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NAVIS-based Knowledge Transfer from System Experts to their Heirs Apparent

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Abstract—**All organizations that survive for decades or more face the challenge of training new personnel to follow in the footsteps of system experts. The need for efficient and effective transfer of knowledge from system experts to the next generation of designers, builders, operators, and maintainers within complex systems is of critical importance in high-consequence domains (e.g., nuclear power, nuclear weapons, hazardous chemicals, bridge building, aircraft transport, space exploration, electric power grids). Unfortunately, data have indicated the presence of 10–40 year cyclical trends where organizations "forget" critical knowledge, experience an incident or accident, then "regain" critical knowledge for a finite period of time. While the causes of these recurring cases of "organizational amnesia" are varied, there is evidence that part of the problem is due to ineffective knowledge transfer from experts to their heirs apparent. Recently, a decision making process was developed that incorporates a unique taxonomy for understanding and aiding mitigation of perceptual/decision making biases. This taxonomy is comprised of twenty-seven recognized biases ordered into the categories of *normative knowledge*, *availability*, and *individual specific* biases (NAVIS). Foundational to the NAVIS approach are ten, well-defined critical thinking processes that can be used to mute the impact of undesirable biases, regulate the application of one's knowledge to a decision, and guide information gathering activities. In this paper, an application of the NAVIS approach is described which may greatly improve the efficiency and effectiveness of knowledge transfer from system experts to those seeking expert status.**

I. INTRODUCTION[1]

In complex, high-consequence systems the efficient and effective transfer of knowledge among personnel is critical for maintaining safety, system stability, and continuous improvement. A large component of this knowledge resides not in manuals and procedures but in the "minds and hands" of system experts. In addition, it often requires the insights and experience of system experts to make proper use of the knowledge base that is documented (e.g., manuals, procedures, event reports, technical references). To complicate matters, the experts with the accumulated "system wisdom" (including both explicit and *implicit* skills & heuristics) often have non-system specific academic and experiential histories that differ greatly from those of aspiring heirs apparent. While completely informal integration of new personnel into the "culture of the experts" may partially succeed over time, opportunities for omissions and misinterpretations abound.

In this paper, an application of the NAVIS approach is described which may greatly improve the efficiency and effectiveness of knowledge transfer from system experts to those seeking expert status. The technique proposed can help to systematically reveal implicit biases/tendencies and heuristics that guide both knowledge holders and knowledge seekers within the context of a specific complex system. The NAVIS-based approach provides a basis for enabling system experts and their heirs apparent to (1) readily understand each other's backgrounds and biases, and (2) achieve a disposition of inquiry, observation, and inference that supports effective and efficient transfer of system knowledge.

II. NEED FOR CONTINUITY AND GROWTH OF EXPERTISE

Organizations wishing to survive and thrive into perpetuity must be capable of transmitting expertise between generations of system personnel. For complex, high-consequence systems this need is heightened by the potential for loss of life, injury, and other damages that can result from system failure. Not only must these types of organizations nurture the transfer of currently held system knowledge, but they must strive to continually expand the system knowledge base. Furthermore, other complex organizations aimed at generating scientific and technological advancements must also excel at knowledge transfer. While these organizations are not poised at the near-term precipice of potential "life or death" consequences, they are key to financial security and leadership in a global, knowledge-based economy.

A. The Cyclical Nature of System Knowledge

In high-consequence industries (e.g., chemical processing, space exploration) fluctuations in system knowledge[2], notionally represented in Figure 1, typically involve "forgetting" system details as key personnel retire or leave the system and time elapses without the occurrence of any or many noteworthy near misses, incidents, or accidents. Relearning of critical system knowledge typically follows the occurrence of a

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[2] In this case, knowledge consists of 'known knowns'–accumulated knowledge proven to a high degree of confidence; 'known unknowns'–areas of uncertainty known to exist, but no clear/practical way to increase knowledge in those areas is available; and 'unknown unknowns'–gaps in knowledge not identified at all.

severe accident. Data from several industries indicate a temporal cycle for such oscillations ranging between 10–40 years [1, 2].

