Developing Rational-Empirical Views of Intelligent Adaptive Behavior

Gary Berg-Cross, Knowledge Strategies
Potomac, Maryland 20854, USA

Abstract

A developmental perspective is useful to understand how intelligent human behavior comes to be performed because it combines insight of evolutionary factors that enable dynamic genetic-environmental interactions within individual humans. Such developmental adaptations may now be studied experimentally using developmental and epigenetic robots. Resulting insights is a useful step toward more complete, valid understanding of intelligent behavior, its adaptive nature and it structural roots. Taken together these broaden the concept of "engineering mind" to include the larger concept of "development". This paper overviews recent work of evolutionary and developmental psychology, epigenetic robots and cognitive science. A synthesis of these suggest means by which the fluid nature of adaptive knowledge arises developmentally within a heterogeneous architecture adapted for adaptation itself as part of a rational-empirical process. At this top-level of intelligence, situation-specific adaptive functions are processed using a dynamic mix of belief-based, rational-empirical cognitive processes and socialized methods adjusted within human cultures. General research goals of such an integrated, consilient view of intelligence are outlined for future research.

1. Introduction

In "The Engineering of Mind" (Albus, 1999) cited a range of research which, taken together, provided new insights into the nature of mind. These included work on learning & language, image understanding, rule based reasoning & planning, advances in real-time sensory processing using world modeling and data fusion, intelligent hierarchical controls, and effective use of parallel processing on focused attention as well as general progress in the cognitive/ neurosciences. Albus (1999) argued that what was lacking was synthesis of a "general theoretical model which ties all these separate areas into a unified framework that includes both biological and machine embodiments of the components of mind". Building on earlier work (Albus 1991) structured a reference model using widely discussed concepts of intelligence and mind – controlled behavior generation, via underlying knowledge bases and world models choosing goal appropriate action in uncertain environments. Berg-Cross (2002, 2003) noted that much of this underlying reference model represents a mid-level, plan based on a symbolic information processing view of intelligence which is amenable to hierarchical modeling and engineering, but which may not capture the full complexity of intelligence. For one thing, Albus reference architecture of mind is organized around a small number of general purpose mechanisms that are assumed to be content-independent. The functional modules have a variety of names such as "learning," "induction," "cognition," "world modeling," "or "sensor fusion". In Albus's information processing views these are organized around the world model, which combines with the other functional mechanisms to explain how an agent acquires a language or learns to navigate city driving.

Another way to view such phenomena is as a result of a rational process. Anderson (1990), for example, processes identifies 6 steps developing a theory of rational agents:

(1) Goals: specify precisely the goals of the cognitive system.
(2) Environment: develop a formal model of the environment to which the system is adapted.
(3) Computational limitations: make minimal assumptions about computational limitations.
(4) Optimization: derive the optimal behavior function, given 1–3 above.
(5) Data: examine the empirical evidence to see whether the predictions of the behavior function are confirmed.
(6) Iteration: repeat, iteratively refining the theory.

This paper addresses some aspects of an analysis of steps 1 and 2 recognizing the evolutionary roots of some goals and the essential importance of adaptation within the environment.

2. Unifying Views

As previously noted Berg-Cross's (2002) proposed a fundamentally different reference architecture than Albus (1999). A portion of this 3 part architecture is shown in the left portion of Figure 1. While not strictly hierarchical it is easier to introduce it in top, middle and bottom terms. There is an upper level for belief-intention driven pragmatic processes which provides intentional control and strategic guidance. In a lower level there are situated-reactive processes which also pass factual input to intermediate planning level. This architecture is beyond the traditional scope of engineering which attempts to decompose functions using mechanistic principles, but does reflect some pragmatic elements of the view of mind found embedded in Albus [1](1991). In particular the reference model provided a pragmatic view, shown in the middle portion of Figure 1, to the ubiquitous cognitive idea of a "rational agent' using 'knowledge' to 'succeed' in the world. Berg-Cross (2003) identified two key aspects that structure the new reference architecture:

[1] "Intelligence is a faculty of the system that provides an ability of a system to act appropriately in an uncertain environment, where appropriate action is that which increases the probability of success, and success is the achievement of behavioral sub-goals that support the system's ultimate goal."

