ABSTRACT
The metaphysical assumptions of cognitive science are explored with the goal to develop a problem-centered science relevant to the design and engineering of effective products and technologies. Radical Empiricism is suggested as an ontological foundation for pursuing this goal. This ontology poses a single reality where mind and matter come together to shape experience. Peirce’s triadic semiotic system is suggested as a framework for parsing this reality in ways that reveal important aspects of the dynamics of communication and control. Rasmussen’s three analytic frames of the 1) Abstraction Hierarchy, 2) the Decision Ladder, and 3) Ecological Interface Design are suggested as important tools for achieving insight into the dynamics of this triadic semiotic system. These ideas are offered as a challenge to both scientists and designers to reassess the basic assumptions that guide their work. The hope is that by facing these challenges we can take the first tentative steps toward a coherent science of what matters.

Keywords
Ontology, Radical Empiricism, Semiotics, Cognitive Systems Engineering, Abstraction Hierarchy, Decision Ladder, Ecological Interface Design

ACM Classification Keywords
H. Information Systems; H.1 Models and Principles; H.1.2 User/Machine Systems

1. INTRODUCTION
What must be admitted is that the definite images of traditional psychology form but the very smallest part of our minds as they actually live [14]

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ECCE 2009, September 30 – October 2, 2009, Helsinki, Finland.
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This quote from James remains as true today as when it was first published more than 100 years ago. Despite enormous advances in our understanding of the biological mechanisms of the brain and nervous system and despite countless volumes of empirical research on human performance and human information processing, there still appears to be a huge gap between the science of cognitive psychology and the experiences of every day life. Thus, those who look to cognitive science for inspiration for designing products and technologies that enhance the qualities of every day life and work are generally disappointed.

Over the years, there have been attempts to bridge the gap between cognitive science and work experience through an expanded portfolio of empirical research that recognizes the value of naturalistic field studies [13, 17] and design driven research [18]. And there is some evidence that people are recognizing and escaping from the false dichotomy of basic versus applied research to appreciate the value of a problem-centered science in the spirit of Pasteur [31]. Yet, despite these changes in attitude toward research, the gap and the associated incoherencies [21] remain.

Thus, I have come to the conclusion that the only way to close the gap is to return to first principles. To reconsider the basic ontological assumptions that set the foundation for cognitive science and, in fact, for science in general. In this paper, I would like to direct attention to an alternative ontology suggested by James [15], which has been largely ignored, but which I believe can help to close the gap and reduce the incoherence between cognitive science and cognitive engineering. From this foundation I would like to reconsider basic principles of semiotics, communication, and control [30,39] and the overarching framework of Cognitive Systems Engineering articulated by Rasmussen [25] to see if it might be possible to assemble a more coherent story that better captures the every day experiences of life.

2. RADICAL EMPIRICISM
Metaphysics means only an unusually obstinate attempt to think clearly and consistently... as soon as one's purpose is the attainment of the maximum of possible insight into the world as a whole, the metaphysical puzzles become the most urgent of all. [14]

Most books on psychology and/or cognitive science begin with some consideration of the ontological options available...
as foundations from which to launch scientific explorations of human experience. Typically, three options are explored: Idealism, Materialism, and Dualism. Of these three, Idealism, the assumption that there is no basis for reality outside of the mind, is generally dismissed as antithetical to science. The other two are both offered as credible starting positions.

Materialism chooses the world of matter as the basis for all experience. This view dismisses ‘mind’ as an epiphenomenon whose ultimate ‘causes’ are based in the material substrates of biology, chemistry, and ultimately physics. I get a strong sense that Materialism is the preferred ontological position of many scientists, including most cognitive scientists (many of who now prefer the label neuroscientist). The problem with this approach is that it invites a reductionist approach that leads the scientist further and further into the microstructure of brains, and further from the macro-level experiences of most interest to the designer and the cognitive engineer. Despite the attractiveness of Materialism for many scientists, most keep an open mind to the possibility of Dualism. The Dualist ontology considers the possibility of two kinds of reality — one of mind and one of matter. This ontology is driven by observations of aspects of human experience that can’t be easily explained using the formalisms of biology or chemistry. The term ‘emergent’ is often used to characterize these properties. Thus, the Dualist ontology suggests that there may be emergent properties and principles of mind that cannot be completely described in terms of or reduced to simple functions of matter. I believe that it is this plausibility of a separate reality of mind that attracts many to the social sciences. And in fact, I believe that despite a preference for Materialism, most Cognitive Science and in fact most of Western thought is based at least implicitly in a Dualistic ontology. Further, I would argue that this Dualism is a primary source of the incoherence and the ultimate gap that separates cognitive science from both the everyday experiences of life and from productive generalizations in design and engineering.