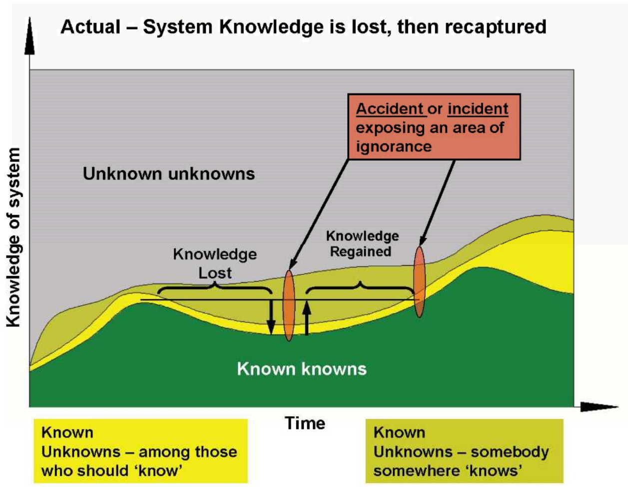

Figure 1. Fluctuations in system knowledge over time.

B. The Need for Science and Technology Innovation

It has been stated that, "The essence of modern economic growth is the increase in the stock of useful knowledge and the extension of its application" [3]. Recently, the U.S. National Academy of Sciences, National Academy of Engineering, and the Institute of Medicine alerted the nation that its scientific and technological base is readily declining just as other nations are rapidly gaining strength [4]. Specifically, they called for improvements in mentoring to produce/sustain a population of future science and technology innovators. The NAVIS-based approach is proposed as a means to improve capacities for transmitting scientific, engineering, and technology innovation knowledge from current experts to the future experts and innovation leaders.

III. Knowledge Transfer Within Complex Systems

Recognition of expertise and efforts aimed at transmitting one's expertise to others has an ancient past—such activity is required for sustainment/advancement of a human community. In recent centuries, dramatic increases in bodies of knowledge and related complex, high-consequence technologies have led to a proliferation of specialized expertise that must be continually passed on to less experienced personnel. This section briefly describes characteristics of expertise, processes for transmitting expertise, and some of the challenges that work against these processes.

A. Expertise

If one hopes to improve transfer of knowledge between experts and their heirs apparent, it is helpful to delineate important aspects of what constitutes expertise. For instance, an expert is one who can leverage many years of expertise in a great variety of contexts to recognize patterns. An expert selectively retrieves relevant information and extrapolates from a given pattern to fluidly produce an appropriate response [5]. Often, it will be difficult for the expert to describe the pattern precisely or to articulate how the recognition of a given pattern should lead to a specific behavior [5, 6]. The expert pattern recognition process draws upon both broad and deep tacit[3] system knowledge. Experts know when a given rule applies and can identify when an unusual pattern requires an exception [5]. Attainment of true expertise, as contrasted with competence, often takes ten years or more to develop [10].

In complex, high-consequence systems experts have knowledge in areas involving critical technical skills, management systems, and the norms and values of the organization [5]. System experts are critical for helping others interpret events, understand technology and organizational processes–especially in the realm of the "power perspective" of knowing who does what and how to navigate an organization's political system. Experts also provide feedback on relationships with clients and partners, and can teach an heir apparent what it means to behave, look like, and be a system expert. The archetypical expert can also make the best estimates of what types of risk taking is likely to be interpreted as judicious or reasonable (even if the outcome is bad) versus those risks which would be foolish, imprudent, or outright dangerous [5].

Other personnel in the system will have varying degrees of such knowledge depending upon whether they are student interns, new employees at their first job, or personnel with various levels of 'life' and 'system' experience. All of these personnel will be prime candidates for some type of semi-formal mentoring to improve their knowledge and abilities. A much smaller subset will have the prerequisite knowledge base for being identified as an heir apparent to a system expert–as is the focus in this paper.