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 2004**	2. REPORT TYPE	3. DATES COVERED **00-00-2004 to 00-00-2004**

4. TITLE AND SUBTITLE **Developing Rational-Empirical Views of Intelligent Adaptive Behavior**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Knowledge Strategies,Potomac,MD,20854**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Proceedings of the 2004 Performance Metrics for Intelligent Systems Workshop (PerMIS -04), Gaithersburg, MD on August 24-26 2004

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

- Unification of a belief-based, rational-empirical view of intelligence, reasoning & knowledge
    - for example, propositional representations are not primary knowledge but an ingredient to which becomes knowledge via interpretation. Thus there is a relation between propositions and the system of beliefs that cognitive agents know/use
- Characterization of agent knowledge as a fluid, inconsistent mix of approximate facts, hypotheses, goals and concepts that serve in a rational-empirical process (Sowa, 1999).

The current paper addresses a developmental perspective to further explain how pragmatic foundation for these constructs come into existence. It finds features of rational-adaptive nature of intelligence embedded in biological systems. This shown in the right side of Figure 1 which provides a very high-level view of the evolutionary and developmental influences to Sowa's (1999) rational-empirical knowledge cycle. In particular these help address the questions of primitives of cognitive processes within a rational-empirical cycle and how they might arise developmentally. These are not new questions, but discussion in the context of aspects of the reference architecture is. Both an evolutionary and epigenetic approach is introduced to provide a richer, plausible basis for fluid, adaptive knowledge structures and processes. Overlaying this are additional social processes which further shape adaptive structures and knowledge.

Discussion of the developmental nature of intelligence is in the spirit of unifying scientific approaches (Wilson, 1998) for biological, psychological and social science. A synthesis of these can enhance a strictly engineering view of mind. One initial goal is to add a biological frame to the information processing model and outline our understanding of intentions and beliefs that co-exist with rational and underlying reactive processes. A key idea uniting these is the adaptive nature of human intelligence and resulting human behavior which may be usefully viewed and discussed from 3 different points of view as a:

1. species evolutionary product (see Caporael, 2001 for an overview of Evolutionary Psychology - a distal explanation operating over evolutionary time),
2. result of broad epigenetic-environmental interactions within the lifespan development of individual humans/agents (such as discussed in Piaget 1950) and
3. bio-ecological phenomena based on situation-specific functions processed by a rational-empirical cognitive apparatus that is socialized and adjusted within human cultures (Bronfenbrenner & Morris,1998).

Each provides a useful, somewhat complementary, step to a more complete and valid understanding of intelligent behavior, its adaptive nature[2] and it structural roots. Taken together these broaden the concept of "engineering mind"

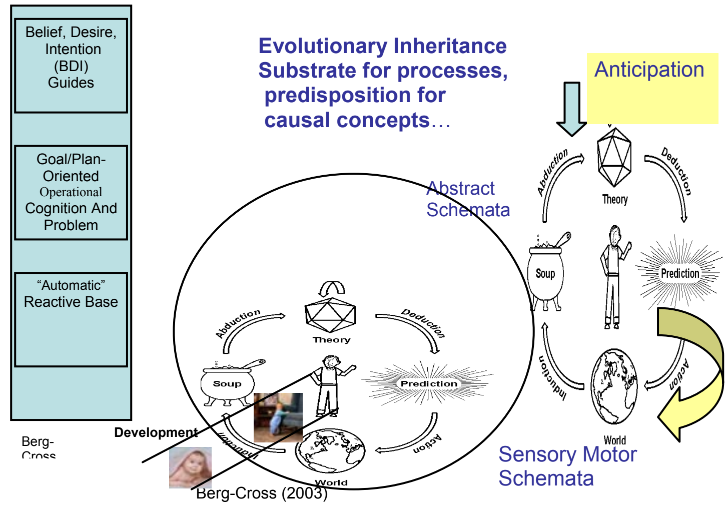

Figure 1: Three Level Hybrid architecture, Sowa's Rational-Empirical Knowledge Cycle, Evolutionary process articulated by Piagetian developmental processes

(Albus, 1991, 1999) to include the larger concepts of evolution, "development" and social influences on this development and to help understand the complexity of the issues.