It is important to appreciate that the philosophical arguments that have dominated cognitive science over the last half a century have not been about ontology, but about epistemology. While the dualism of mind and matter has been generally accepted, there have been violent arguments about how these separate realities might interact — that is how the reality of mind can become aligned with or come to know the reality of matter. This is the problem of epistemology and the dominant debate has been between the Constructivists [e.g., 12] and the Realists [e.g., 9, 10]. The Realists argue that the reality of matter is directly and completely specified to the mind through constraints on perception and action. This perspective is typically associated with ecological approaches to psychology. The Constructivists, on the other hand, argue that the reality of matter is incompletely specified by the constraints on perception and action. Thus, this epistemological position argues that complete knowledge of the reality of matter can only be constructed by the mind from the inherently ambiguous cues available to perception and action using the tools of logic and inference. This perspective is typically associated with information processing approaches to psychology.

For most of my career, I have lived under the illusion that the three ontological positions outlined above were the only plausible options. And of these options, I found the Dualist ontology with a Realist epistemology the most comfortable stance for exploring problems like the visual control of locomotion [7, 8], graphical interface design [1, 2], naturalistic decision making [4], decision-aiding [3], and general issues associated with performance of human-machine systems [5]. Recently, however, I have discovered an alternative ontology that I find far more satisfying. This is James’ [15] Radical Empiricism.

In order to appreciate this alternative ontology, it may help to first consider why the ultimate conclusion of one of the recognized ‘fathers’ of psychology has been completely ignored by modern cognitive science. Modern science tends to be dominated by an “either/or” form of reasoning [28]. In this context, a phenomenon has to be either mind or matter. It can’t be both. Thus, we are left with the option of dismissing one or the other as an epiphenomenon (idealism or materialism) or we have to include two exclusive sets or boxes one for things that are really and exclusively mind and the other for those things that are really and exclusively matter (dualism).

Radical Empiricism has been ignored because it does not fit this ‘either/or’ form of reasoning. James came to the conclusion that human experience is a single reality that is both mind (mental, subjective) and matter (material, objective). James concluded that the distinction or dualism between subjective and objective did not reflect distinct realities, but rather, reflected the different perspectives of the scientist. We call objective those properties of experience that tend to be invariant across wide changes in perspective and we call subjective those properties of experience that tend to vary with changing perspectives (or observers if you like). But these are not two distinct realities, but rather facets of or perspectives on a single reality of experience. Thus, Radical Empiricism was James’ monistic alternative to the dualistic view that still dominates Western thought.

Since James, others have reached a similar conclusion. Most notably, Pirsig [23, 24] has introduced the term ‘quality’ to characterize the ultimate reality of experience. This quality is neither subjective nor objective, but is both! The biologist Rayner [28] suggests an inclusionary approach based on a both/and logic with the specific goal of integrating across the many dichotomies created by either/or thinking (e.g., subjective versus objective; aesthetics versus pragmatics; emotionality versus rationality). Also, the physicist Wheeler’s [5, 38] metaphor of the surprise version of the twenty question game, illustrates an inference from quantum physics that suggests that the idea of an external nature, somewhere ‘out there’ apart from the observer, waiting to be discovered is an illusion. Nature is a single reality that emerges from the interactions of constraints some of which have been classically attributed to mind and other that have been attributed to matter.

Note that the choice of an ontological stance is ‘meta’ science. It is not right or wrong; true or false. One choice may be more or less useful for some specific purposes or it may be that one choice leads to more elegant and aesthetical stories. I suggest that Radical Empiricism is a choice that should be considered. And I want to offer the hypothesis that a shift to the ontological position of Radical Empiricism or to a Metaphysics of Quality may be a good first step toward a
coherent science of what matters – a first step to bridging the gap between cognitive science and cognitive engineering.