B. Types of Knowledge Transfer

Given the many tacit knowledge dimensions of expertise it should be noted that the most effective development of an heir apparent into an expert is close involvement with the relevant expert(s). Knowledge management systems or expert systems that capture key aspects of expertise and facilitate their dissemination to others are needed and encouraged, in fact, the approach to be presented here could be used to inform such systems. However, many aspects of true expertise need to be transferred person-to-person to an aspiring expert [11].

Formal systems of knowledge transfer have existed for millennia under designations such as guild, artisanship, and apprenticeship [12]. The continuum of expertise within the apprenticeship system includes: novice (beginner), apprentice (intermediate), journeyman (advanced), and master (virtuoso) [5]. In this paper, the focus is primarily upon the transition from heir apparent to expert, which is analogous to moving from journeyman to master. However, features of the NAVIS-based approach to be proposed can benefit transitions throughout the continuum.

[3] Explicit, figurative, or declarative knowledge (involving semantic memory) is concerned with knowing 'facts.' Tacit, operative, or procedural knowledge (involving episodic memory) involves understanding where the 'explicit' knowledge comes from or what underlies it. Tacit knowledge also involves the capacity to use, apply, transform, or recognize the relevance of explicit knowledge in novel situations [7-9].

Typical contemporary forms of knowledge transfer within complex, high-consequence systems include *mentoring* and *shadowing*. Mentoring seems to be associated with many specific definitions [12]; however it is generally understood as a relationship (formal or informal) between a more experienced and a less experienced person within a system/organization that is aimed at achieving beneficial result for the individuals and for the organization. Teaching, guiding, counseling, encouraging, and coaching are all associated with mentoring relationships [12]. Mentoring is associated with 'learning by doing' or discussing how things should be done either in a direct or 'storytelling' fashion [13]. Shadowing is a term that is more closely tied to 'observing an expert in action' [5]. The one who is shadowing is assumed to be an active learner who absorbs the observations and then may learn more from the expert in a 'debrief' of the observations. A significant mentoring relationship will likely include many shadowing-type activities.

It appears that informal mentoring is more successful than formal mentoring relationships [5, 14]. That is, it is better to use informal means to bring experts and heirs apparent together. A good match can be readily made when there is sufficient commonality in 'paradigmatic formation' and experiences such that a spark ignites and a relationship forms [15, 16]. Within the past few years, the author has been involved in a mentoring relationship which has followed such an informal path. The relationship was made possible by several system experts who acted as an informal screening committee to filter access to a particular system expert. Once identified, the author/heir apparent was introduced to the expert. An excellent informal knowledge transfer relationship began, and has been sustained for a few years.

The problems associated with some formal mentoring programs tend to occur due to a lack of training for mentors/experts, unwilling/uninterested mentors or mentees, and/or poor strategies for matching mentors with mentees [12]. A key challenge with the mentor-type process, especially when applied to teaching heirs apparent (i.e., journeymen) to become experts (i.e., masters) is that many experts have achieved their position without becoming good or willing teachers. Recent research involving these types of mentor-type relationships have shown that some experts do not know how to bridge gaps between their knowledge and the heir apparent. They may become impatient or frustrated in their attempts and may quickly alienate the expert-to-be. Other experts may excel at metering out information in appropriate doses and probing for appropriate understanding by their 'pupil' [5].

In order for mentoring relationships to consistently succeed, it is important to provide mentors/experts training on how to 'teach' system expertise. An essential part of such training goes beyond technical aspects of teaching methods, but extends into the social realm, for example, mentors should be taught to see their mentee as a complete person—not simply as a mind to be trained [12]. They should also be made explicitly aware of the importance of nonverbal forms of communication. It has been estimated that 2/3 of meaning is transmitted through non-verbal cues [17]. Once the appropriate training is provided, the establishment of specific mentoring relationships should be encouraged gently, not formally forced. The NAVIS-based knowledge transfer approach to be presented in this paper is proposed as an aid in facilitating successful heir apparent-to-expert relationships. It can add rigor to the process of explicitly understanding one's knowledge bases, biases, values, (i.e., attributes which are often implicitly held) and facilitating interpersonal transfer of that information.

