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Information Processing Approaches to Cognitive Development

Technical Report AIP-59

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[1]Paper read at symposium on "Theories of Child Development: Updates and Reformulations", at the biennial meetings of the Society for Research in Child Development, Kansas City, Missouri, April 27-30, 1989.

[2]These comments are a radical condensation of a chapter of the same title, appearing in *Annals of Child Development, Vol. 6*, R. Vasta (Ed.), J.A.I. Press, Greenwich, CT, 1989.

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION Unclassified	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; Distribution unlimited
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AIP - 59	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Carnegie-Mellon University; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION Computer Sciences Division Office of Naval Research
6c. ADDRESS (City, State, and ZIP Code) Department of Psychology Pittsburgh, Pennsylvania 15213	7b. ADDRESS (City, State, and ZIP Code) 800 N. Quincy Street Arlington, Virginia 22217-5000
8a. NAME OF FUNDING/SPONSORING ORGANIZATION Same as Monitoring Organization; 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER N00014-86-K-0678
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS p4000ub201/7-4-86

PROGRAM ELEMENT NO	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO
N/A	N/A	N/A	N/A

11. TITLE (Include Security Classification)
Information processing approaches to cognitive development

12. PERSONAL AUTHOR(S) Klahr, David

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Technical	FROM 86Sept15 TO 91Sept14	1989 August 4	12

16. SUPPLEMENTARY NOTATION
These comments are a radical condensation of a chapter of the same title, appearing in ANNALS OF CHILD DEVELOPMENT, Vol. 6, R. Vasta (Ed.), JAI Press, 1989

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	information processing, cognitive development, self modification, production systems

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Information Processing Approaches

Klahr, D. (1989). Information processing approaches. In R. Vasta (Ed.), *Annals of Child Development*, JAI Press, Inc. 133-185.

ABSTRACT

This chapter reviews the history and current status of information-processing approaches to cognitive development. Because the approach is so pervasive, it is useful to characterize research in terms of distinctive features, and to organize the features according to whether they are "soft-core" or "hard-core" aspects of the information processing approach. Each of these features is illustrated by example, and the hard-core approach is expanded into a detailed analysis of self-modifying production systems and their potential for formulating theories of cognitive development.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr. Alan L. Meyrowitz	22b. TELEPHONE (Include Area Code) (202) 696-4302; 22c. OFFICE SYMBOL N00014

DD FORM 1473, 84 MAR — 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

Unclassified

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One of the standard techniques of any good radio or tv evangelist is assert that "we are all sinners". Once the audience is persuaded that they are all sinners, and that the evangelist himself has sinned (quite recently, in fact), then the rest is easy. For only a reformed sinner has the expertise to take his listeners on the road to salvation.

Therefore, in my assigned role as an evangelist for information processing approaches to cognitive development, I will make an analgous assertion: we are all information processing psychologists. That will make my job easier. But here the analogy breaks down, for I am unrepentent, and my goal is not to lead you away from information processing approaches, but instead to take you farther down that path.

Information processing approaches come in two styles: hard core and soft core. My talk will to characterize the nature of the soft-core approaches, and illustrate how widespread they are, and then describe the hard-core approach. Finally, if any of my alloted 18.5 minutes remain, I will speculate about the future of IP approaches.

I believe that the soft and hard core approaches can be defined in terms of family resemblance: the more features a particular line of investigation uses, the better it exemplifies the concept. I will run through the basic features of both approaches, and then elaborate each of them in turn.

- SC1: The assumption that the child's knowledge can be represented symbolically.
- SC2: The assumption that congition derives from an IPS that operates on these symbol structures.
- SC3: Consequently, cognitive development is a process of self-modification of the IPS.

METHODOLOGICAL FEATURES

- SC4: Use of formal notational schemes.
- SC5: chronometric analysis.
- SC6: Use of error-patterns and verbal and behavioral protocols. "High density data"
- SC7: Formal task analysis.

Features of hard-core information processing approaches:

HC1: Use of computer simulation.

HC2: Commitment to elements of the simulation as theoretical assertions, rather than just metaphor or computational convenience.

HC3: Goal of creating a complete self-modifying simulation that accounts for both task performance and development.

Now I will elaborate these 10 features and exemplify them to various degrees.