3. SEMIOTICS, COMMUNICATION, AND CONTROL

Every model is ultimately the expression of one thing we think we hope to understand in terms of another we think we do understand [36].

Although our ontology takes a holistic attitude toward mind and matter, in the face of complexity we must ultimately become reductionists. That is, we need to find a way to parse the complexity into “chunks” or “long threads” that can ultimately be woven into a coherent narrative. So, following the quote above, the thing that we hope to understand is the dynamics of experience, which according to the above ontological position, is both mind (mental) and matter (physical). So the next decision is to choose from the things we think we do understand that thing that will provide the best ‘image’ or ‘language’ for building a coherent model or narrative.

A good place to start is semiotics, where two perspectives have competed for dominance. The first approach, which set the stage for modern linguistics and cognitive science, is attributed to Saussure. This approach parses the semiotic problem into two components that reflect the signal (e.g., the symptoms of a patient) and the interpretation (e.g., the diagnosis of the physician). This dyadic approach tends to frame semiotics as a problem of mind, of interpretation, with little consideration for the ecology that is typically the source of the signals (e.g., the actual health of the patient). Peirce [20], a contemporary and colleague of James, offered an alternative perspective. He suggested a triadic view of semiotics that includes the source of the signals (the situation or ecology), the signals (the representation or interface), and the interpreter (awareness or belief) as illustrated in Figure 1.

It is important to note that the three elements identified by Peirce are components of a single semiotic system. Thus, these are three facets of a single reality or a single dynamic.

Figure 1. Alternative images of the semiotic system.

In describing the dynamics of experience within this semiotic system, Peirce introduced the logic of hypothesis or abduction as an alternative to more classical normative models of rationality (i.e., deduction and induction). Figure 2 illustrates this dynamic, which can best be described in the language of communication and control systems (e.g., Cybernetics, Information Theory, Control Theory, General Systems Theory, and Dynamical Systems Theory) that began developing some 50 years later as scientists and engineers began to explore the design of communication, control, and ultimately computing technologies.

Figure 2. Dynamic coupling of perception (observation) and action (control).

The labels on the links in Figure 2 are taken from the language of communication and control systems. Note that the flow around this system can be viewed from the perspective of either a controller (action) or observer (perception) metaphor, and in fact both dynamics are operating simultaneously in a cognitive system (i.e., perception and action are coupled). The first terms in the paired labels of three of the links are associated with the servomechanism metaphor. With this metaphor intentions stimulate performatory actions, which in turn have consequences that can be fed back and compared with the intentions. The differences are termed ‘errors’ and the servomechanism is typically designed to reduce these errors. That is, to stabilize around a steady state where the consequences match the intentions (i.e., error is zero).

The second set from the paired terms in Figure 2 is associated with the ideal observer metaphor. With this metaphor, expectations (or hypothesis) lead to exploratory actions or tests, which in turn have consequences that are fed back and compared with expectations. The differences are termed ‘surprises’ and the observer is typically designed to reduce surprise. That is it is designed to stabilize around a steady state where the expectations match the consequences (i.e., surprise goes to zero).

The language of the observer metaphor matches best with the language Peirce used to describe abduction. However, it is clear that Peirce, James and other Pragmatists such as Dewey recognized the intimate connection between control and observation. From the pragmatic perspective, the ultimate test of a hypothesis is whether it leads to successful control – that is, whether it leads to satisfactory results relative to the motivating intentions.

In engineered systems, much of the observer problem (e.g., identifying the state variables) is solved, a priori, by the control system designer, who then designs the control system around the variables that have been identified. However, biological systems must simultaneously solve both the control problem and the observer problem. For example, the novice driver must discover the appropriate variables to attend to and the appropriate gains for linking perception and action while driving (e.g., how hard to press the brakes in order to stop at a specific point). This process of learning by
doings often involves active hypotheses (tapping on the brakes) and adjustment of expectations based on the results of the active ‘tests’ of hypotheses. Hypotheses that lead to successful actions (e.g., comfortable braking) are retained. Hypotheses that lead to surprise (e.g., sudden jerks) are revised. This can be contrasted with inductive and deductive systems of rationality where ‘truth’ is evaluated relative to the forms of the arguments, independent of any actual correspondence with the ecology. With an abductive logic, there is no absolute ‘truth,’ there is simply the degree to which the action or belief leads to successful action (i.e., satisfies the intention).

