques have been shown to be effective under specific circumstances. Principally, such techniques involve increasing the decision maker's awareness of possible cognitive biases, and then mandating a procedure that has been shown to reduce the particular bias [Smith et al., 2007]. However, in practice, few professionals remember the presence of biases, and almost none implement proven de-biasing processes. What is needed is a single abstract model of biasing, and the ability to apply the model generally.

Attribute substitution, as described by Kahneman, is an abstract model that is broadly applicable, and so easily remembered. At its essence is the collapse of attention from a broader question to one that is narrower, but more easily answered. Kahneman pointed to attribute substitution [Kahneman and Frederick, 2002] as the abstract biasing model that explained many of the specific cognitive biases described in his papers [Kahneman and Riepe, 1998; Tversky and Kahneman, 1981] and books [Tversky and Kahneman, 1982]. The present authors claim that the concept of attribute substitution is even more broadly applicable, and should be the principal abstract bias that systems engineers have in their mental toolboxes.

The authors note that many theories, theorems, models, and concepts that first arose in disparate fields of study, such as von Neumann's game and decision theory and Arrow's Impossibility Theorem for voting systems, have become interdisciplinary tools incorporated into systems engineering. It is proposed that attribute substitution is an essential mental tool for systems engineering, especially since attention widening is crucial in systems engineering.

1.1. Heuristics and Biases School of Behavioral Economics, and Prospect Theory

The seminal paper on human cognitive biases and the use of heuristics when making decisions under uncertainty, *Judgment Under Uncertainty: Heuristics and Biases*, was written by Tversky and Kahneman [1974]. Their work led to Prospect Theory [Kahneman and Tversky, 1979; Tversky and Kahneman, 1992]. Prospect Theory breaks human subjective decision making into a preliminary screening stage and a secondary evaluation stage. In the screening stage, values are considered not in an absolute sense (from zero), but subjectively from a reference point established by the subject's perspective before the decision. In terms of wealth, for example, losses and gains are considered by the subject's predecision wealth, and losses are weighted more heavily than gains. Probability also undergoes a subjective translation in the preliminary screening stage. In the evaluation stage, a final score for each alternative prospect (choice, for example, a gamble) is assumed to be calculated mathematically, where each "prospect" is one choice in a gamble situation involving multiple alternatives. Kahneman won the Nobel Prize in Economics in 2002 "for having integrated insights from psychological research into economic science, especially concerning human judgment and decision-making under uncertainty" [RSAS, 2002].

1.2. Attributes in Systems Engineering

As pertains to systems engineering, it is highly important to determine the attributes necessary to satisfy customer needs. Because attributes are highly related and important to satisfying customer needs, the authors propose that attributes fit into the systems engineering process, shown in Figure 1. Note that attributes are less well defined than requirements, hence their placement before Requirements, as follows:

Customer Need — **Attributes** — Requirements — Functions — Design Synthesis — Product

Attributes are complex intangible characteristics that are difficult to capture, but yet are crucial in directing systems engineering activities. Attributes become tangible when they are embodied in requirements, which form the basis for contractual agreements. Requirements, if not yet specific, in turn become measurable through high or low-level Measures of Performance, Measures of Effectiveness, Measures of Suitability, evaluation criteria or more specific, lower-level specifications. Ideally, there will be one measure per attribute, but the complexity of nontangible attributes, and the challenging subjectivity of their decomposition, does not always lead to a one-to-one correspondence between attributes and measures. Ultimately, the validity of a product is judged by the customer who refers back to his or her own attribute preferences.

Customer needs are described in the problem statement, which also states the goals or capabilities of the project, delineates the scope of the problem, reports the concept of operations, describes the stakeholders, lists the deliverables, presents key decisions and (in the final version) highlights the preferred alternatives. Attributes are rarely described in the problem statement, but may ultimately be the basis of acceptance or rejection by the customer.

The system's goals, objectives, or capabilities are contained in the Mission Statement, the Concept of Operations or the Business Model. These high-level documents describe the environment the system will operate in and the architecture of the system. In a Zachman Framework these documents would be in rows 1, 2, and 3. In a DoDAF they would be in the AV-1 and OV-1 views. In these high-level documents and descriptions, high-level goals and capabilities should not be called requirements, since they lack the formality of requirements. "Requirements" in the Mission Statement, Concept of Operations, and the Business Model are properly called goals or capabilities because they refer to high-level characteristics and abilities that form the general basis for the customer requirements.

The term "requirement" is reserved for formal requirements typically written in a System Requirements Document or Requirement Specification. System and lower-level requirements occur in the Zachman Framework's rows 4, 5, and 6. Formal requirements derived from UML diagrams are contained in the: (1) Specific Requirements Sections of the Use Cases, (2) Supplementary Requirements Specification [Daniels and Bahill, 2004].

Note that the term "Capabilities" is often used in systems engineering. Capabilities can be placed before Requirements and Functions in the order above, with the reasoning that

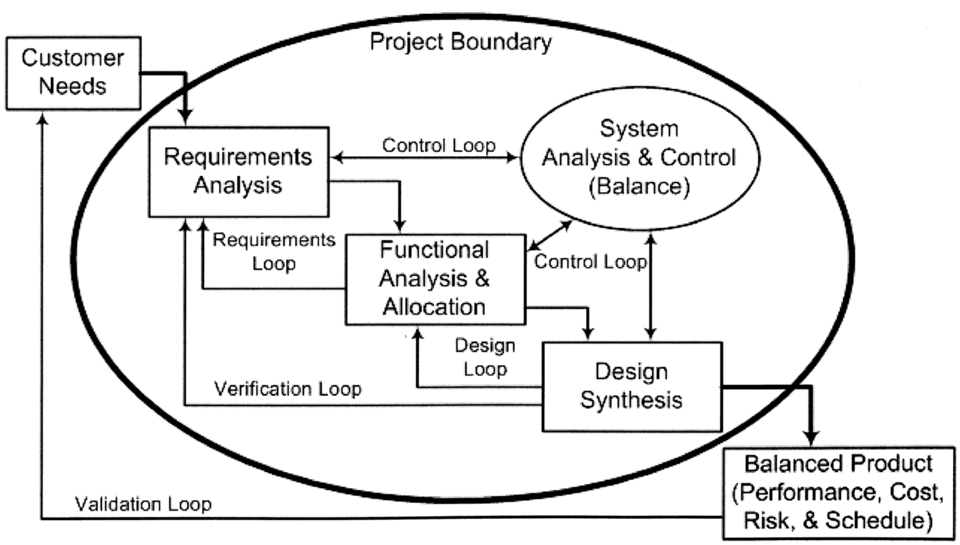

Figure 1. Systems engineering process.

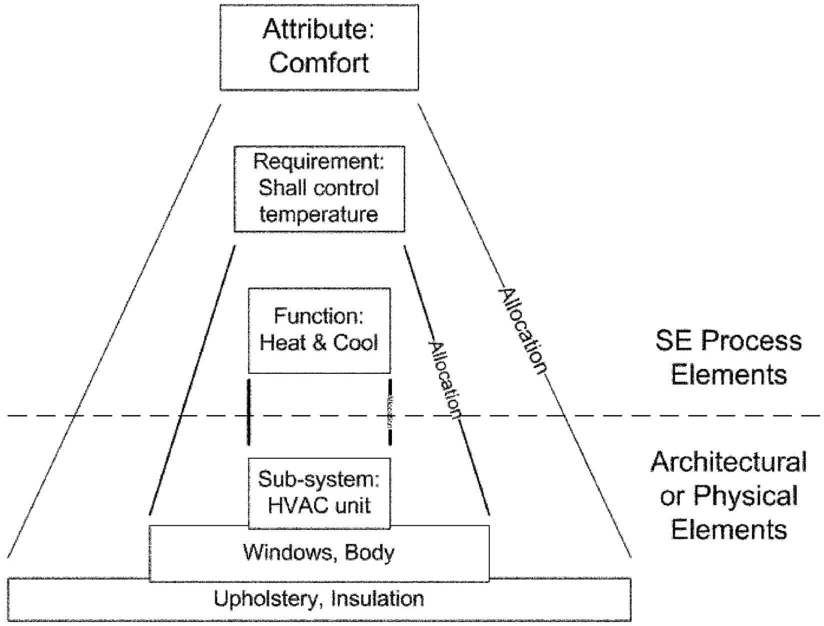

Figure 2. Allocation of SE Process Elements to Physical Elements.

Capabilities have aspects of Requirements and Functions. Note that Capabilities can be defined as: The system *shall* be capable of performing some *function*. The term Capabilities also includes some sense of an attribute, as is true of all phases of the systems engineering process.

1.3. Attribute Allocation

Attribute allocation is fuzzier than requirement allocation, which is fuzzier than functional allocation. In the example of a passenger automobile, shown in Figure 2, the function of Heat & Cool is allocated almost exclusively to the Heating Ventilation & Air Conditioning (HVAC) subsystem, and the engine heat radiator. The corresponding requirement that 'temperature shall be controllable within the automobile" is fulfilled by these subsystems and more, specifically, the windows and the impermeability of the automobile body shell. The corresponding attribute of "Comfort" is provided also by the insulation and upholstery, which must have good ergonomic characteristics; in addition, the "look and feel" of the automobile must be properly balanced to provide subjective feelings of comfort. Note that the systems engineer must always make reasonable assumption in the allocation process, since these are almost never provided by a customer needs statement.