C. Benefits of Intentional Knowledge Transfer

The benefits of intentional knowledge transfer (e.g., mentoring, shadowing) have included increased job satisfaction, higher employee retention, better performance, and more rapid promotions. In well-managed programs, these benefits are realized all along the continuum of experience [5]. It would be logical to infer that promoting a culture in which individual knowledge transfer relationships often succeed would further the success of the overall system or organization. Of course, gathering extensive empirical support for such a relationship is challenging, fortunately several data collection efforts are underway [5]. In addition, there have been interesting simulation efforts that suggest support for this relationship [18]. An additional potential benefit of intentional knowledge transfer approaches is that they may increase the diversity of individuals who eventually achieve expert status in complex systems/organizations [19–21].

D. Challenges Facing Knowledge Transfer

Training system experts to be effective teachers and facilitating opportunities for experts and heirs apparent to informally enter into productive knowledge transfer relationships can clearly benefit complex, high-consequence systems to reduce risks and improve system success. However, developing system experts requires a substantial amount of time from both the expert and the heir apparent, and the costs of time, training resources, and relationship facilitation are immediate. In many organizations shadowing activities are not billable and obtaining project-based funding for mentoring activities can be a challenge. There is also the increasing trend for individuals to be required to work in many different specialties within one organization [5]. Thus, special relationships may be needed in which a promising heir apparent becomes an understudy of multiple system experts [22].

Experts may be concerned as to whether they will be rewarded by management for putting forth the effort to transfer their expertise. Management may become more reluctant to support knowledge transfer if a series of promising heirs apparent gain expertise and then promptly take that expertise outside the organization, or simply switch jobs within the organization. As aptly stated by Swap et al. "mentoring requires a light—and sophisticated—managerial hand" [5, p. 108]. To aid in such sophistication, the NAVIS-based knowledge transfer approach will be proposed as having relatively direct application to preparing the willing expert to be an effective teacher, preparing the willing heir apparent to be proficient learner, and helping identify promising matches of heirs apparent and experts.

IV. NAVIS TAXONOMY OF BIASES

The unique, recently developed NAVIS-based decision making method includes a framework for understanding key aspects of risk perception and decision making and provides a systematic technique for making improved decisions regarding complex, high-consequence systems [23, 24]. The components of the method include the NAVIS taxonomy of twenty-seven recognized bias processes; a list of ten specific, carefully defined critical thinking skills[4] [25]; and an iterative, team-based, strategic decision making approach. The method is purposefully designed to be a very comprehensive, normative tool; although its components are amenable to various types of stand-alone applications for specific analyses/decisions. The taxonomy of biases begins with the categories of *normative knowledge*, *availability*, and *individual specific* attributes into which the many biases/tendencies are grouped (see fig. 2 at end of paper). Normative knowledge involves a person's skills in combinatorics,[5] probability theory, and statistics. Research has shown that training and experience in these quantitative fields can improve one's ability to accurately determine event likelihoods. The availability category of biases includes those which result from the structure of human cognitive machinery. Individual specific biases include a particular person's values, beliefs, personality, interest, group identity, and substantive knowledge (i.e., specific domain knowledge both in general and the knowledge related to the decision to be made). This unique framework represents the author's attempt at arranging risk perception and decision making biases/tendencies into categories that are somewhat orthogonal in two major respects. First, they are proposed to be different with regard to how easily one may improve their capacities for decision making in those areas (i.e., through training and experience). Second, the first two categories (i.e., normative knowledge and availability) comprise biases that are relatively easy to "depersonalize" from a given person. That is, different individuals have varying capacities for success on normative tasks due to specific training and experience histories. Availability biases result from the fact that the decision makers of interest here are all human beings. Only the individual specific biases are intimately connected to each person's unique identity and personality (i.e., the core of the individual). Listed below are the three main categories of the NAVIS taxonomy with brief descriptions of the associated biases.