Systems that are engineered to simultaneously solve the control and observation problems are called adaptive control systems. And natural systems where adaptive control processes are observed are typically called ‘self-organizing.’ The phase shifts often observed in these systems (e.g., gait transitions in animal locomotion) typically reflect how competing tensions between the observation and control demands are resolved by shifting from one locally stable organization to another.

Thus, Peirce’s triadic semiotic model provides a logical partitioning of the reality of experience, and the languages of communication and control theories provided a theoretical calculus for describing the dynamic interactions among these elements. Together these set the foundations for Rasmussen’s approach to Cognitive Systems Engineering.

4. COGNITIVE SYSTEMS ENGINEERING

The central issue is to consider the functional abstraction underlying control theory and to understand the implications of different control strategies on system behavior and design requirements. [25].

In approaching the problem of safety in the operation of nuclear power plants, Rasmussen realized that in order to improve the stability of control systems such as a nuclear power plant, it was essential to address the three elements in Peirce’s semiotic system: 1) to understand the constraints of the ecology – the work domain of nuclear power; 2) to understand the constraints on human awareness – the decision strategies of the plant operators; and 3) to understand the constraints on the representations – the design of the human-machine interfaces.

4.1 Ecology - Abstraction Hierarchy

Objects in the environment in fact only exist isolated from the background in the mind of a human, and the properties they are allocated depend on the actual intentions [25].

As we unpack the triadic semiotic system, it is important to keep in mind, as implied in this quote from Rasmussen, that the three facets are different perspectives on a single, unitary ontology or system. Thus, it is important to understand that the ‘ecology’ is not a distinct objective environment. It is perhaps more appropriate to think of this ecology as an Umwelt [35] or problem space [19]. As such, its properties are best conceived as affordances [9,10] that reflect the functional constraints shaping the field of possibilities and the consequences for good or ill associated with the different capabilities and intentions.

Significant states within this problem space are the goal states corresponding with design and operator intentions. Significant dimensions of this space should reflect distinctive attributes of the process needed to characterize the goals and changes associated with motion through the state space with respect to these goals (e.g., masses, pressures, temperatures, etc. of the thermodynamic processes being controlled relative to process goals). For example, these would be the dimensions that might be used to characterize ‘error’ with regard to intentions and ‘surprise’ with regard to expectations in Figure 2.

In addition to the states of the problem space, it will also be important to consider the ‘operators’ [19] or constraints on action that determine what motions within the state space are possible and/or desirable in terms of associated costs (e.g., effort). This allows the identification of significant paths and functions within the problem space that correspond with physical laws and limits (e.g., mass and energy balances or maximum pressures) and functional values and regulatory constraints (e.g., optimal paths such as the minimum time path from an initial state to a goal state). In control theoretic terms the operators reflect the control interface to the plant dynamic and the functional values and regulatory constraints reflect properties of a ‘cost functional’ as required to formulate an optimal control model.

The essential challenge in specifying the ecology is to find a way to represent the ‘deep structure’ of the problem space. Rasmussen [25] proposed that this problem space be specified in terms of “goal-means or means-ends relationships in a functional abstraction hierarchy” (p. 14). He proposed a nested abstraction hierarchy of five levels with the top or dominant category reflecting the functional purpose of the system. Within this broad set of constraints, lower levels add more detailed constraints associated with physical laws and values; general functional organizations; types of physical components; and detailed physical arrangements and forms.

The Abstraction Hierarchy has sometimes been represented as a triangle with the Functional Purpose as the apex and the Physical Form level at the base. The pyramid reflects the increasing number of details or degrees of freedom at the lower levels due to the finer discriminations. However, I prefer to visualize the abstraction hierarchy as a categorical nesting, where the higher levels of abstraction set a fairly broad level of categories that become a context for evaluating lower levels, where finer distinctions are introduced [6].