2. ATTRIBUTE SUBSTITUTION

Several heuristics and biases, notably representativeness, anchoring, base-rate neglect and the conjunction fallacy, summarized by Smith [2006], are now considered by Kahneman to be instances of a super-heuristic called attribute substitution [Kahneman, 2003]. Human judgment is mediated by this heuristic of attribute substitution when, without realizing that it is so,

> an individual assesses a specified target attribute of a judgment object by substituting another property of that object—the heuristic attribute—which comes more readily to mind. Many judgments are made by this process of *attribute substitution.* For an example, consider the well-known study by Strack, Martin, and Schwarz [1988], in which college students answered a survey that included these two questions: How happy are you with your life in general? How many dates did you have last month? The correlation between the two questions was negligible when they occurred in the order shown, but it rose to 0.66 when the dating question was asked first [Kahneman and Frederick, 2002: 53].

In this example, the target attribute, Happiness, is assessed by mapping the value of another attribute, Number of dates last month, onto the target attribute scale. Figure 3 illustrates the top-level, ill-defined attribute of Happiness, and the well-defined sublevel attribute of "number of dates last month."

This process of attribute substitution "will control judgment when these three conditions are satisfied:

(1) the target attribute is relatively inaccessible [Happiness];
(2) a semantically and associatively related candidate attribute is highly accessible [Number of dates last month]; and
(3) the substitution of the heuristic attribute in the judgment and the immediacy of the response is not rejected by the critical operations of System 2" [Kahneman and Frederick, 2002: 54].

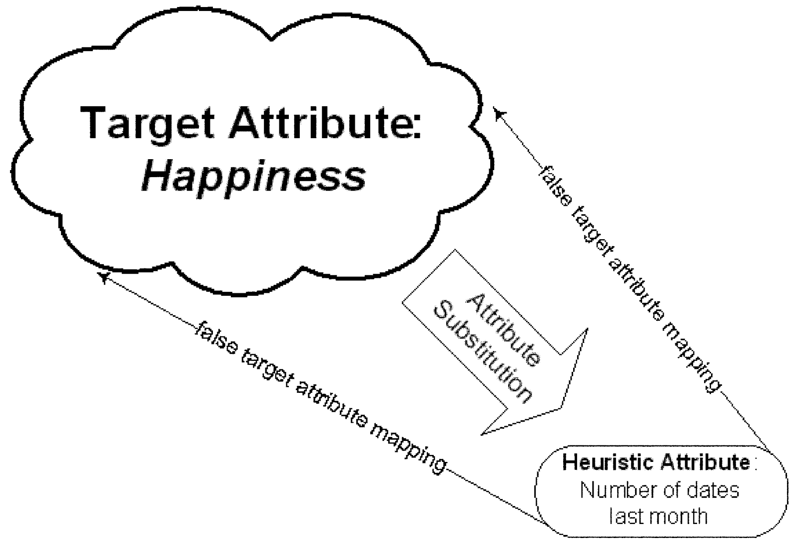

Figure 3. Happiness attribute substituted by "number of dates last month."

System 2 is defined by Kahneman as being composed of those mental operations that are "slower, serial, effortful, more likely to be consciously monitored and deliberately controlled" [Kahneman, 2003: 698]. In general, System 2 consists of explicit cognitive processes, as opposed to mental operations that are automatic, effortless, associative, and implicit, which are performed by what Kahneman calls System 1. The division between System 1 and System 2 is typical across mental operations research. The extension of the mental process of attribute substitution to many other heuristics and decisions is quite straightforward [Kahneman and Frederick, 2002].

Figure 4 illustrates attribute substitution with a hierarchical tree of attributes. When erroneous attribute substitution holds sway, and a person is asked a question about a top-level attribute, they are likely to substitute the top-level attribute with a lower-level attribute that is less inclusive and more definitely and specifically defined. Concomitant with the move to a lower-level attribute is the construction of a more easily answered question about the lower-level attribute.

Just as "the map is not the territory" [Korzybski, 1948], a heuristic attribute is not the target attribute. Recognizing the "super-heuristic" of attribute substitution quickly leads one to question what other mental constructs must be differentiated from the reality they represent. Systems engineering models, for example, are only abstract representations of real systems. It is interesting to note that the process of attribute substitution involves two steps that reduce complexity:

1. Representation of the real system by the formation of an abstract model with a more definite and possibly reduced set of attributes
2. Attribute substitution, or choosing one of the subattributes to represent the abstract model under examination.

Step 1 involves the structuring of the decision space, and is reminiscent of Newton's replacement of a naturalistically

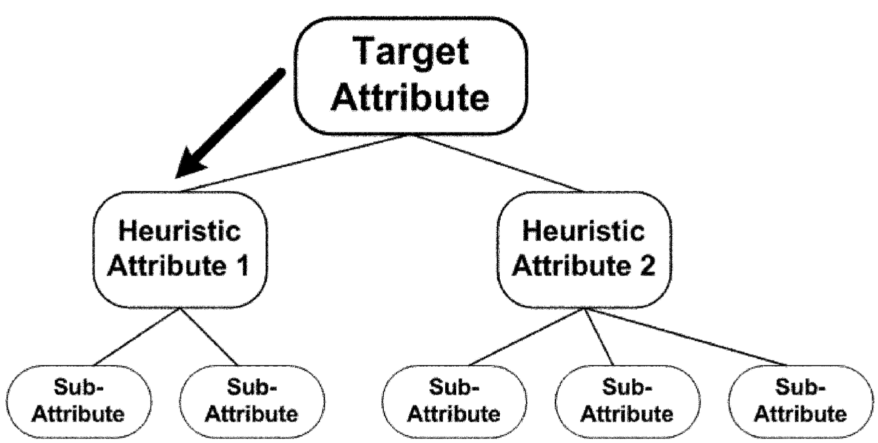

Figure 4. Attribute substitution illustrated with hierarchical decomposition.

ambiguous world of causes and effects with a world of distinct variables and mathematical relations among them.

Step 1 and Step 2 are described in *Competitive Engineering* by Gilb [2005: 153], who speaks of measurable scalar attributes, and the possibility of omitting important subattributes:

> You can decompose many scalar attributes into arbitrarily large or small sets of specific elementary attributes. The selection of exactly which elementary attributes to define is a practical matter of knowing your domain well enough to decide which of them will give you best control over your critical success factors. At best we make reasonable guesses with some effort to begin with. Then we learn some hard lessons, usually about what we forgot to exercise control over.

Step 2 involves either an erroneous or unconscious lower-level attribute substitution, or a beneficial reduction of problem scope for increased efficiency in decision making. Keeney, in *Value-Focused Thinking* [1992], has pertinently stressed the importance of a continual realignment toward understanding an analogous dichotomy, stressing the conscious pursuit of fundamental objectives, instead of immediately focusing on and capturing seemingly-practical means objectives.

In systems engineering, the possibility of biasing on a heuristic "attribute" is present in many practices, and in the use of many systems engineering tools, as will be shown below. For example, model building may involve the limitation of the perception of reality, and the introduction of biases during model construction. The use of a testing prototype may also introduce a biased focus. In a more abstract sense, the possibility of introducing attribute substitution as a "bias of limitation" also exists when heuristics are employed in solving a problem. The choice and use of metrics and indexes may also involve attribute substitution, shown in another example that will be developed below.

Attribute substitution is not a mistake if it is deliberate and disclosed. In fact, the construction and use of heuristic attributes, or measures, is a most useful tool in engineering. Lord Kelvin drew a distinction between unmeasurable attributes and measurable variables when he said:

> I often say that when you can measure what you are speaking about and can express it in numbers, you know something about it; but when you cannot express it in numbers, your knowledge is of a meager and unsatisfactory kind. It may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the state of Science, whatever the matter may be [Kelvin, 1891–1894, 3 May 1883: 73].

3. EXAMPLES OF ATTRIBUTE SUBSTITUTION IN SYSTEMS ENGINEERING TOOLS

Following are a diverse set of examples of attribute substitution organized according to the following system design stages:

3.1. Diagnosis of Problem
3.2. Needs of Customer
3.3. Attribute Decomposition and Analysis
3.4. Requirements Definition and Analysis
3.5. Functional Decomposition, Analysis and Allocation
3.6. Analysis of Designs
3.7. Tradeoff Studies of Alternatives
3.8. Architectural Design
3.9. Management

3.1. Diagnosis of Problem

"Experts spend more time trying to understand the problem. This process involves building a mental representation of the problem from which relations that define the situation can be inferred. … An understanding of the problem often leads to a more efficient path to the solution without following fruitless courses of action" [Hutton and Klein, 1999: 34].

3.1.1. Battery Failure Example

A battery failure scenario posed as a problem illustrates attribute substitution. Ask the question of an audience: "What do you do if you find that turning the ignition key in your car does not turn the motor over?" In my S2000 it means that you must press the red start button. Systems Engineering indicates that, after the failed functionality is noted, the problem should be diagnosed by first examining all possibly operational mistakes. First determine that if, in that particular car, there is a start button, the transmission must be in neutral or park, the clutch must be disengaged or that the brake must be depressed. Then inspect possible failed physical systems: the ignition key mechanism, wiring, starter, solenoid, and battery. Testing should proceed logically with respect to the cost of inspecting each component; for example, the battery charge and continuity of the wiring could first be tested with an electrical multimeter. This is not how everyday trouble-shooting proceeds, however. Figure 5 illustrates the battery example.