3. Evolutionary Views and Levels of Explanation

The evolutionary perspective provides a biological view of our complex, characteristic intelligence in the form of a, neural system adaptive by evolutionary challenges. Thus, in an evolutionary perspective, such as posited by Evolutionary Psychology (EP), the human mind resides in a brain that is "a system of organs of computation designed by natural selection to solve the kinds of problems our ancestors faced in their foraging way of life" (Pinker 2000). Biology and thinking follow the same evolutionary path since long-term evolution has shaped all human minds as it has human bodies, around fitness structures and functions suited for hunter-gatherers. Current evolutionary neuroscience perspective on brain reorganization (left-right cerebral hemispheric asymmetries, human-like third inferior frontal convolution etc.) in light of brain imaging studies suggests the story that Homo intelligence arouse from a dynamically configured set of brain areas that collaborate adaptively to meet particular cognitive challenges. Evolutionary biologists (EB) do a form of reverse

[2] Following Pfeifer & Scheier (1998) adaptivity may be understood as an organisms' capability to modify its behavior so that they can more efficiently maintain their critical parameters in a "zone of viability". The pathway to this includes all of species, group and individual development. Piaget includes such ideas within his equilibration process.

engineering[3] when they hypothesize adaptive problems a species might have encountered during its evolutionary history, and then ask themselves, "What would a machine capable of solving these problems well under ancestral conditions look like?" Using this insight, EBs empirically explore the design features of the evolved "machines" that, taken together, comprise an organism. This is a one form of evolutionary explanation, but its goal is a more integrated explanation at several levels. A view of the explanatory role of evolutionary principles in the context of other ideas (e.g. brain structure) is represented in Figure 2 based on a framework found in the work of Cosmides and Tooby (1987). Their work uses an evolutionary focus to propose an outline the human mind's "design". Knowing what cognitive programs are posited to come into existence evolutionarily, in turn, guides the search for neural explanations as shown in the Figure. Taken together this theoretical outline of adaptive problems helps guide the integrated search for the cognitive programs that solve adaptive problems as part of integration of explanation. Wilson (1999) calls such integration across scientific disciplines consilience, a common ground of explanation that links scientific systems of thought. Belief in the possibility of consilience is a meta-assumption because systems of explanation do not spontaneously unify. Integration requires that a common body of abstract principles and related evidence be constricted and EP/EB suggests one such path for evolved intelligent agents.

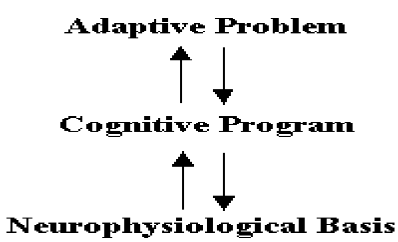

Figure 2: Three "complementary" levels of explanation in evolutionary psychology. Explanation at one level (e.g., adaptive function) does not preclude or invalidate explanations at another (e.g., neural, cognitive, social, cultural, economic). Constrained, plausible inferences between level s are represented by the arrows –after Cosmides and Tooby (1987).

Such definitions of adaptive problems may not uniquely specify the design of the mechanisms that solve them, because as a rule, there are multiple ways of achieving any solution. As result empirical, psychological studies are needed to focus in on which mechanism nature may have actually adopted. The engineering principle here is that the more precisely researchers define an adaptive information-processing problem -- the "goal" of processing -- the more clearly one can see what a mechanism capable of producing that solution would have to look like. This research strategy has been used in the study of vision, for example, so that it is now commonplace to think of the visual system as a collection of functionally integrated computational devices, each specialized for solving a different problem in scene analysis -- judging depth, detecting motion, analyzing shape from shading, and so on. This differs from the type of engineered "mind" described by IP models which are essentially unspecialized with general-purpose mechanisms that subjects all information to the same processes and stores it in the same places. Faces, words, geometric shapes, most other sensory information will be perceived, processed, rehearsed, and stored in the same fashion. An evolutionary perspective brings the unsettling notion that the evolution of cognition has produced memory/knowledge systems that specialize in the processing of particular types of information. It is well known that human perceptions and reasoning are biased - involving anchoring and stereotyping, and parceling out reality according to the limitations of experience and that they tend to focus on what is considered important by the person (see Dawes 1988 for a summary). This perspective provides one useful idea of the varied and inconsistent basis of an individual's knowledge – it is based on a mix of specialized modules. Seen at a distance the result is an intelligence that includes fluid, heterogeneous, ever changing, and often in-consistent knowledge leading to its characterization by Sowa (2000) as a knowledge soup. The soup metaphor serves to capture the idea of fluid material with solid chunks; corres-ponding to the pieces of alike kind of knowledge that have a type of internal consistency. Between chunks there may be inconsistency arising from various sources. This seems to be the case for the human visual system, for example. It is still early to say that a research program using this frame has yielded firm answers to many of the issues of intelligence. A number of issues revolve around the Tooby & Cosmides (1992) 6 meta-theory principles of adaptationism that may provide a coherent view[4]:

1. functional efficiency criteria for identifying adaptations shaped by natural selection,
2. the context-sensitive psychological adaptation (rather than the "instinctive behavior") as the appropriate level of analysis for human nature,
3. a highly modular view of the mind comprised of hundreds of domain-specific psychological adaptations,
4. a computational metaphor for the mind imported from cognitive psychology,
5. the universality of evolved human nature rather than the heritability of individual differences,
6. hominid small-group living in Pleistocene Africa as the most relevant ancestral environment for understanding most of human nature.

[3] Regular engineers figure out what problems they want to solve, and then design machines that are capable of solving these problems in an efficient manner.

[4] The last five of the six remain controversial, even among adaptationists

This meta-model remains controversial and it is not clear, for example, that point 3 is correct. It may be that adaptation has lead human mental abilities to use a "universal structure" or at least generalized/universal functions, which would simplify the measurement of intelligence. At this point we probably can say that the structure of computation-like neural networks has emerged in some form despite short-term influences which to Pinker includes culture, belief, or individual desires. But there is a large, interactive story to describe how these inherited structures serve an adaptive function to become phenotypic structures during development. I think it possible that an empirical-rational process is the general adaptive function. There is much to do to prove this hypthesis.

4. Dynamic Development and the Epigenetic Robotic Approach

It seems useful to consider intelligent performance as part of a dynamic system in which agent architecture/engineering and its environment join forces over time creating agent "development". A consilience-like convergence of data and theory from genetics, embryology, and developmental biology suggests to many the possibility of a more epigenetic, contingent, and dynamic view of how organisms develop (Lickliter & Honeycutt, 2003).

Developmental dynamics, properly formulated, can add to proximal details to the distal view of evolutionary psychology. Putting it simply, development and evolution can usefully be considered 2 views of intertwined phenomena. The standard model is to view mechanisms of evolution as essential to understand development, and the mechanisms of development are likewise essential to understand evolution (Griffiths, & Gray, 1994, 2001). This was changed by such things as Waddington's "Epigenetic Landscape" concept that " the degree to which a trait is innate is the degree to which its developmental outcome is canalized which is defined as the degree to which the developmental process is bound to produce a particular end-state in the face environmental fluctuations both in the development's initial state and during the course of development." Lickliter & Honeycutt (2003) hold the view that development is a self-organizing, probabilistic process in which order and pattern emerge to change as a result of transactions among developmentally relevant resources both internal and external to the organism. It follows that development should not be described as the result of the interaction between genetic and environmental factors, because neither operates as independent causes. In this dynamic view it is more accurate to say that development results from and bidirectional and dynamic transaction of genes, cells, tissues, organs, and organisms during the course of individual ontogeny. Lickliter & Honeycutt's (2003) argue that a study of developmental dynamics could reveal how underlying mechanisms unfold over time and provide insights that are complementary to, not mutually exclusive with, the functional explanations already provided by evolutionary psychology. This has now begun to be studied using "epigenetic robots" designed using Piagetian ideas of development. When applying these ideas to the development of intelligence these formulations parallel some of Piaget's (1950) views on adaptation to the environment. For example, Piaget introduced the term epigenesist to refer to such development, determined primarily by interaction rather than genes. Over the last few years biological thinking has emerged in a "new robotics" partly in response to lack of progress with the information processing paradigm which has proven ill-suited to come to grips with natural, adaptive forms of intelligence (Pfeifer et al 2004). One sub-set of this, called epigenetic robotics, focuses on experimental studies of Piagetian stage-theory processes[5] involving prolonged epigenetic development[6]. The approach is:

1. Start with some 'innate' components/substrate (as previously discussed)
2. Consider the nature and demands of the environment
3. Let development proceeds by an interaction between developing components & a dynamic environment
4. Along the developmental "path" temporary structures and processes may bridge to increasingly more complex cognitive structures (fitter ones) tuned to the environment by interactions with the environment (physical and social)

This developmental path to intelligence provides a substantial set of intermediate knowledge products for an agent. By Piaget's account, the sensori-motor stage in biological systems is a structuring process, where sensing mechanisms are gradually integrated with motor actuating mechanisms on the developmental path to a mature performing system. For human babies this takes lasts 2 years. The first four months organize a substrate of reflexive responses into more coherent motor strategies called physical schemas -scruffy knowledge structures proposed as the basis on which more abstract knowledge is built. In addition, sensory modalities are coordinated and attentional mechanisms begin to emerge – all satisficing environmental constraints and inherited motivators which are realized in a series of intermediate forms on the path to adult structures. From four to six months, reactions are "practiced" until an infant exhibits what seems like intentional

---

[5] Piaget theory of children's intelligence sees it is as controlled by construction of mental organizations, which he called schemes. These are used to represent the world and designate action. This adaptation is driven by a biological drive to obtain balance between schemes and the environment (equilibration).

[6] One interesting aspect of this process is its underlying ability to deal with and solve complex multi-level integration problems – unsolved challenges in engineering intelligent systems. The epigenetic robotics paradigm proposes that epigenetic development allows systematic exploration of this complex issue.

prolonging of special interactions. Taken together this path evidences the emergence of a belief, desire, intention structure such as described in Berg-Cross (2002). In Piagetian terms stable agent-world interactions patterns emerge that are evidence of satisficing, temporary cognitive structure built in a bottom up fashion. These are initially constructed as physical schemata, but may be used by an agent to handle other instances of this type of interaction. In a fluid model of knowledge, knowledge starts as physical schemata , is extended to other physical examples of a phenomena. These extensions are often tentative and prove less than optimum for situations and are thus highly modifiable as discussed in the Sowa (2000) model of a rational-empirical "cycle". Epigenetic robotic implementations can help clarify, evaluate, and even further such cognitive, developmental theories, which due to the complexity of the interactional processes involved have up to now remained somewhat speculative. An interesting line of psychological work suggests some direction for research into corresponding top-down processes, such as proposed in the 3 part reference architecture of Berg-Cross (2003). Gergely and Csibra's (1998) have proposed a theory of the one-year olds 'naïve theory of rational action' based on evidence for causal and other beliefs such as are hypothesized as belief-desire-intention processes. Infants seem to "comprehend" a goal-oriented aspect of agent behaviour of agents (see Berg-Cross, 1971 for an early experiment into a child's ability to detect intentions). This is also seen in the form and function of so called declarative pointing which is characterized by coordination of an extended arm and index finger intended to draw attention to a distal object. Unlike other pointing, it is not necessarily a request for an object. Instead, children often use declarative pointing to draw attention to objects when they are clearly outside their reach (e.g. the moon or a bird passing overhead). Further, declarative pointing only occurs under specific social conditions. Children do not point unless there is someone to observe their action. Other research on children's attentional responses (using habituation) shows that they take goals into account and anticipate future actions in coordination with these goals. For example, evidence of "teleological" interpretation by a 1 year old can seen in their attributions to an agent desires (e.g. to drink water) as an explanation of an

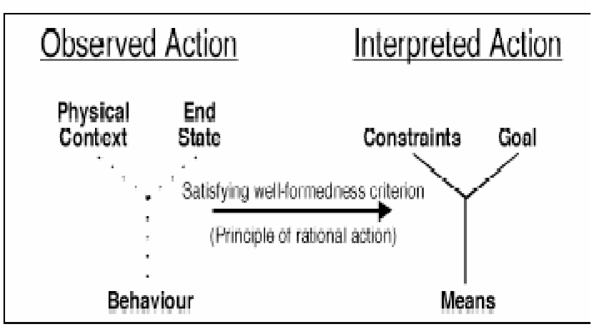

Figure 3 Teleological reasoning in infancy: the infant's naive theory of rational action (after Gergely. and Csibra,1997)

abstract figure's jumping action over an obstacle. Controlled studies also show child beliefs (e.g. a belief that there is water in the bottle). Thus, there is developmental evidence for an early teleological model (see Figure 3) that over time can develop into an interpretive understanding of others as intentional agents (i.e., agents that have mental states such as goals and desires, and whose actions are related to their goals and desires). This is a rational model that helps one agent predict the behaviour of another. The second point leads to the constructive, interpretive aspect of intelligence with evolutionary roots. These concern the origins and development of an understanding of others as social/interactive agents that influence each other, interact with each other, and can have thoughts, emotions and dispositions about/towards each other. Developmentalists have long argued for its central role in child development.