Thus, for example the physical laws, the general functions, the physical components, and the physical forms can all be classified with respect to their role as means for accomplishing specific purposes. Likewise, the general functional organization can be understood in the context of the physical laws that govern the process; the physical components can be understood relative to their roles in the general functional organization; and the physical details can be understood in the context of the physical components employed. In this way, higher levels of abstraction provide semantic categories for organizing the details at lower levels of abstraction. And the categories don’t simply propagate from one level to the next, but they propagate all the way from top to bottom – with distinctions at the highest level suggesting important semantic distinctions for all levels below.
Details about the different levels and the relations across levels can be found elsewhere [25, 33]. However, for this paper we want to focus on one attribute of the Abstraction Hierarchy that can be puzzling, when viewed through the lens of the more conventional dualistic ontology of mind and matter. How is it that ‘goals and intentions’ can dominate physical laws? Conventional wisdom would suggest that intentions are dominated by or are subservient to the physical laws (Materialism) or are independent from them (Dualism). We can’t choose to violate the laws of motion, or the laws of thermodynamics. In the conventional view of nature, the physical dimensions associated with physical laws are taken as fundamental properties of reality and the goals and preferences of humans tend to be treated as either derivative or independent properties.

However, in a monistic ontology of experience as reflected in James’ Radical Empiricism or Pirsig’s Metaphysics of Quality, the quality of experience is fundamental and the properties used to characterize the patterns of conventional physical laws are considered derivative properties. This is important to understand. The patterns of the physical laws can be described using extrinsic, observer independent dimensions such as Newton’s dimensions of space and time. However, the meaning or significance of those patterns CANNOT be specified without reference to a goal or value system. Distance can be specified independent of any observer (or actor). But properties like too far, or too close, or close enough cannot be specified independent of some value system (e.g., the potential damage from a collision) and are typically only meaningful relative to some action capability (e.g., quality of brakes). I argue that properties such as too close (e.g., the imminence of collision) are the most fundamental or concrete properties of experience, and that the distance in terms of meters is a useful, but nevertheless a semantically arbitrary abstraction.

In the ontology of experience that we are proposing meaning is fundamental! Thus, the properties most important to the quality of experience are the most basic or the most dominant. And all other dimensions can only be understood in relation to those properties. Thus, although there may be room for much discussion about the best way to carve up the ecology into functional levels of abstraction, we believe that Rasmussen’s choice to make the functional purposes the dominant or most basic level of description is exactly the right choice! Meaning can only be understood in the context of intentions and values.

Thus, we would amplify the opening quote from Rasmussen to leave out his qualifier (‘in the mind of the human’) to state that the real (i.e., ontologically most basic) properties of the environment can only be defined in relation to the intentions and values of the semiotic system (i.e., human, animal, agent, or organization being studied)?

Note that to illustrate the different layers of abstraction we have used examples from technical systems (e.g., nuclear process control) to reflect the origins of Rasmussen’s discoveries. However, I believe that the need to characterize the ecology generalizes to all types of experiential contexts, from highly technical (e.g., aviation and process control), to more social/biological (e.g., medical decision-making), and to more personal and idiosyncratic (e.g., libraries and consumer products). There can, however, be important differences in the nature of the dominant functional goals that shape performance. For example, Vicente [33] uses the distinction correspondence –driven versus coherence-driven to distinguish domains such as nuclear power from domains like libraries. In technical and safety critical systems the functional goals and constraints tend to be far more clearly specified and rationally justified. As we move into socio-biological systems and consumer products the functional goals and constraints can be increasingly ambiguous/tacit, diverse, and idiosyncratic; and far more tightly linked with emotional, spiritual, and aesthetic aspects of experience. However, I would argue that at the non-technical end of this spectrum, the ecological constraints remain an important and significant facet shaping the dynamics of the semiotic system. Such constraints are no less real and no less important, though they may be far more difficult for the scientist to discover and specify.

4.2 Awareness – Decision Ladder

... it is very important to analyze the subjective preferences and performance criteria that guide an operator’s choice of strategy in a specific situation. Unless these criteria are known, it will not be possible to predict the strategy that an operator will choose, faced with a specific interface design [p. 23].

Rasmussen’s view of the awareness facet of the semiotic system was strongly influenced by his early work on electronic trouble-shooting [26]. Observations of the diagnostic processes of electronic technicians showed that the search for faults was often not consistent with conventionally rational hypothetical-deductive processes. Rather, the search process tended to be impulsive and highly context dependent.