The first assumption most nonengineers make is that the battery has failed, and after using jumper cables and finding that the car does not start, most will proceed to buy a new battery. Sometimes, in less affluent countries, the battery posts are cleaned first. Cognizance of other possibly failed components is surprisingly limited, and car owners often express unreasonable frustration when a replacement battery fails to fix the car-starting problem.

> Target attribute: Capability of starting the car
> Heuristic attribute: Battery charge.

Admittedly, "the decision may even be a means to an end rather than the end itself. For example, a course of action may be chosen to gather more information or put oneself in a better position to take subsequent actions" [Hutton and Klein, 1999: 37].

3.1.2. Anchoring

When estimating numerical values a person's first impression dominates all further thought. In an example from Piattelli-Palmarini's *Inevitable Illusions: How Mistakes of Reason Rule Our Minds* [1994], people were shown a wheel of fortune with numbers from 1 to 100. The wheel was spun, and then

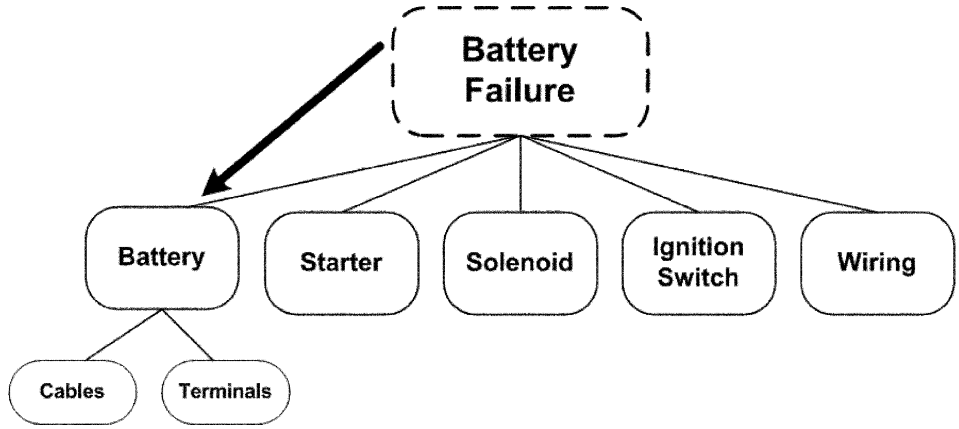

Figure 5. Battery failure example of attribute substitution.

the subjects were asked to estimate the number of African nations in the United Nations. The wheel of fortune thus provided a random anchor for estimated answers to the question. Surprisingly, if the wheel showed a small number, such as 12, the subjects inevitably underestimated the correct answer. If the number on the wheel were large, such 92, the subjects overestimated the correct answer. The answer has changed recently, but historically it has been approximately 50. Clearly, parameter estimation is best approached from an un-anchored, absolute perspective.

Target attribute: The number of African nations in the United Nations
Heuristic attribute: Distance from a random anchor.

3.1.3. Sentence Parsing

Complex sentences in English or other languages can sometimes only be fully understood after the sentence has been read and understood in its entirety. Therefore, the mental formation of linkages of meaning between the words should be suspended until the whole sentence is read. In effect, an attempt to ascertain complex meanings should be postponed and ideally made before simple meanings of the sentence are precipitously considered—lest the fitting of complex linkage sets be precluded by the application of simpler linkage sets. In practice, it is common experience that humans try to quickly draw a simple meanings from sentences.

Target attribute: Complete sentence meaning
Heuristic attribute: Partial sentence meaning.

3.1.4. Domains of Knowledge

Mark Twain said: "To a man with a hammer, everything looks like a nail." In the diagnosis of problems, the wide availability of knowledge domains is crucial.

Target attribute: Complete knowledge domain pertinent to problem
Heuristic attribute: Limited knowledge domain available to particular diagnostician.

3.2. Needs of Customer

3.2.1. Not Designing to Customer Needs

A significant driver for the traditional development of systems engineering as a corrective practice is the tendency for specialty engineers to hastily decide on a prototype for a system that has not been fully designed and expressed in terms of a coherent abstract architecture. It is too often supposed that a prototype will fix the architecture.

Identifying true customer needs can be difficult because stakeholders often refer to both problem and solution domains—whichever comes most naturally [Mannion and Hermann, 2006]. Maier and Rechtin [2002] discuss the difficulties of ill-structured problems given by customers who often only intuitively and qualitatively understand their problem, and do not understand more formalized descriptions of their problem. In essence, customers do intuitively sense attributes important to them, although they may not even be willing to work with an attribute tree, for example.

However difficult, the customer needs and problem statement must be written before looking for solutions [Wymore, 1993]. Not stating the problem in terms of customer needs, but rather committing to a class of solutions, causes a lack of flexibility. Unfortunately, since knowing customer needs can be difficult, decision makers sometimes substitute their own representative ideas of customer needs.

Target attribute: Customer needs
Heuristic attribute: Needs that are easily met by an available system design.

3.3. Attribute Decomposition and Analysis

3.3.1. Sustainability Example

Decomposition is a principle tool of systems engineering [Grady, 2007: 26], and is used to decompose attributes into sub-attributes; where "attributes," in this Sustainability example shown in Figure 6, refers to capabilities. Sustainability refers to the potential for a system to be supported materially and technologically over an extended period of time. Sustainability can be decomposed into the subattributes: Durability,

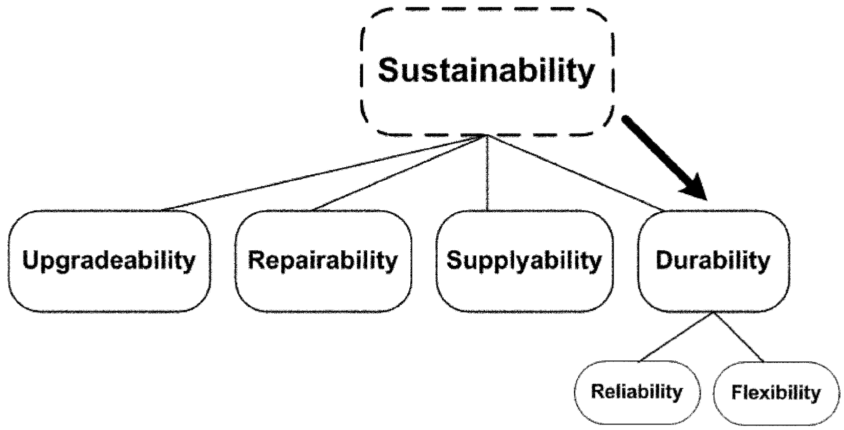

Figure 6. Sustainability decomposed into subattributes.

Repairability, and Upgradeability. Durability refers to the characteristic of toughness over a significant range of conditions. Durability is not enough sufficient, however, to ensure Sustainability. Repairability ensures that a durable system, on the occurrence of a breakdown, can be restored to working order. Supply-ability provides that the system can indeed be fed the necessities for continual operation. Upgradeability, furthermore, provides that the system will not soon become obsolete, but can be improved over time with technological evolution. It can be seen that Sustainability is a rich attribute, implying many necessary subattributes. Sustainability is also a complex attribute, since it may be difficult to define a set of subattributes that do not overlap or partially imply similar characteristics. For example, a system cannot be upgradeable if it is not repairable.

What is clear is that it would be a mistake to commit the error of attribute substitution, by improperly substituting one of the subattributes when being questioned about the higher-level attribute, Sustainability. For example, a question asked about Sustainability may be difficult to answer, since an answer may have to consider all the subattributes simultaneously. It would be tempting to quickly answer a question about Sustainability with readily available information relevant to Supply-ability, perhaps in a situation where a supply of parts was ensured for a long time into the future. Similarly, ready information about Durability may improperly be used to answer a question about Sustainability.

Note that the subattribute Durability is itself a significantly complex attribute, since it pertains to a broad range of operating conditions. Durability can be assessed by knowing the Reliability of the system over many well-defined operating conditions. The ability of the system to operate without failure when being transferred from one operating condition to the next is also important in the determination of Durability, and may be termed Flexibility. Thus, Durability may be decomposed into many defined Reliabilities and Flexibility.

Target attribute: Sustainability
Heuristic attribute: Durability.

3.3.2. Coherence Example

In software, an important top-level attribute may be deemed to be Coherence, which may be composed of Alignment, Assurance, and Agility. That is, the software components have to Align with customer needs and with themselves, the software components need to Assure good service, and the software components need to be flexible or Agile in response to changing customer needs. It would be a mistake, as shown in Figure 7, to think that software Assurance alone will keep a software company in business.

Target attribute: Coherence
Heuristic attribute: Assurance.

3.3.3. Project 10^{100} Example

Google's Project 10^{100} is meant to gather good ideas for the world's benefit. Submitted project ideas may address critical issues such as providing food and shelter, building communities, improving health, granting more access to education, sustaining the global ecosystem and promoting clean energy. Ideas will be judged based on their reach, depth, attainability, efficiency, and longevity [Google, 2008].

Target attribute: Good for world
Heuristic attributes: Reach, Depth, Attainability, Efficiency, or Longevity.