A. Normative Knowledge

These are the biases related to one's skill in combinatorics, probability theory, and statistics.

- *Insensitivity to Sample Size*–People often do not associate confidence in statistics with the size of the sample from which they are gathered [26].
- *Means and Medians Estimated Well*–People are relatively good at guessing values of central tendency [27, 28].
- *Coefficient of Variation is Noticed*–People tend to think in terms of the standard deviation divided by the mean [27, 28].
- *Variance Largely Ignored*–People do not display skill at guessing variance, or standard deviation as distinct metrics [27, 28].
- *Gambler's Fallacy*–Chance is often viewed as a self-correcting process in which a deviation in one direction induces a deviation in the opposite direction to restore a hypothesized equilibrium. In fact, deviations are not "corrected" as chance processes unfold, they are merely diluted [29].
- *Small Probabilities Overestimated*–This appears to occur at probabilities below approximately 0.1 [28, 30, 31].
- *Large Probabilities Underestimated*–This appears to occur at probabilities above approximately 0.1 with an upper bound near 0.95 [28, 30, 31].
- *Regression to the Mean*–This phenomenon involves many data generating processes both natural (e.g., heights of offspring, diameter of peas, etc.) and those related to human performance (e.g., cognitive and motor skill tests) such that measurable variables oscillate about a stable mean (or one that moves very slowly over time). First articulated by Francis Galton in the 1870s, regression to the mean is the insight that many processes do follow symmetric, generally normal distributions which oscillate about an "average ancestral type" [29]. One example comes from a discussion with experienced flight instructors who commented that praise for an exceptionally smooth landing is typically followed by a poorer landing on the subsequent try, while harsh criticism after a poor landing is usually followed by an improvement on the next try. The instructors inferred that verbal rewards are detrimental to learning, while verbal punishments are beneficial, in opposition to accepted psychological doctrine. This conclusion is patently unwarranted in light of regression to the mean. Failure to understand this phenomenon leads to overestimating the effectiveness of punishment and to underestimate the effects of reward [26].
- *Changing the Number of Options, Leads to Dramatic Changes in Probability Assignments*–Provide people with two options and probabilities may be split 50/50. Add one additional option and the breakdown of percentages for options A, B, and C will likely be closer to 10/15/75 [32].
- *Probability of Conjunctive Events is Overestimated*–These events involve series combinations and the overestimation results from anchoring toward simple individual probabilities [26, 30].
- *Probability of Disjunctive Events is Underestimated*–These events involve parallel combinations [26, 30].

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[4] The critical thinking skills are taken from the excellent compilation developed by Arnold B. Arons [20].

[5] Combinatorics is the branch of mathematics concerned with counting, arranging, and ordering (ref. 13).

B. Availability

These biases relate to the human cognitive machinery that enables perception, learning, remembering, and communication.

- *Anchoring Effect*–People are biased toward the first option or value they see or the first judgment they make [26].
- *Illusory Correlation*–This involves associating two things together without proper reflection on how weak that connection is or should be. It appears when multiple items that are easily recalled together (e.g., they may have been encoded into memory at nearly equivalent points in time) may be perceived as having a causal relationship [28, 33].
- *Recency*–Recent events are typically easier to recall [9].
- *Imaginability*–People tend to generate several instances of events from memory and evaluate the frequency of occurrence based on the ease with which these events can be constructed [9, 26].
- *Salience*–This is associated with the level of stimulation of the senses and how strong sensory input demands attention resources [34].
- *Retrievability*–The ease with which an item can be brought out of memory, or constructed using memory-type mental processes [9, 26].
- *Representativeness*–People will associate the probability of A belonging to class B, or of A being from process B by the degree of similarity between A and B [26].
- *Explicitness*–One who is able to imagine an event in detail will tend to attach greater weight to that event. Highly explicit descriptions in spoken, written, or visual form will enhance the intensity of the experience of that description, i.e., occupy more attention resources, and encourage cognitive "replaying" of the description many times; this strengthens the coding of that explicit description in long-term memory [9].
- *Framing Effect*–This phenomenon, regardless of unvarnished facts, means that word choices, image choices, and all aspects of presentation greatly influence resulting interpretations [35].