Often, when working on electronic equipment in the shop, the search involved high numbers of observations using simple procedures, rather than more normatively efficient processes guided by studying the functioning of the system. On the other hand, when asked to evaluate a safety critical system in the experimental reactor, where a mistake could be embarrassing and expensive, more formal analytic thinking was employed. Although, the observed search processes were often not optimal in terms of the number of tests, they did tend to work and they tended to minimize the cognitive demands. That is, they tended to rely on information that was directly accessible in perception-action loops, rather than to rely on more abstract forms of reasoning. In other words, the rationale of the search process tended to be more abductive and pragmatic.

The term that is typically used to characterize the pragmatic reasoning processes that Rasmussen and many others have observed is heuristic decision-making [11, 16, 32]. The gist of all of these observations is that humans take short cuts in the sense that they use search strategies that tend to reduce cognitive demands and generally work. However, these shortcuts typically violate general prescriptions of normative logical and economic models of rationality.

When compared and evaluated relative to the prescriptions of normative models of rationality the heuristics are often characterized as biases and these processes are typically attributed to limitations on cognitive abilities and resources. However, this perspective fails to appreciate that when grounded in the constraints of problem spaces, these short cuts can be the basis for smart, fast, and frugal decision-making [11, 32]. Rather than being symptoms of weakness,
the heuristics can reflect humans’ ability to leverage experience (i.e., expertise) in order to think productively about difficult problems [37]. Rather than relying on global context independent forms of reasoning, people tend to utilize problem-solving processes that leverage experience with local ecological constraints. This is postulated as the explanation why experts are able to 'see' good alternatives as one of the first options considered [17].

To illustrate the short cuts that expert problem solvers employed to solve complex problems, Rasmussen [25] introduced the Decision Ladder. Figure 3 shows a cartoon version of the Decision Ladder illustrating that there is more than one way to solve a problem. With this representation the dark outer arrows illustrate the more formal, cognitively intensive path from a problem to a solution, while the inner paths depict short cuts for connecting perception and action. These shortcuts often significantly reduce the demands on formal reasoning (i.e., what Rasmussen termed Knowledge-based reasoning).

Rasmussen distinguished two types of short cuts. Rule-based reasoning reflects short cuts based on explicit patterns or consistencies in the work domain. These short cuts typically reflect standard operating procedures or other learned rules that generally can be easily verbalized by the operators and that reflect typical solutions to common or routine situations.

The second form of short cut is termed Skill-based. Skill-based processes are based on invariant patterns that directly specify the links between perception, action, and consequences. Examples of such patterns are the optical invariants associated with control of locomotion [7, 8]. The skill-based short cuts typically result in automatic forms of behavior where the human is only tacitly aware of the patterns that are being leveraged. Thus, it is typically difficult for people to verbalize the basis for directly linking perception and action at this level.

Again, it is important to realize that the patterns that are the scaffold for both rule- and skill-based behaviors are not arbitrary, they are the products of experience and they typically reflect not only the constraints on awareness, but also the constraints within the ecology. The natural evolution of the abductive, dynamical process illustrated in Figure 2 is toward a match between the constraints or structure in the ecology and the constraints or structure of awareness. The more experience that a person has in a specific ecology or work domain the less the rule-based and skill-based short cuts will appear as biases (i.e., overgeneralizations from other contexts), and the more they will appear as resonance with the deep structure of the problem space (i.e., ecologically rational solutions)! This process fits well with the abductive form of rationality that Peirce hypothesized as the basis for human reasoning.

This progression from a loose association between the constraints on awareness and the constraints in the problem ecology to increasingly tighter couplings is the development of expertise, skill, or more simply learning. In this context, the heuristics are not symptoms of information limitations, but a natural product of experience. They reflect an evolution from cognitively demanding, normative, formally rational rote processes toward more efficient, recognition-primed [17] ecologically grounded [11, 32], smart cognitive mechanisms [29]. Rasmussen often commented how often reasoning processes that appeared irrational when viewed from outside the context of a specific domain, would appear as elegant and efficient, once one came to appreciate how the deep structure of the problem domain was being leveraged.