5. Social Roots of Rational Behavior

A standard principle of rationality is that it operates under normal circumstances to optimize the adaptation of the behavior of the organism. A long research line, growing out of Brunswick (see Oaksford and Chater 1996), shows that people behave irrationally with respect to logic, but that the behavior is rational when the context is broadened to encompass a person's '''normal'' life conditions'. One summary idea is that people can be seen to behave rationally with respect to the environment, where their behavior and underling intelligence has been structured and which evolution has provided a developmental substrate, but appear to be operating irrationally with respect to a artificial, experimental tasks. That is, adaptive behavior arises when intelligent-capable agents strive to maintain "ecological balance" of its relationship, both physical and mental, between their environment, material structure, and a degree of pragmatic control.

Tying some of the previous discussion together, a plausible story is that certain biological features found in normal human infancy were selected by a social process, during the stages of human evolution post-dating the invention of tools. These features might have been selected for their facilitative value in the process of what Vygotsky's colleague Leontiev (1981) called 'appropriation'. Infancy is then seen as a specific niche in which adaptive parameters are set by processes of individual appropriation. In this account, the biology of human infancy is a product of the co-evolution of culture and biology. Recent studies of infant cognition and social behavior lend support to such an account. Infancy, in this account, played a crucial role in the 'socialization' of human biology. Thus at any given point an agent has a degree of adaptive intelligence but as a developing agent it has a measurable "zone of proximal task intelligence" (after Vygotsky , 1978). Within this zone agent have not yet master autonomous skill but has a belief and intentions to do with tasks the guidance of humans or more skilled agents. Social explanations of adaptation problem are detailed by Bronfenbrenner and Morris (1998) who point out how the human individual is an active constituent of any context it inhabits. This way of theorizing emphasizes that social context, including child rearing, is inherently relational and that human life is part of an open system, characterized by indeterminacy and the creation of novelty.

6. Summary

The views presented here provides an expanded view and framework of intelligence in the spirit of consilience. At a very high level, it represents a start on an integrated view of major aspects of human adaptation, including the development of approximate knowledge, the role of evolutionary substrate, intermediate structures and rational processes. A working hypothesis is that the proper use of epigenetic robotics may test developmental dynamic hypotheses and properly will over time add to the theoretical and empirical foundation of adaptive intelligence. Time will tell the merits of these concepts within a joint evolutionary and developmental. Relevant questions include those now attached to both evolutionary psychology and epigenetic robotic research:

- Does the theoretical perspective guide researchers to new and important domains of discovery?
- Does it lead to specific predictions about new, poorly predicted phenomena?
- Does it explain existing scientific findings in a parsimonious manner (better than current theories)?
- Does it yield significant new empirical data?
- Does it provide new insights in the frequently argued issues with adaptation[7]?