3.3.4. Aristotle's Division of Value into Attributes

"Value" is the word used modernly to signify the unification of all beneficial high-level attributes at the mission, business

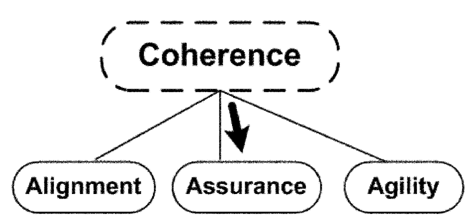

Figure 7. Coherence and subattributes.

and operational levels. Aristotle in about 350 B.C. conceived of Value as composed of these attributes [Sullivan, Wicks and Luxhoj, 2006: 582]:

1. Economic
2. Moral
3. Aesthetic
4. Social
5. Political
6. Religious
7. Judicial.

This division of value seems just as good today as it was almost 2500 years ago. A systems engineering effort on a large public project would do well to consult these subattributes of Value.

Target attribute: Value
Heuristic attribute: Any one of Aristotle's subattributes of Value.

3.3.5. Criteria Definition for the Measurability of Attributes

Criteria are defined by the present authors as a more concrete and measurable form of attributes; therefore, criteria generating difficulties indicate possibly greater attribute generation difficulties.

As an example of criteria generation difficulties, Figure 8 from Ozernoi and Gaft [1977] depicts a criteria-generating process.

3.3.5.1. Forer Effect. Previously existing criteria may be blindly adopted if the:

1. Analyst believes that the criteria apply to the present problem,
2. Criteria are well presented, and
3. Analyst believes in the authority of the previous criteria writer.

For example, the analyst might fail to question or rewrite criteria from a legacy tradeoff study document that originated from a perceived authority and is now seemingly adaptable to a present tradeoff. This would be an instance of the Forer effect.

Psychologist Bertram R. Forer [1949] gave a personality test to his students in 1948. He then asked them to evaluate a personality analysis, supposedly based on the test's results. Students rated the analysis on a scale of 0 (very poor) to 5 (excellent) as to how well it applied to them. The average score was 4.26. Actually, Forer had given the same analysis to all the students. He had assembled the analysis as one of a generally likeable person from horoscopes.

Factors that contribute to this fallacy in judgment are that the subject believes the analysis only applies to them, the subject believes in the authority of the evaluator, and the analysis lists mainly positive traits. The analyst avoids the effort of formulating criteria from scratch by substituting the rather inaccessible but true criteria of the situation with a plausible and more easily accessible set of preformulated criteria. In contrast, the use of Value-Focused Thinking [Keeney, 1992] guides one to consider the underlying fundamental values in formulating criteria.

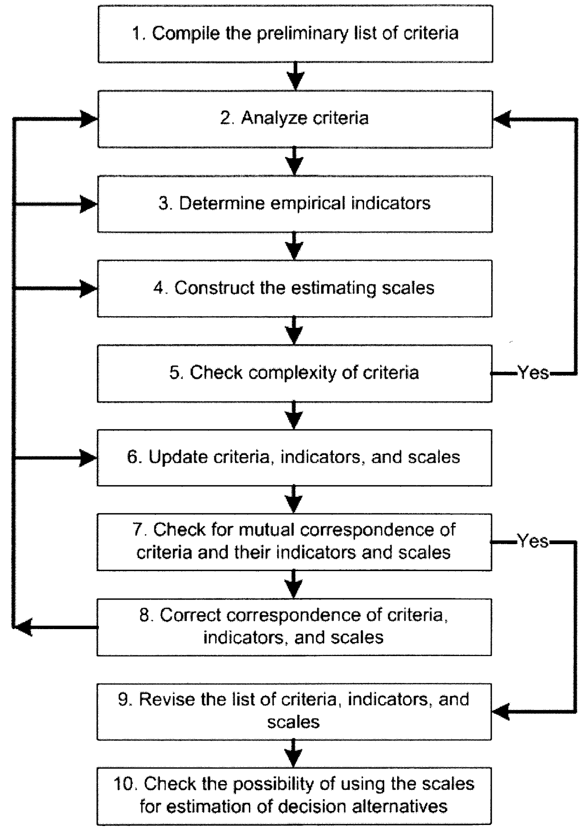

Figure 8. "Sequence of 10 steps for establishing a set of criteria" [Ozernoi and Gaft, 1977].

Target attribute: Objective decision criteria
Heuristic attribute: Preexisting criteria.

3.3.5.2. Tree of Criteria: Confounded Criteria and Dependent Criteria. Although attributes can be highly complex, constructing an objectives or criteria tree can create a map that is useful and indicates exactly where attribute substitution may occur. A criteria tree is constructed so that the location of each criterion in a hierarchy is explicitly known. The criteria tree makes explicit the hierarchical composition of each attribute. Unknowing attribute substitution can thus avoided.

The determination of criteria independence must be thorough, however, because of the high importance of independent evaluation criteria. For evaluating humans, Height and Weight are not independent; however, Sex (male versus female) and Intelligence Quotient are independent. In selecting a car, the following criteria are not independent: Maximum Horse Power, Peak Torque, Top Speed, Time for the Standing Quarter Mile, Engine Size (in liters), Number of Cylinders, and Time to Accelerate 0–60 mph. Because dependent criteria should be grouped together as subcriteria, these seven subcriteria for the car could all be grouped into the criterion Power. Suggestion: Questions designed to get a value for a criterion should be tightly coupled to the criterion.

Target attribute: Unconfounded tree of independent criteria
Heuristic attribute: Seemingly workable criteria tree.

3.3.5.3. Quadrant of Probability and Value: Confounding of Independent Criteria. Edwards [1955] created the quad diagram in Figure 9 that shows the combinations of two binary parameters: (1) Probability, in either Objective or Subjective form, and (2) Value, in either Objective form called "Value" (as in "numeric value"), or Subjective form called "Utility" (as in human-judged utility). This diagram thus gives four attribute forms for the combinations of probability and value. "Neither EV nor SEU by themselves capture the complexities of decision behavior. Further, research is beginning to show that when people are taught these strategies, they don't use them in real-life settings, such as in personal life or in the workplace" [Hutton and Klein, 1999: 37]. The reader is invited to answer the question: With probability and value being central to most human decision making, how much of this decision making is done with awareness that one is using a specific quadrant, or some known combination of quadrants?

Target attribute: Quadrant that exactly describes decision making at hand
Heuristic attribute: Blurring of quadrants into one sphere of personal decision making.

3.4. Requirement Definition and Analysis

3.4.1. Requirement Substitution

In the article "Managing Requirements," Ivy Hooks [2004] relates how System requirements are often incorrectly written as more specific Subsystem requirements. For example, instead of mandating that:

The system shall perform guidance and navigation,

an immature requirements writer will mandate that:

The guidance and navigation subsystem shall … [Hooks, 2004: 5]

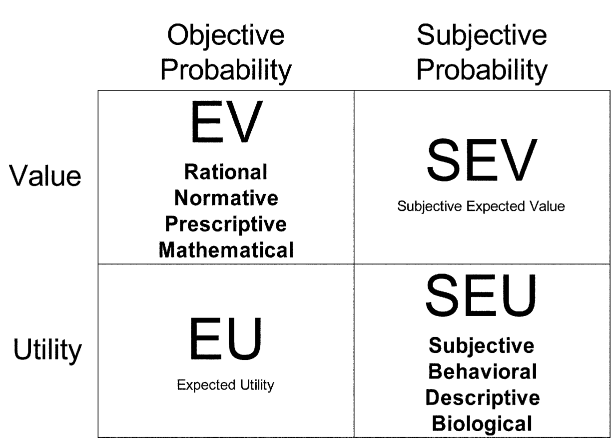

Figure 9. Quadrant of objective and subjective probability and value.

Target attribute: System requirement
Heuristic attribute: Subsystem requirement.

3.4.2. Requirement Specialization

Ivy Hooks also describes how busy managers, if put in charge of requirement development and maintenance, will reduce their focus to cost and schedule requirements.

> Most program managers come from a technical background [but] will focus on the non-technical aspects of the program, since these are new and alien. The program managers know that they do not fully understand budgets, so more attention goes to budgets. Besides, the program manager's boss will focus on budgets, and not on requirements, so the program manager places more attention on that which interests the boss [Hooks, 2004: 9].

Target attribute: Requirement database
Heuristic attribute: Cost and schedule requirements.

3.4.3. Data and Metrics

Because real-time assessment of complete actual environments or complex systems is difficult, summary metrics and indexes are often used. An attribute substitution bias results when it is forgotten that such proxies are merely substituting for a complete set of attributes.

Target attribute: Complete system
Heuristic attribute: Data or metric.

3.4.3.1. Failure To Consider Both Magnitude and Reliability. People tend to judge the validity of data first on its relative magnitude or salience ("strength"), and then according to its reliability ("weight") [Griffin and Tversky, 1992]. Metrics with outstanding magnitudes but poor reliability are likely to be chosen and used, because they draw human attention. Magnitude seems more attractive than reliability as a heuristic attribute. Of course, it is a mistake to not consider the reliability of data.

Target attribute: Expected value of Metric = Magnitude · Reliability
Heuristic attribute: Magnitude of metric.

3.4.3.2. Failure To Average Measurements. When a medical measurement or test reveals an unexpected result, often the patient is alarmed—because of a premature biasing on a single measurement. Usually the physician and/or the patient will ask for a second measurement. If the second measurement is pleasing, the first measurement is surprisingly often forgotten and only the result of the last measurement is considered—obviously biasing on the second measurement.