C. Individual Specific

These biases are shaped by a particular person's values, personality, interests, group identity, and substantive knowledge (i.e., specific domain knowledge, both in general and that related to the decision to be made).

- *Loss Aversion*–Many people are not highly risk-averse, they are perfectly willing to choose a gamble when they feel it is appropriate; people are loss averse. The key is how different individuals mentally account for the concept of loss [29, 36]. This concept also includes the widely discussed *dread* factor [37, 38].
- *Law of Effect*–The tendency for people to strongly avoid negative stimuli (i.e., pain, discomfort, embarrassment) and seek to increase positive stimuli, i.e., pleasure [9, 39].
- *Constantly Requiring More*–In 1738, Daniel Bernoulli offered his definition of utility; he claimed that different people will pay different amounts for desirable things, and as one accumulates more of that thing, the less they will pay to acquire more [40]. People routinely violate this definition of utility by demonstrating various tendencies toward insatiable acquisition. Recall the phrase, "keeping up with the Joneses" [29].
- *Locus of Control*–Defined by Rotter [41] as a person's perception of the control they have over job performance and work-related rewards such as pay and promotion. People identified as having an internal locus of control believe that such things are under their control. Those identified as having an external locus of control believe such things are the result of luck, chance, or whether the boss likes them–i.e., not within their control. In the NAVIS taxonomy, locus of control is generally used to refer to one's perception of control in choices involving a risk-related object.
- *Ambiguity Aversion*–People will wager on vague probabilities when they feel knowledgeable, but prefer to wager on chance when they do not feel competent in the specific decision domain [29, 42].
- *Confirmation Bias*–People tend to seek out evidence which confirms their current position and to disregard evidence that conflicts with their current position (ref. 32). In fact, several studies have specifically shown that preliminary hypotheses based on early, relatively impoverished data interfere with later interpretations of better, more abundant data [43–45].
- *Hindsight Bias*–This is the bias in which a person recalls having greater confidence in an outcome's occurrence or lack of occurrence than they had before the resulting events were known [46].

D. Critical Thinking Skills

This section mentions ten critical thinking processes or skills that are deemed foundational for competent decision making as they can mute the impact of unhelpful biases, regulate the application of one's knowledge to a decision, and guide information gathering activities. The critical thinking skills are associated with the categories of normative knowledge and individual specific attributes as shown in figure 2. These processes, briefly listed below, were articulated by the late Arnold B. Arons and can be found in his superb book *A Guide to Introductory Physics Teaching*, [25]. See refs. 23 & 25 for extended discussion and examples of the processes below.

1. Consciously raising the questions "What do we know...? How do we know...? Why do we accept or believe...? What is the evidence for...?" when studying some body of material or approaching a problem.
2. Being clearly and explicitly aware of gaps in available information. Recognizing when a conclusion is reached or a decision is made in absence of complete information and being able to tolerate the ambiguity and uncertainty. Recognizing when one is taking

something on faith without having examined the "How do we know...? Why do we believe...?" questions.
3. Discriminating between observation and inference, between established fact and subsequent conjecture.
4. Recognizing that words are symbols for ideas and not the ideas themselves. Recognizing the necessity of using only words of prior definition, rooted in shared experience, in forming a new definition and in avoiding being misled by technical jargon.
5. Probing for assumptions (particularly the implicit, unarticulated assumptions) behind a line of reasoning.
6. Drawing inferences from data, observations, or other evidence and recognizing when firm inferences cannot be drawn. This subsumes a number of processes such as elementary syllogistic reasoning (e.g., dealing with basic propositional "if...then" statements), correlational reasoning, and recognizing when relevant variables have or have not been controlled.
7. Performing hypothetico-deductive reasoning; that is, given a particular situation, applying relevant knowledge of principles and constraints and visualizing, in the abstract, the plausible outcomes that might result from various changes one can imagine to be imposed on the system.
8. Discriminating between inductive and deductive reasoning; that is, being aware when an argument is being made from the particular to the general or from the general to the particular.
9. Testing one's own line of reasoning and conclusions for internal consistency and thus developing intellectual self-reliance.
10. Developing self-consciousness concerning one's own thinking and reasoning process.