### 4.3 Interface – Ecological Interface

... the goal is to make the invisible, abstract properties of the process (those that should be taken into account for deep control of the process) visible to the operator [27].

Research on problem solving by Gestalt Psychologists [e.g., 37] clearly demonstrates the impact that alternative representations can have on problem solving. A shift in the form of the representation can be the difference between confusion/uncertainty and clarity/insight. With their seminal papers on Ecological Interface Design (EID), Rasmussen and Vicente [27, 34] framed the challenge of interface design around these insights. The key challenge was to go beyond the observations of the Gestalt Psychologists to provide a prescriptive framework for designing effective representations as interfaces to complex work domains.

I believe Rasmussen and Vicente’s answer to this challenge can be best appreciated from within the triadic semiotic system. The focus of EID is to specify the structure (e.g., constraints) of the work ecology as clearly as possible. One way to do this is to create a geometric representation that parallels the nested structure revealed by the Abstraction Hierarchy. That is, global properties (e.g., symmetries) of the interface should reflect the functional/intentional context. Relations within these global patterns should reflect the physical laws and organizational constraints on control (e.g., mass and energy balances; feedback relations). And finally, elements within the display should represent the physical details of the process (e.g., relative positions of valves and other components; values of specific variables such as flow rates, volumes, pressures, and temperatures).

Note that once again, mind and matter are intimately related in the interface. The prescriptions of EID will be relevant whether the interface refers to an external display (e.g., engineered interface in a Nuclear Control Room) or to an internal representation (e.g., the learned conceptual visualization of a physics expert). To be effective, the representation must correspond with structure in the functional work ecology and it must be ‘as clear as possible.’ That is, it must be presented in a way that matches the perceptual abilities, the intentions, and the expectations of the

humans. The image of the Decision Ladder provides some guidance for the subjective side of this relation. In addition to matching the constraints in the ecology, the representation should also leverage the heuristics as reflected in a decision ladder, in order to support rule- and skill-based interactions. This can reduce the demands on more formal knowledge-based forms of reasoning, which might be freed to engage in more strategic planning and anticipation. In complex domains, consideration must also be given to supporting knowledge-based reasoning as well. It is in these domains where strategic and anticipatory awareness will have the highest payoff and where the inevitable challenge of unanticipated variability will require more formal analytic thinking.

However, I would argue that it is not sufficient to ‘match’ any heuristics that humans bring to the work situation. Rather, the ultimate goal should be to shape the heuristics of the humans. When we view the semiotic system as a resilient, adaptive, self-organizing control system – the goal is for the system to evolve in ways that drive both error and surprise as low as possible. That is, the intentions and expectations need to become increasingly congruent with the consequences. In other words, the heuristics that shape awareness should ultimately match the deep structure of the work ecology. Thus, an ecological interface can play an important role in the education of attention. Helping to make functionally significant structure in the ecology salient, so that it can shape the intentions, expectations, and heuristics such that awareness becomes well tuned to the functional demands of the ecology.

This approach comes into stark contrast with much conventional work on interface design and HCI framed in terms of the dyadic semiotic system. The prescription motivating the conventional work is often to match the operator’s mental model, with little consideration to how that mental model corresponds with the deep structure of the work ecology (which sits on the other side of the interface - outside the dyadic semiotic system). Returning to the medical context of semiotics, the goal of these conventional approaches is to match the symptoms with the physician’s conceptual model of disease, assuming that the model is valid. The validity of the model, itself, falls outside the dyadic semiotic system. For the EID approach, the ecological foundations of the conceptual model are included as part of the semiotic problem. Thus, interface designers are invited to work with the domain experts to explore and test alternative models of disease, so that testing the ecological validity of the representation (at least in a pragmatic sense) becomes an essential component of the design challenge.

Thus, the representation can be the hinge that determines whether the dynamics of experience converge to a stable solution where consequences align well with intentions and expectations; or whether the dynamic diverges in ways that lead to increasing confusion and surprise and ultimately to catastrophic levels of error.