Target attribute: True value of a measurement
Heuristic attribute: Latest or most pleasing measurement.

3.4.3.3. Stock Market Indices. Stock market swings are often a result of attribute substitution on the economic indices released on any particular day, with the market swinging wildly as good and bad indicators are released on alternate days. The fact that the entire market, composed of millions of decision makers, can be led into taking one or a few indices are indicators for overall market health illustrates the two sides of attribute substitution. On the one hand, focusing on a narrow index is a mistaken reduction of attention, but, on the other hand, an index as defined, and its determined value, are undeniably true on the day of information release. (Note that the market closing price becomes the substituted attribute at the end of each day.)

Target attribute: Market health
Heuristic attribute: Economic index.

"Buy the Rumor; Sell the Fact" is a long-time market truism that eludes to investor optimism when considering the attractive attributes of an anticipated and inchoate market event. When the event actually occurs, however, there is a collapse of anticipated attributes to a lesser number of actual attributes embodied by the event. For instance, in the spring of 2009, the anticipated economic stimulus plan of President Obama maintained some optimism in the stock market, but the Dow Jones Industrial Index fell 298 points when President Obama finally signed the congressionally passed stimulus bill.

Target attribute: Stimulus plan expectations
Heuristic attribute: Actual signed stimulus plan.

3.5. Functional Decomposition, Analysis, and Allocation

The allocation of functions to subsystems and components may occur incorrectly because of attribute substitution. For example, less than the necessary functionality could be allocated to a subsystem, or less than the necessary hardware could be allocated a function.

3.5.1. POSIWID: Purpose Of a System Is What It Does

"Stafford Beer coined and frequently used the term POSIWID, or the Purpose Of a System Is What It Does, to refer to the commonly observed phenomenon that the de facto purpose of a system is often at odds with its official purpose. Beer coined the term POSIWID and used it many times in public addresses. Perhaps most forcefully in his address to the University of Valladolid, Spain in October 2001, he said 'According to the cybernetician the purpose of a system is what it does. This is a basic dictum. It stands for bald fact, which makes a better starting point in seeking understanding than the familiar attributions of good intention, prejudices about expectations, moral judgment or sheer ignorance of circumstances'" [Wikipedia, 2008].

In this case, Attribute Substitution is applied conversely, because it negates any system-promoter posited quality of completeness of a system, when in fact the usefulness of the system is much less, and is composed only of the functions that the system actually performs.

Target attribute: Functional purpose of system
Heuristic attribute: Touted purpose of system.

3.6. Analysis of Designs

3.6.1. Simulation or Optimization in Model Analysis

A simulation or optimization model should not be confused with the system itself. However, after analysts have invested significant time and money in formulating a model, they often choose to not continue to make a distinction between the simulation or optimization model, and the system itself.

Target attribute: Actual system
Heuristic attribute: Simulation or optimization model.

3.7. Tradeoff Studies of Alternatives

"People who are confronted with a difficult question sometimes answer an easier one instead" [Kahneman, 2003: 707]. When confronted with a choice among alternatives that should properly be decided by a full tradeoff study, there is a strong tendency to substitute a seemingly equivalent yet much simpler decision question in place of the tradeoff study process [Bahill, 1999].

Target attribute: Tradeoff study
Heuristic attribute: Simpler decision question or strategy.

3.7.1. Tradeoff Studies: Alternative Consideration

There are a variety of problems that can result from attribute substitution when ranking alternatives in tradeoff studies, some of which are covered in *Common Mistakes in Tradeoff Studies Made by Systems Engineers* [Bohlman and Bahill, 2009].

3.7.1.1. Serial Consideration of Alternatives. When solving a problem, people often reveal a confirmation bias [Nickerson, 1998] when seizing on a hypothesis as a solution, and holding on to it until it is disproved. Once the hypothesis is disproved, they will progress to the next hypothesis and hold on to it until it is disproved [Petroski, 2003]. This confirmation bias can persist throughout a serial consideration of alternatives, or even throughout a tradeoff study, as an analyst uses the whole study to try to prove that a currently favored alternative is the best. It is simpler to prove the current superiority of a hypothesis given serially presented data, than to calculate the true rank of a hypothesis in parallel with all other hypotheses in the face of all available data.

A tradeoff study of alternatives addresses the problems of serial consideration of alternatives. Alternative solutions are all evaluated in parallel from the beginning of the tradeoff study, so that a collective and impartial consideration will permit the selection of the best alternative from a complete solution space. All alternatives should be given substantial consideration [Wickelgren, 1974]. Slovic and Fischhoff [1977] and Koriat, Lichtenstein, and Fischhoff [1980] have demonstrated the effectiveness of strategies that require equal consideration for all alternatives.

Target attribute: Parallel consideration of alternatives through a tradeoff study
Heuristic attribute: Serial consideration of alternatives, often with a preferred alternative.

3.7.1.2. Isolated versus Juxtaposed Alternatives. Hsee, Loewenstein, Blount, and Bazerman [1999] showed the following example. The two music dictionaries described in this Table I were evaluated in isolation, and juxtaposed. When the dictionaries were evaluated separately, most subjects were willing to pay more for dictionary A. However, when the dictionaries were evaluated in juxtaposition, most subjects were willing to pay more for dictionary B. In isolation, each dictionary was judged most critically according to the Condition criterion. Further, when the dictionary descriptions were juxtaposed, the values of the Number of Entries criterion became easier to compare, and the importance attached to the Number of Entries criterion increased.

Criteria or features that are hard to assess in separate evaluations may be easier to evaluate in a comparative setting. With an alternative presented in isolation, assessment of the relative weights of importance of its criteria predominates; with alternatives presented in juxtaposition, a choice among alternatives becomes clear, and distinguishing criteria take higher importance. This phenomenon has implications for the presentation of alternatives. Specifically, alternatives that are evaluated serially (perhaps as they are conceived) may receive different levels of attention than the same alternatives evaluated in parallel, with distinguishing criteria becoming clear. Thus, attribute substitution is dependent on the number of alternatives, and how they are presented for evaluation.

Target attribute: Better dictionary overall
Heuristic attribute: Book Condition if evaluated separately; Number of Entries if evaluated juxtaposed.

3.7.1.3. Failing To Consider the Effects of Adding Alternatives, and the Status Quo Alternative. A study in medical decision making by Redelmeier and Shafir [1995] investigated distinctiveness by the addition of alternatives. The objective was to determine whether situations involving multiple options could paradoxically influence people to choose an option that would have been declined if fewer options were available. It was found that the introduction of an additional alternative can increase decision difficulty and thus the tendency to choose a distinctive alternative. Note that the distinctive alternative was rather unnoticeable before the additional alternative was added. A distinctive criterion becomes the heuristic attribute. In another scenario involving a patient with osteoarthritis, family physicians were less likely to prescribe a medication (53%) when deciding between two medications than when deciding about only one medication (72%). The difficulty in deciding between the two medications led some physicians to recommend not starting either. Similar discrepancies were found in decisions made by neurologists and neurosurgeons concerning carotid artery surgery and by legislators concerning hospital closures [Redelmeier and Shafir, 1995].

Table I. Alternative Dictionaries

Music Dictionary	Number of Entries	Condition
A	10,000	Like new
B	20,000	Cover is torn

Target attribute: Tradeoff study with Status Quo alternative
Heuristic attribute: Distinctive alternative.

3.8. Architectural Design

3.8.1. Systems Thinking

Retaining and using systems thinking is a constant challenge. Systems thinking involves active consideration of: the parts of the system, all the relations among the parts, emergent behaviors, and a plan for modeling, altering, or managing the system. Anyone working with a system is susceptible to losing sight of the entire system.

Target attribute: System
Heuristic attribute: Part of the system.

3.8.2. Levels

The natural world has many levels at which different laws operate. Most systems exist on various levels simultaneously. "Identifying levels in models is a basic modeling principle. This principle is not specific to any field of application: it applies to models in general [and is] not restricted to engineering. A common mistake in modeling systems is mixing elements of different levels in the same model" [Bahill et al., 2008: 553].

Target attribute: System model
Heuristic attribute: Level-specific model.

3.8.3. Views in Architectural Descriptions

Modern systems engineering architectural standards emphasize that the presentation of all relevant views is key to producing a good architectural description. This focus on views is promoted by IEEE-1471 [2008], which is now the same as ISO/IEC-42010, a recommended practice for architectural description that holds that view generation should be flexible and generous, so that the collection of views is comprehensive to the degree of detail necessary.

IEEE-1471 resists the common theme of intolerance, or the unwillingness to see things from any point of view that differs from one's own. However, individualism usually persists, and drawn views usually correspond to those near and dear to the architects in charge.

Target attribute: Architecture as defined by all relevant views
Heuristic attribute: Views that are easily accessible or preferred.

3.8.4. Reflexivity and Context

Besides the internal complexity of a system, systems theory must take into account the contextual factors, including how all elements within an environment are interconnected. Once context is included, however, reflexivity comes into play. Reflexivity is the condition that being inside a larger system makes it impossible to consider supposedly limited systems from an outside or objective perspective. Being inside a larger system makes objective examination of "smaller" systems difficult, if not impossible. For example, we exist within the current economic/political/social system, a condition that makes the examination of the current economic system non-objective. Imagining a truly alternative approach may be difficult, and implementation and replacement may be harder.