V. Application of NAVIS to Knowledge transfer

A NAVIS-based knowledge transfer approach is proposed to have relatively direct application to preparing a willing expert to be an effective teacher, preparing a willing heir apparent to be proficient learner, and helping identify promising matches of heirs apparent and experts. This can be achieved by learning about one's unique "paradigm," bias processes and critical thinking skills and applying those insights to understand and transfer knowledge to others. The NAVIS-based knowledge transfer approach can aid in the following specific ways:

- Serve as a structured basis for generating *explicit* self-inventories of biases, values, interests, beliefs, and substantive knowledge (elements of one's paradigmatic formation).
- Bias inventories could be used to identify needs for bias awareness and mitigation training, critical thinking processes training, etc. This training could help one become aware of bias and critical thinking processes and can enable explicit connections to be made between those processes and one's core individual attributes.
- Periodic inventories could help identify when an heir apparent may be ready to seek expert-level capability, or identify when one may now be an expert.
- Comparison of NAVIS inventories could aid in identifying potential matches of experts and heirs apparent
- Review of NAVIS inventories by parties in a knowledge transfer relationship could enable improved communication; e.g., reveal blind spots in knowledge bases, build common contexts for meaning, provide information for the expert to use in tailoring the manner in which they provide knowledge-rich experiences to the heir apparent, etc. This process may be particularly valuable in situations where an expert and heir apparent have widely diverse elements of paradigmatic formation between them (e.g., gender, race, ethnicity, etc.). A structured comparison/review could also be beneficial if one is managing/monitoring multiple expert relationships with a single heir apparent.

It should be noted that research is still required to fully articulate an efficient inventory/assessment and training process based upon the NAVIS approach[6]. However, reference 23 does contain many specific bias mitigation techniques and a thorough exposition of the critical thinking processes that could be readily applied to improving knowledge transfer. A NAVIS-based foundation for assessment and training would likely improve the level of sophistication/specificity for various types of knowledge transfer activities. It is further argued that integrating a technical basis founded on the NAVIS approach into a semi-formal, "lightly-managed" process can result in an effective knowledge transfer system.

VI. Conclusion

The maintenance and improvement of safety, stability, and innovation within complex organizations depends upon transmission of expertise between generations of personnel. This paper has introduced a novel approach for applying aspects of the unique, recently developed NAVIS-based decision process to knowledge transfer in complex systems. The NAVIS approach can provide a systematic basis for experts and their heirs apparent to understand each other's backgrounds and biases, and to improve methods of inquiry, observation, and inference that support effective and efficient transfer of system knowledge.