5. SUMMARY

A tale told by an idiot, full of sound and fury, signifying nothing.” Macbeth Quote (Act V, Scene V)

For most of my career, I have felt a deep degree of impatience for the philosophical debates that to me often seemed to be full of sound and fury and of no practical value. This led me to pursue what I considered to be the most concrete, the most practical aspects of human performance as the focus for my research. And this ultimately led me to the field of engineering psychology and the work of Jens Rasmussen. However, I am just beginning to appreciate the wisdom of Rasmussen’s insights. A dramatic step forward for me was the discovery of Peirce’s semiotics and abduction, and then connecting the dots with the underlying metaphysics of James’ Radical Empiricism [15], Pirsig’s Metaphysics of Quality [23, 24] and Rayner’s concept of Inclusionality [28].

But ultimately, the discoveries that helped me to connect the dots between the philosophy, the science, and the design implications did not come from the literature, but from my own experiences of everyday life and from the opportunity to explore the experiences of drivers, pilots, surgeons, emergency room physicians, emergency medical and military commanders. I think this is the challenge that unites James, Peirce, Pirsig, and Rasmussen – a focus on the phenomenon of human performance as it is lived, rather than how it might be simulated in a mechanistic, logical machine. This leads to an appreciation of human cognition as an exquisite ability to successfully adapt to the constraints of complex ecologies, rather than as a collection of general, limited information processing mechanisms.

Appreciation of this exquisite ability, however, is difficult to achieve if the research frame does not include the ecological constraints as an integral component of the system of interest (i.e., the semiotic system). On the other hand, it can be impossible to see anything if one tries to see everything. The challenge is to reconcile an expansive ontology that spans both mind and matter, with the practical need to reduce or parse the phenomenon into manageable chunks. In my view, James and Pirsig provide the best guesses about such an expansive ontology. Peirce and Rasmussen provide the best guesses about how to parse that ontology into chunks consistent with the intuitions of communication and control theory (and more broadly dynamical systems theory). And, further, I suggest that these different perspectives fit together in a rather elegant way that might lead toward a problem-centered science motivated by a desire for both theoretical coherence and practical utility.

In sum, the hypothesis of this paper is that the vast gap between cognitive science and cognitive engineering and design (that we all struggle with) is a symptom of a dualistic ontology that places the constraints on products and technologies in one reality and the constraints on cognition (and emotion) in another. I suggest that this is a symptom of an exclusive-or (either/or) form of reasoning that is the source for many false dichotomies (e.g., subjective vs. objective; aesthetics vs. pragmatics; emotional vs. rational; mind vs. matter) that make it difficult to frame a coherent story about the dynamics of human experience. The dichotomy of most concern for this paper is the one between basic and applied science. Unfortunately many of our scientific research paradigms do not represent the practical constraints of natural environments and the resulting theories greatly underestimate the resilience of natural systems. When psychology frames its research questions around abstract general information processing mechanisms, without due consideration for the ecological problems of natural environments, it leads to a basic science that has little to offer and little to learn from the engineering and design community.
Ironically, neither the basic science community (with its emphasis on empirical methods and strong inference based on domino models of causality) nor the design community (with its emphasis on practical innovation and economic success) has much patience for metaphysics, which is typically dismissed as of academic interest only. But this is where both I and James most disagree with the conventional wisdom, we have both come to believe that the only way to close the gap between science and design, the only way to resolve the incoherencies in our theories is to go back to first principles and to reconsider the fundamental assumptions we have made about nature and reality; the fundamental assumptions about mind and matter; the fundamental assumptions about what matters. At the end of the day I believe that the quality of our science, the quality of our products, and ultimately the quality of our lives is a joint function of both mind and matter!

Finally, let me make it absolutely clear that Radical Empiricism, Peirce’s triadic image of the semiotic system, and Rasmussen’s formalisms (Abstraction Hierarchy, Decision Ladder, and EID) are not the ends of the search for what matters. Rather, I suggest only that they are a good place to start the search and may provide a tentative direction for productive exploration in our joint search to discover what matters!

6. ACKNOWLEDGMENTS
I first want to give special thanks to the conference organizers for their kind invitation to present this keynote address. This provided a challenge for me to attempt to connect a wide range of influences that have shaped my address. This provided a challenge for me to attempt to connect a wide range of influences that have shaped my assumptions about what matters. At the end of the day I believe that the quality of our science, the quality of our products, and ultimately the quality of our lives is a joint function of both mind and matter!

7. REFERENCES