Target attribute: Objective, outside perspective on systems
Heuristic attribute: Seemingly objective viewpoint, erroneously considered as objective.

3.8.4.1. Manufacturing Improvement Movements. Manufacturing improvement movements, including Zero Defects, Batch Production, Quality Function Deployment (QFD), Six Sigma, Total Quality Management, Platforming, Lean Manufacturing, Agile Manufacturing, and Mass Customization, have swept through the production field as supposedly complete solutions for timely, efficient, and error-free manufacturing. These reform movements were each once thought to solve all problems in manufacturing. In fact, these reform movements were each focused on particular techniques, and not on higher-level attributes that would have indicated the limitation of the specific technical approaches. In hindsight, these movements can be seen as incomplete solutions to the total manufacturing problem, which is the broad problem of producing goods with zero waste.

Each movement, in its time, claimed to provide total value, when in reality each movement focused on its own set of subattributes, and technical implementations based on those subattributes. Perhaps the problem with these manufacturing improvement movements was that they implied the consideration of all attributes relevant to manufacturing, but did not catch their mistakes by specifying all attributes, and those actually addressed.

Lean Manufacturing, for example, seems to address the total manufacturing problem, with its motto of "More value with less work," and its practical focus on the elimination of the expenditure of resources for anything other than the creation of value for the customer. However, Lean Manufacturing has been criticized for its overemphasis on the reduction of resource use—a seeming attribute substitution mistake. Testing & Evaluation, for example, is overlooked by Lean Manufacturing as old-fashioned and costly, but the value added by Testing & Evaluation will never be overcome and negated by the simple application of Lean methodologies. Perhaps Value Engineering can solve attribute substitution issues in manufacturing.

Target attribute: Total manufacturing system
Heuristic attribute: Specific system with high applicability at particular time.

In the Quality area, Deming, Juran, and Conway have said: "Productivity will result from focusing on Quality, but Quality does not come about by pursuing Productivity" [Spewak and Hill, 1993: 4].

Target attribute: Quality
Heuristic attribute: Productivity.

3.9. Management

Management directives are often wrong or misguided, in hindsight, when management directs the pursuit of subattributes. For example, the recent pursuit of large sport utility vehicles by Detroit automobile manufacturers fulfilled a set of subattributes that are now shown to not encompass the fuller set of attributes that turned out to be important to car buyers in recent times of high fuel costs. Program managers and leaders of enterprises must always examine and heed all relevant attributes, using, for example, the attribute substitution model to illuminate management errors.

Good management has much to do with attributes, and guidance, within fields of attributes, via good leadership that establishes direction. Sauser [2006] has discussed NASA technology attributes, management styles and the selection of alternatives.

4. REQUISITE VARIETY DESCRIPTION OF ATTRIBUTE SUBSTITUTION

A more general description of attribute substitution is provided by Ashby's Law of Requisite Variety, which states that "only variety can absorb variety," or, more specifically, that a control system must have more actions available than the perturbations it is trying to control. Cyberneticist Beer [1985] emphasized the fact that variety control constantly plays a major role in human interaction with the world.

Attenuation of variety occurs when information processors, whether they are humans or computers, cannot process all the information available from the environment, and so must attenuate the information, by either summarizing the information, or selecting only that information that can be processed. The attribute substitution examples above are examples of variety attenuation at work.

Amplification of variety occurs when general information must be differentiated in order to meet exterior needs. For example, a shoe manufacturer would be happy to produce just one model of shoe—if it were not for market demands that call for a veritable infinite variety of shoes. A responsive shoe manufacturer will at some point reach a sufficiency of shoe types. Sufficient requisite variety exists when sufficiency criteria have been satisfied; for example, the criterion is "shoe variety" for the shoe example, and "control" for the traditional control theory definition of requisite variety.

Note that a description of attribute substitution in the form of requisite variety is a generalization that is more widely applicable, but involves the loss of specificity. Requisite variety examples and explanations are almost ubiquitous.

4.1. Management Levels Explained with Variety Attenuation

Beer [1985] pointed out that the concept variety attenuation goes far toward explaining the strata of management levels. Lower levels in corporations, for example, the production level, by necessity have to process much information at that level. A level above must necessarily be served with summary reports of the activity at a level below, because of the impossibility of reprocessing all the relevant information at the level below. Upper management must necessarily attenuate production information relevant at levels below.

Enterprise management, contrariwise, has to deal with a greatly expanded environmental sphere at upper levels in the enterprise, and must summarize the influences of the environment attributes when communicating necessities to the levels below. In this way, many instances of attribute substitution between management levels are necessary and beneficial.

5. ASSOCIATIVE WEB OF CONNECTIONS

Quantum mechanics has explained that underlying the logical visible world is a web of interconnections that spans the universe. Interestingly, the subconscious associative mind works on the basis of an underlying web of relevant connections between elements, although the connections may not be those chosen as important by the conscious logical mind. In this section, we substitute the model of an underlying web of associative connections for the models of attribute substitution, and the models of requisite variety. Where a perfunctory reference to requisite variety is lacking in specifics, a detailed associative web can lend structure to a system analysis. Requisite variety models are useful in recalling a plethora of available units for consideration, but note that requisite variety only obliquely refers to an associative property or organization of available units, unless specifically structured.

Systems thinking in fact can be defined as including the underlying associative web of connections of separate concepts that otherwise may be logical and linear. Systems engineering drawings, at their best, elucidate underlying associative webs. The explicit documentation of important connections is illustrated by Holt and McNeillis [2007] in *The Role of Systems Engineering in Global Standardization,* in which the North Sea fishing industry is described with different views of important aspects of the complex system. In other examples, systemigrams are drawn to illustrate the relations among system elements. Yet there is always a difficulty for humans: How many systemigrams can you recall from memory? … and not have to reconstruct by serially recalling individual connections?

The World Wide Web (WWW) has, of course, come to embody the presence of an untold number of connections among humans and ideas. Wikis, as compared to e-mail, embody the possibilities of a physical architecture based on an associative web of connections. Wikis provide for the rapid and unexpected collection and organization of information, as contrasted with email, which can be rather linear. Learning as facilitated by the WWW may seem chaotic and unorganized, but can be rapid and unexpectedly effective. YouTube.com, besides providing popular content, has demonstrated the ability to provide education material in subjects that would not be otherwise supported by traditional educational institutions.

Computer programming underwent a revolution with the introduction of object-oriented programming. Relatively simple hierarchical procedural languages like Fortran and Pascal were supplanted by object-oriented languages like C and Java, which make possible webs of associated classes and allow vast increases in complex connections. In the associated modeling arena, Structured Analysis gave way to the Unified Modeling Language, which emerged to model the new complexities.

5.1. Law as Summary of Extensive Associative Webs

Law, as a field of knowledge encompassing many important societal attributes, is a reduced summary of rules derived from a vast, complex subject matter. Memorizing legal rules is akin to memorizing the results of general questions that consider heuristic attributes, and remaining ignorant that in reality the rules arise from all the relevant human associations present in the judiciary and legal fields, as well as the fields of sociology, political science, and others. After legal training, lawyers are more aware of this vast associative web of responsibilities and liabilities than the average citizen.

Law is often taught and recalled in a seemingly haphazard order, owing in part to the fact that it is truly impossible to completely organize all the vast relevant fields of facts and knowledge. Law school professors are known to teach in the Socratic style, in which freewheeling discussions follow a thread of discussion only as long as another thread does not become more interesting. Interestingly, perhaps this is the most effective means of teaching within a vast associative web, because when recall is necessary, the student may be more open to the various associations that may be important. In this way, the law is recalled from unconscious memory after Socratic discussion has created a significantly large web of associations.

Legal education, as an example of the educational process, indicates education is a process of teaching and learning both more specific ideas, or separate and concretized “heuristic” attributes or objectified ideas, and learning more associations among such ideas. The process of discretization and association lead to a more lucid understanding of fields of knowledge that otherwise can only be unconsciously sensed and guessed.

Common law cases are tried only when there are actually aggrieved parties present before the court. The reasons for these requirements become clear when the underlying basis for law is recalled, namely, the vast and usually unconscious web of associative connections. How can a case be tried when the judge and jury members, as human beings, cannot recall all the relevant associative webs? One answer is that only the interested and aggrieved parties have standing before the court, since they alone can provide the intense interest necessary to elucidate a case by drawing attention to all relevant legal issues. Aided by motivated lawyers, the adversarial parties assure that all issues associated with the case are fully discussed. The presence of such a complete discussion ultimately aids the judge and jury, who are legally and ultimately morally and personally responsible for deciding legal issues and arriving at a decision. Thus, the judicial community restricts hearings only to “actual cases and controversies” in order to review only highly relevant and fully argued cases, which will sometimes become formational precedents to the evolving body of case law.

6. PROCESSES

Processes involve many functional steps at which biasing can occur by improperly collapsing focus to a subattribute while trying to answer a question about a higher-level attribute or a complete set of attributes. Suppose, for the sake of discussion, that the problem of attribute substitution has been addressed with an expanded mental focus, or the use of correction techniques. How can debiasing help systems engineering processes?