References

1. Albus, James.S. (1991). "Outline for a Theory of Intelligence". *IEEE Transactions on Systems, Man and Cybernetics*, **2 1** (3): p. 473-509
2. Albus, James S: (1999) "*The Engineering of Mind*", Information Sciences, v.117, pp. 1-18
3. Anderson, J.R. (1990) *The Adaptive Character Of Thought*, Erlbaum
4. Anderson, J. R. & Milson, R. (1989). Human Memory: An Adaptive Perspective. *Psychological Review*, 96, 703-719.
5. Berg-Cross, L.G. (1971) Intentionality, degree of damage, and moral judgments. *Child Development*, 46, 970-974.
6. Berg-Cross, G. and Price, M. E. (1989). "Acquiring and managing knowledge using a conceptual structures approach: Introduction and framework." IEEE Transactions on Systems, Man and Cybernetics **19**: 513-527.
7. Berg-Cross, Gary (1992) "Can a large knowledge base be built by importing and unifying diverse knowledge? Lessons from scruffy work," *Knowledge-Based Systems*, vol. 5, no. 3, 1992.
8. Berg-Cross, G., A Pragmatic Approach to Discussing Intelligence in Systems, presented at PerMIS 2003.
9. Bronfenbrenner, U., & Morris, P. A. (1998). The ecology of developmental processes. In R. M. Lerner (Ed.), *Handbook of child psychology: Vol. 1. Theoretical models of human development* (5th ed., pp. 993c1028). New York: Wiley.
10. Caporael, Linnda Revolutionary *Psychology: Toward a Unifying Theory and a Hybrid Science,* Annual Review of Psychology February 2001, Vol. 52, pp. 607-628.
11. Cosmides, L. & Tooby, J. (1987). From evolution to behavior: Evolutionary psychology as the missing link. In J. Dupre (Ed.), *The latest on the best: Essays on evolution and optimality.* Cambridge, MA: MIT Press.
12. Dawes, Robyn *Rational Choice in an Uncertain World* (New York: Harcourt Brace Jovanovich College Publishers, 1988.
13. Gergely, G., Nádasdy, Z., Csibra, G., & Bíró, S. (1995). Taking the intentional stance at 12 months of age. *Cognition, 56*, 165-193.
14. Gergely, György (2003) What should a robot learn from an infant? Mechanisms of action interpretation and observational learning in infancy. In Prince, Christopher G. and Berthouze, Luc and Kozima, Hideki and Bullock, Daniel and Stojanov, Georgi and Balkenius, Christian, Eds. *Proceedings Third International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems* 101, pages pp. 13-24, Boston, MA, USA.
15. Griffiths, P. E. and R. D. Gray (1994). Developmental Systems and Evolutionary Explanation. *Journal of Philosophy* XCI (6): 277-304.

---

[7] A core set of epigenetic research questions amenable to exploration via robotics includes:

- How much is inherited, the nature of motor primitives
- Models of planning and control, perceptual-motor mapping, equivalence of actions.

16. Griffiths. P.E & Gray, R.D (2001) Darwinism and Developmental Systems *Cycles of Contingency: Developmental systems and evolution* Oyama, S, Griffiths. P.E & Gray, R.D Cambridge, Mass., MIT Press: 195-218.

17. Grupen, Roderic A. (2003) A Developmental Organization for Robot Behavior. In Prince, Christopher G. and Berthouze, Luc and Kozima, Hideki and Bullock, Daniel and Stojanov, Georgi and Balkenius, Christian, Eds. *Proceedings Third International Workshop on Epigenetic Robotics: Modeling Cognitive Development in Robotic Systems* 101, pages pp. 25-36, Boston, MA, USA.

18. Leontyev, , A.N. (1981). Problems of the Development of the Mind. (Trans. M. Kopylova). Moscow: Progress Publishers.

19. Lickliter, R., & Honeycutt, H. Developmental dynamics: Toward a biologically plausible evolutionary psychology. *Psychological Bulletin,* 2003 *129,* 819 – 835.

20. Oaksford M, Chater N 1996 Rational explanation of the selection task. *Psychological R iew* 103: 381–91

21. Piaget, J. (1950). *The Psychology of Intelligence*. New York: Harcourt, Brace

22. Pfeifer, R., F. Iida and J. Bongard (2004) New Robotics: Design Principles for Intelligent Systems, *Artificial Life, Special Issue on New Robotics, Evolution and Embodied Cognition*, MIT Press.

23. Sowa, John F. *Knowledge Representation: Logical, Philosophical, and Computational Foundations*, Brooks Cole Publishing, 2000.

24. Tooby, J., & Cosmides, L. (1992). Cognitive adaptations for social exchange. In J. Barkow, L. Cosmides, & J. Tooby (Eds.), *The adapted mind: Evolutionary psychology and the generation of culture* (pp. 163–228). New York: Oxford University Press.

25. Vygotsky, L. S. (1978). *Mind in society: The development of higher psychological processes.* Cambridge, MA: Harvard University Press. (Original works published in 1930, 1933, and 1935)

26. Wilson, Edward O. *Consilience: The Unity of Knowledge* (Alfred Knopf, 1998)