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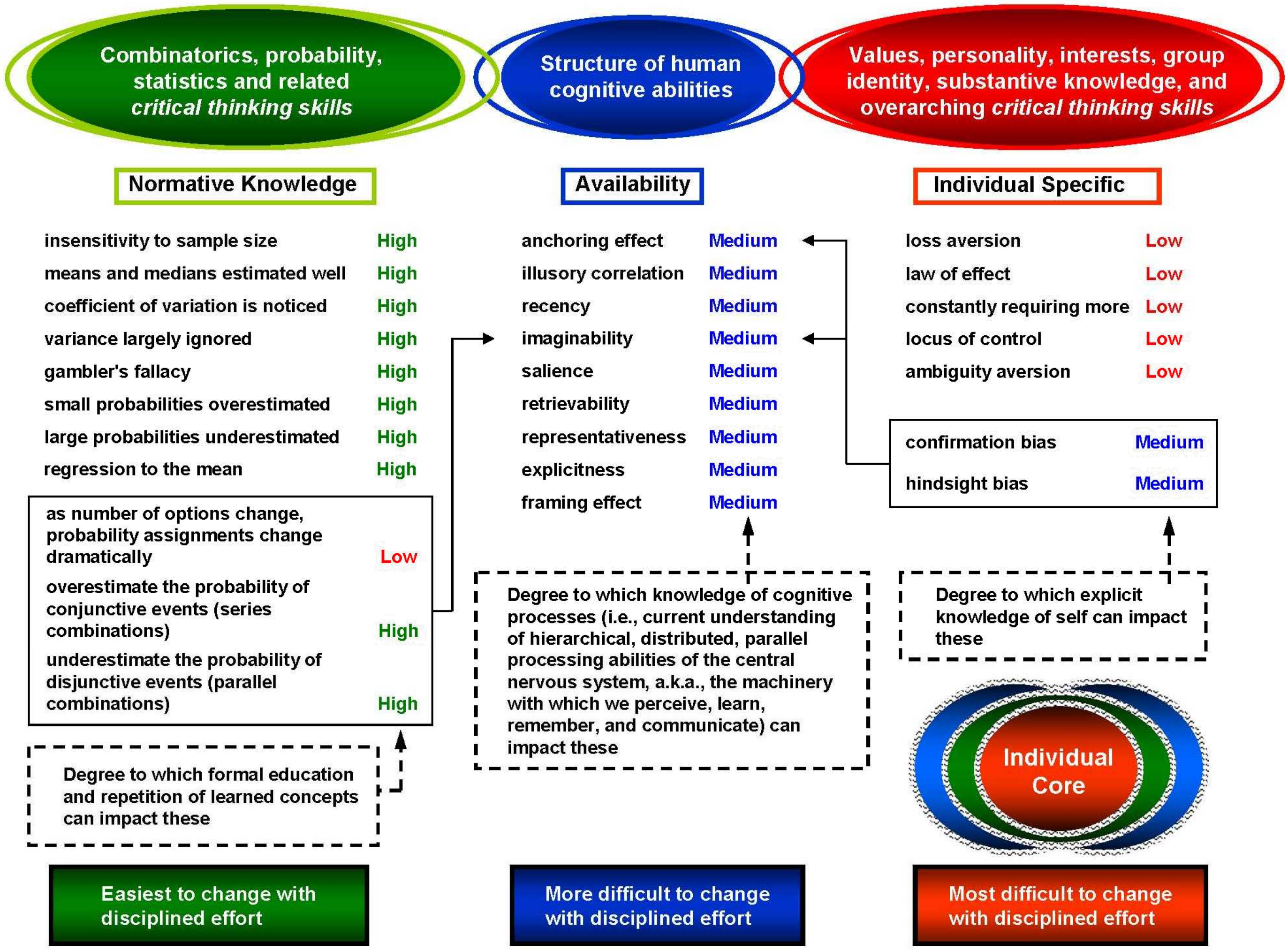

Figure 2. The unique NAVIS-based framework in which one may understand decision making biases/tendencies that researchers have identified. The unique aspects *introduced by the author*, following an extensive review of relevant data, include: (1) the three categories into which previously investigated biases are ordered, (2) strong interdependencies hypothesized between biases as indicated by solid lines with arrows, and (3) the degree to which biases may be mitigated via disciplined efforts by a specific decision maker as indicated by dashed lines with arrows; high, medium, and low ratings[7]; and the green, blue, and red boxed items. Note also the prominence of critical thinking skills (discussed in ref. 4) in the normative knowledge and individual specific category descriptions. The nested ellipses in the lower right corner represent the way in which, over time, normative and availability biases are important filters that mediate what becomes part of an individual's core values, beliefs, etc [47, 48].

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[7] The high, medium, and low ratings should be interpreted as comparative measurements on an *ordinal scale*, i.e., these are high-to-low assessments without specific delineation of the separating intervals. Further research is required to locate the biases on an *interval* or *ratio scale*. See Stevens [47] and Conover [48] for a thorough discussion of scales of measurement.