6.1. Debiasing in Standard System Engineering Processes

Systems engineering processes, as emphasized by ANSI/EIA-632 [2003], and flow-chart representation of processes, could generally include a "debiasing" process step, for the purpose of explicitly naming the continual need to reexamine and possibly amplify the problem solving scope while engaging in engineering, or project or program management. Figure 10 shows the insertion of a debiasing step into a typical requirements determination process. Briggs and Little [2008: 21] have noted how biases in cultural processes sometime result in erroneous technical choices: "At the group level, we must consider the character and culture of the organization. These attributes describe and even define how the group arrives at and accepts decisions."

6.2. Process Flow from Attributes

As competence in debiasing from erroneous attribute substitution and skill in determining correct attribute structure increases, confidence in basing action directly on attributes will also increase. Attribute-based action has the promise of increasing sensing fidelity and decreasing reaction times. An intelligence community officer has written:

> Not all problems are of the same type, even though they may look similar. Each has a different set of attributes that require a different approach to progress toward a solution. The starting point for these processes must be tied to and conditioned by the attributes of the problem set. The process, from start to finish, needs to ensure a creative engagement with each problem, i.e. considering multiple solutions as opposed to focusing on just one.
>
> Problem analysis and categorization elicits attributes that can guide the selection of the appropriate resources—people, processes and technology. Categorizing each problem allows the anticipation of the types of personnel, subject matter expertise, technology, and resources that will be required to address the issue. Additionally, it allows the project teams to choose from a set of flexible heuristic-based system engineering processes (i.e. experimental problem-solving techniques that are self-educating and evolutionary) adapted to each category that will jumpstart progress toward a solution.
>
> In general, the problem process flow is to analyze the problem, categorize the problem, select the appropriate resources, and distribute the results. The best solution to these challenges is to establish a flexible framework of training, processes and technology that allows the solution of each problem according to the attributes it possesses [Dullnig, 2008].

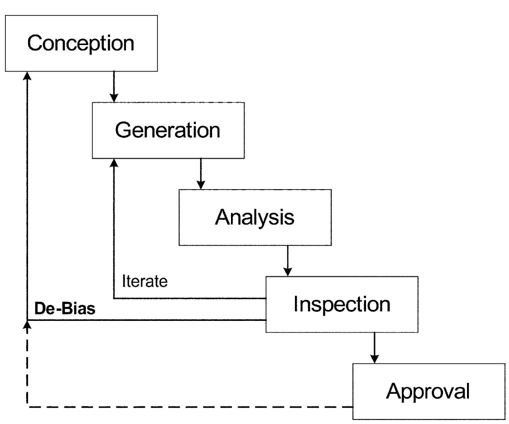

Figure 10. Debiasing loop introduced into a typical systems engineering process.

6.3. Time Biasing

Time-based biasing by humans is common, and often involves a reduction of attention via short-term thinking and hyperbolic discounting errors [Kenley and Armstead, 2004; Ainslie, 2001], which cannot be well discussed here. Resolutions to such problems often involve increased long-term thinking, and the ability to see antecedents and consequences [Hutton and Klein, 1999]. Significantly, successful stock market investor Warren Buffet has an investment horizon that he characterizes as "forever."

Benjamin Franklin, in a letter to Joseph Priestly, described how consideration of a decision problem should be extended over several days, in order to assure that all relevant attributes are allowed to come to mind [MacCrimmon, 1973]. The attributes should be recorded for parallel and/or simultaneous consideration.

7. SUGGESTIONS FOR AMELIORATING ATTRIBUTE SUBSTITUTION AND OTHER BIASING ERRORS

7.1. Generic Attributes

Awareness of attributes, their importance, and their general applicability has increased in recent years and is becoming standardized [EIA/IS-731, 2002]. Research is now being conducted on generic attribute appraisal process improvement [Wells, Ibrahim, and LaBruyere, 2003], which should increase the availability of engineering practices to better distinguish and use attributes effectively.

7.2. Analogies

An analogy is a model with elements and relations among elements that correspond generally one-to-one to the system in question. Analogies are akin to attribute substitution in that analog models are often abstract, and thus entail a significant reduction of complexity. Note, however, that analogies do not necessarily involve a reduction in complexity. In fact, analogies of greater complexity are often useful because they increase the perception of possibilities, some of which may be applicable to the system being engineered. A strategy for meeting requisite variety is to find an analogy of greater complexity than the current problem situation; for example, management problems are often solved by examining analogous situations where novel resolutions were employed.

7.3. Cognitive Skills

Frank [2006] examined a questionnaire and interviews to determine cognitive characteristics important for a high capacity for engineering systems thinking. A ranked list of important cognitive characteristics appears in Table II, along with the associated structures discussed in this paper. It is suggested here that increased understanding of the attribute substitution model and other structures associated with these important cognitive abilities will decrease biasing errors. The general theme is to increase the scope of consideration.

7.3.1. Systems Thinking: Tolerance for Ambiguity and Uncertainty, versus Details

The following quotation emphasizes important feature of systems thinking:

> 3.6. Understanding Systems without Getting Stuck on Details; Forest Thinking; Tolerance for Ambiguity and Uncertainty. It was found in three studies that engineers with high CEST [Capacity for Engineering Systems Thinking] are able to conceptually and functionally understand the system, even without understanding all its minutiae. They avoid getting snagged by the details. They are able to understand the whole/overall picture and continue to act without understanding fully all of the system's details. Such engineers feel comfortable with ambiguity and working in unclear conditions and in an uncertain environment; not knowing all the details does not disturb them or hinder their efforts to solve a systems problem. This thinking skill enables senior managers to set priorities and allocate resources on the organization level.
>
> In opposition, engineers who have to thoroughly understand all the details involved in a given problem in order to be able to form a decision and come up with a solution, usually find it difficult to develop high CEST [Capacity for Engineering Systems Thinking] and work as senior systems engineers [Frank, 2006: 95].

7.4. Hierarchy and Decomposition

Hierarchy and decomposition are traditional SE tools, and should be effective against erroneous attribute substitution. Hierarchical structure can lend insight to the arrangement of attributes, and denote that higher-level attributes are encompassing of lower-level attributes. Decomposition allows easier problems to be tackled first; in the case of attribute substitution, this implies possibly using a lower-level attribute to make a lower-level decision, if awareness is maintained as to higher-level attributes.

7.5. Expert Decision Making Characteristics

Hutton and Klein [1999], in their article *Expert Decision Making*, review characteristics and practices that will allow erroneous attribute substitution to be noticed and corrected as it happens. Usually, expert decision practices are acquired after significant training and opportunities for correction, but it is hoped that the explicit study of expert practices and abilities will allow the novice to at least have guidelines for process improvements.

Experts gain experience through extensive practice that fosters superior memory, refined perceptual abilities, deeper level thought, and faster decision making. Chase and Simon [1973] found that experts can overcome Miller's 7 ± 2 bit limit of short-term memory retention by substituting chunks of information for bits.

Although "experts tend to be experts only in their domain of expertise" [Hutton and Klein, 1999: 33], experts gain the ability "to maintain an ongoing situation awareness through perceptual and recognitional skills" [Hutton and Klein, 1999: 32]. "Experts have strong self-monitoring skills. Experts have an ability to catch themselves when they make errors" [Hutton and Klein, 1999: 34]. Such noncollapsing situational awareness should serve to prevent erroneous attribute substitution.

Table II. Cognitive Characteristics for High Capacity for Engineering Systems Thinking [Frank, 2006: 94]

Cognitive Characteristics	Associated Structure
Understanding ...	
1. Whole system and seeing the big picture	Attribute Substitution; Sub-System Substitution
2. Interconnections; closed loop thinking	Associative Webs of Connections
3. Systems synergy	Associative Webs of Connections
4. Multiple perspectives	Views of Architectures
5. Thinking creatively	Requisite Variety
6. Not getting stuck on details; Tolerance for ambiguity and uncertainty	Attribute Substitution
7. Implications of proposed change	Process Flow; Time Biasing
8. New system concepts	(Novelty); Time Biasing
9. Analogies and parallelism	Analogies
10. Limits to growth	Process Flow; Time Biasing

Experts have an increased ability to see distinctions, and therefore will not blindly replace a heuristic attribute for a target, or higher-level, attribute. "Experts are particularly good at making fine discriminations. … Good examples of this occur particularly in competitions, where expert judges are either required to judge performance at a task, such as high diving or gymnastics, or judge some attribute of a particular item, such as prize bulls, show dogs, or watermelons. The inexperienced audience member is left wondering what it was about the winning dive A, bull X, or watermelon Z that distinguished them from the rest of the competition" [Hutton and Klein, 1999: 34].

8. CONCLUSION

The concept of attribute substitution can be used quite frequently to notice and counterbalance the ready reduction of attention that may occur while using a wide range of system engineering tools, methods and techniques. An awareness of the phenomenon of attribute substitution will help engineers improve systems engineering practice.

Attribute substitution, it can now be seen, is an abstract, simplified, and structured summary model of the loss of information that occurs when a human focuses on a specific decision criterion within a larger set or variety of criteria, an encompassing super-criterion, or even within a veritably infinite web of associative connections. Attribute substitution models how limited logic can reduce awareness of relevant associative webs. Contrariwise, attribute substitution is ideal for focusing attention where appropriate. Most importantly, an awareness of attribute substitution by the systems engineer will avail the engineer of an explicit map of mental considerations that may otherwise remain unexamined.

In general, it is highly important to remember, by whatever useful means, that humans are prone to reducing their field of focus when making decisions under pressure. In order to avoid mistakes, people must, in one way or another, remember the general phenomena of attention restriction that is described in different ways by models of: (1) Attribute Substitution, (2) Requisite Variety, or (3) Associative Webs.

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REFERENCES

G. Ainslie, Breakdown of will, Cambridge University Press, New York, 2001.

ANSI/EIA-632, Processes for engineering a system, American National Standards Institute, Washington, DC, and Electronic Industries Alliance, Arlington, VA, 2003.

A.T. Bahill, Doing tradeoff studies with multicriterion decision making techniques, International Council on Systems Engineering, Seattle, WA, 1999, www.incose.org.uk/incose99/tutt05.htm, retrieved February 2006.

A.T. Bahill, F. Szidarovszky, R. Botta, and E.D. Smith, Valid models require defined levels, Int J Gen Syst 37(5) (2008), 553–571.

S. Beer, Diagnosing the system: For organizations, Wiley, New York, 1985.

J. Bohlman and A.T. Bahill, Common mistakes in tradeoff studies made by systems engineers, Syst Eng (2009), to appear.

C. Briggs and P. Little, Impacts of organizational culture and personality traits on decision-making in technical organizations, Syst Eng 11(1) (2008), 15–26.

W.G. Chase and H.A. Simon, Perception in chess, Cognitive Psychol 4 (1973), 55–81.

J. Daniels, and A.T. Bahill, The hybrid process that combines traditional requirements and use cases, Syst Eng 7(4) (2004), 303–319.

J. Dullnig, Process flow from attributes, personal communication, University of Texas, El Paso, 2008, 1–2.

W. Edwards, "An attempt to predict gambling decisions,"Mathematical models of human behavior, J.W. Dunlap (Editor), Dunlap and Associates, Stamford, CT, 1955, pp. 12–32.

EIA/IS-731, Systems engineering capability model, Electronics Industries Alliance, Arlington, VA, 2002.

B.R. Forer, The fallacy of personal validation: A classroom demonstration of gullibility, J Abnormal Psychol 44 (1949), 118–121.

M. Frank, Knowledge, abilities, cognitive characteristics and behavioral competencies of engineers with high capacity for engineering systems thinking (CEST), Syst Eng 9(2) (2006), 91–103.

T. Gilb, Competitive engineering: A Handbook for systems engineering, requirements engineering, and software engineering using Planguage, Elsevier, New York, 2005.

Google, 10 to the 100 project, 2008, http://www.project10tothe100.com/.

J.O. Grady, System verification: Proving the design solution satisfies the requirements, Academic, London, 2007.

D. Griffin and A. Tversky, The weighting of evidence and the determinants of confidence, Cognitive Psychol 24 (1992), 411–435.

J. Holt and P. McNeillis, The role of systems engineering in global standardization, Insight (INCOSE) 10(1) (2007), 8–16.

I. F. Hooks, Managing requirements for a system of systems, CrossTalk J Defense Software Eng 17(4) (2004).

C.K. Hsee, G. Loewenstein, S. Blount, and M. Bazerman, Preference reversals between joint and separate evaluations of options: A theoretical analysis, Psychol Bull 125(5) (1999), 576–590.

R.J.B. Hutton and G. Klein, Expert decision making, Syst Eng 2(1) (1999), 32–45.

IEEE-1471, Recommended practice for architectural description of software-intensive systems, ISO/IEC 42010, Institute of Electrical and Electronic Engineers, New York, 2008.

D. Kahneman, A perspective on judgment and choice: Mapping bounded rationality, Amer Psychol 58(9) (2003), 697–720.

D. Kahneman and S. Frederick, "Representativeness revisited: Attribute substitution in intuitive judgment," Heuristics and biases, T. Gilovich, D. Griffin, and D. Kahneman (Editors), Cambridge University Press, New York, 2002, pp. 49–81.

D. Kahneman and M. Riepe, Aspects of investor psychology: beliefs, preferences, and biases investment advisors should know about, J Porfolio Management 24(4) (1998), 52–65.

D. Kahneman and A. Tversky, Prospect theory: An analysis of decision under risk, Econometrica 46(2) (1979), 171–185.

R.L. Keeney and H. Raiffa, Decisions with multiple objectives: Preferences and value tradeoffs, Wiley, New York, 1976.

R.L. Keeney, Value-focused thinking: A path to creative decision-making, Harvard University Press, Cambridge, MA, 1992.

L. Kelvin, Electrical units of measurement, Popular Lectures Addresses 1 (1891), 86–87.

C.R. Kenley and D.C. Armstead, Discounting models for long-term decision making, Syst Eng 7(1) (2004), 13–24.

R.M. Koriat, S. Lichtenstein, and B. Fischhoff, Reasons for confidence, J Exper Psychol Hum Learn Memory 6 (1980), 107–118.

A. Korzybski, Science and sanity: An introduction to non-Aristotelian systems and general semantics, The International Non-Aristotelian Library, Lakeville, CT, 1948.

K.R. MacCrimmon, "An overview of multiple objective decision making," Multiple criteria decision making, J.L. Cochrane and M. Zelany (Editors), University of South Carolina Press, Columbia, SC, 1973, pp. 18–43.

M.W. Maier and E. Rechtin, The art of systems architecting, CRC Press, Boca Raton, FL, 2002.

M. Mannion and K. Hermann, Using parameters and discriminants for product line requirements, Syst Eng 11(1) (2008), 61–80.

G.A. Miller, The magic number seven, plus or minus two: Some limits on our capacity for processing information, Psychol Rev 63 (1956), 81–87.

R.S. Nickerson, Confirmation bias: A ubiquitous phenomenon in many guises, Rev Gen Psychol 2 (1998), 175–220.

V.M. Ozernoi and M.G. Gaft, "Multicriterion decision problems," Conflicting objectives in decisions, D.E. Bell, R.L. Keeney, and H. Raiffa (Editors), Wiley, New York, 1977, Vol. 1, pp. 17–39.

H. Petroski, Framing hypotheses: A cautionary tale, Amer Scientific 91(1) (January–February 2003), 18–22.

M. Piattelli-Palmarini, Inevitable illusions: How mistakes of reason rule our minds, Wiley, New York, 1994.

J. Rasmussen, A.M. Pejtersen, and L.P. Goodstein, Cognitive systems engineering, Wiley, New York, 1994.

D. Redelmeier and E. Shafir, Medical decision making in situations that offer multiple alternatives, JAMA 273(4) (1995), 302–305.

RSAS, Press release: Nobel Prize in Economics 2002, The Royal Swedish Academy of Sciences, Stockholm, 2002, http://nobelprize.org/nobel_prizes/economics/laureates/2002/press.html, retrieved September 2008.

T.L. Saaty, The analytic hierarchy process: Planning, priority setting, resource allocation, McGraw-Hill, New York, 1980.

B. Sauser, Toward mission assurance: A framework for systems engineering management, Syst Engineering 9(3) (2006), 213–227.

P. Slovic and B. Fischhoff, On the psychology of experimental surprises, J Exper Psychol Hum Perceptions Performance 3 (1977), 544–551.

E.D. Smith, Tradeoff studies and cognitive biases, Ph.D dissertation, Systems and Industrial Engineering, University of Arizona, Tucson, AZ, 2006.

E.D. Smith, Y.J. Son, M. Piattelli-Palmarini, and A.T. Bahill, Ameliorating mental mistakes in tradeoff studies, Syst Eng 10(3) (2007), 222–240.

S.H. Spewak and S.C. Hill, Enterprise architecture planning: Developing a blueprint for data, applications and technology, QED, Boston, 1993.

F. Strack, L.L. Martin, and N. Schwarz, Priming and communication: The social determinants of information use in judgements of life-satisfaction, Eur J Soc Psychol 18 (1988), 429–442.

W.G. Sullivan, E.M. Wicks, and J.T. Luxhoj, Engineering economy, Prentice Hall, Upper Saddle River, NJ, 2006.

D.D. Sworder and G.A. Clapp, Hierarchical processing by human decision makers, Syst Eng 1(3) (1998), 228–241.

A. Tversky and D. Kahneman, Judgment under uncertainty: Heuristics and biases, Science 185 (1974), 1124–1131.

A. Tversky and D. Kahneman, The framing of decisions and the psychology of choice, Science 211 (1981), 453–458.

A. Tversky and D. Kahneman, "Judgments of and by representativeness," Judgment under uncertainty: Heuristics and biases, D. Kahneman, P. Slovic, and A. Tversky (Editors), Cambridge University Press, Cambridge, UK, 1982, 84–98.

A. Tversky and D. Kahneman, Advances in prospect theory: Cumulative representation of uncertainty, J Risk Uncertainty 5 (1992), 297–323.

S.A.M.M. Ullah, A fuzzy decision model for conceptual design, Syst Eng 8(4) (2005), 296–308.

C. Wells, L. Ibrahim, and L. LaBruyere, A new approach to generic attributes, Syst Eng 6(4) (2003), 301–308.

W.A. Wickelgren, How to solve problems: Elements of a theory of problems and problem solving, Freeman, San Francisco, 1974.

Wikipedia, Stafford Beer, Wikipedia.org, retrieved November 2008.

A.W. Wymore, Model-based systems engineering, CRC Press, Boca Raton, FL, 1993.

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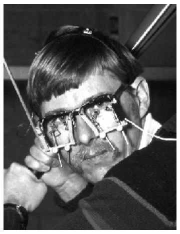

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