SC1: Symbol structures. "Symbolic" means many different things in developmental psychology, but the presumption of an underlying symbolic capacity to support cognition is pervasive. Thus, the kind of symbols I refer to here are at a very microscopic level, where they are assembled into meaningful structures that then support higher level processing. There is a difference between my notion of a symbol structure and the more conventional use of the term. For example, Judy Deloache reported yesterday on her studies of preschoolers' ability to understand the symbolic relationship between a model of a room and the real room. She concluded that -- on some versions of this task -- 2.5 year-old children are "pre-symbolic." That is, they can's use one representation to denote another. However, if one were to formulate detailed models of children's knowledge about this task at both levels of performance, then one would, in both cases, postulate systems that had the ability to process symbols. Thus, even in this ingenious research program directed at determining when children "become symbolic", there remains the presumption of underlying an symbol-processing capacity -- at the microscopic level.

The second example of implicit assumptions about symbol processing comes from Case's (1985, 1986) theory. He postulates *figurative schemes, state representations, problem representations, goals, executive control structures,* and *strategies* in order to account for performance, and *search, evaluation, retagging,* and *consolidation* to account for development, and his central theoretical construct -- what he calls *Short Term Storage Space* (STSS) -- implies that what gets processed in STSS are symbols and symbol structures.

As a third example, I have listed Mickie Chi's extensive investigations of child expertise. In Chi's work, a major explanatory variable is access to symbolic structures (chunks, semantic nets, etc.) that supports the superior performance of the children.

The next two assumptions vary with respect to how explicitly they show up in soft-core approaches, but they are widely used and usually unquestioned.

Soft Core 2: assumes a symbol-processing information-processing system. The cannonical model for the human IPS emerged in the late 60's and early 70's. It is comprised of of shortterm and longterm memories, with various characteristics dealing with capacity, processing rates, and modality specific buffers. This view has been pretty much imported into cognitive development from adult information processing psychology without major modification.

Soft Core 3: assumes that the developmental story can be told in terms of a self-modifying information processing system. To the extent that characterization of that IPS is vague, then so is the developmental theory.

The assumption of a self-modifying IPS shows up in several guises: in Piaget's original assertions about assimilation, and accomodation in proposals for various kinds of structural reorganizations (e.g., Case, 1986; Halford, 1970; Fischer, 1980), in the interaction between performance and learning (Siegler 88), and in explicit mechanisms for self-modifying computer models, several of which are described in a book that I co-edited with Bob Neches and Pat Langley last year. (But this last set moves from soft- to hard-core, so I will defer it for now.)

This emphasis on self-modification does not deny the importance of external influences on the IPS, such as direct instruction, modelling, and the social context of learning and development. However, it underscores the fact that whatever the form of external environment, the information-processing system itself must ultimately encode, store, index and process that environment. Here too, the soft-core approaches tend to leave this somewhat vague and implicit, whereas the hard-core approaches make specific proposals about each of these processes. However, all information-processing approaches to development acknowledge the fundamental importance of the capacity for self-modification.

So much for theoretical features. Now I will turn to four methodological features. (Some of them are very familiar, and I will do little more than list them here.)

The advantages of using formal notational schemes are clear from the work with flow charts, scripts, tree diagrams and story grammars so widely used in developmental psychology.

Mental chronometrics has been a productive methodology that is clearly predicated on the assumption of an underlying information processing system. Perhaps the best known developmental work in this area is the pioneering study by Groen and Parkman on children's strategies for mental arithmetic, work since extended by several other, including Ashcraft and elaborated into a model of strategy creation and choice by Bob Siegler. This approach has allowed us to move from simply testing binary hypotheses to estimating mental parameters, and charting their growth. An example of this can be found in Kail's recent study of the change of processing rates from 8 years to adulthood for mental rotation, name retrieval, visual search, memory search and mental addition.

What about SC6, the use of high-density data from errors and protocols? The basic assumption is that, whether right or not, the child's knowledge structures and processes will have a characteristic profile -- a kind of cognitive fingerprint. Verbal protocols, eye-movements, and error patterns (as well as chronometric methods, mentioned above) all provide this kind of high-density data. This position is neither novel nor radical. Once again, Piaget turns up as a charter member of the soft-core information-processing club. He was probably the first to demonstrate that children's errors could reveal as much, or more, about their thought processes as their successes. Piaget was pretty casual about the generation and analysis of error data, but his basic insight about the importance of error patterns has been elaborated into some sophisticated and revealling investigations. Best known perhaps is the work by Brown, Burton, and VanLehn on "buggy" strategies for subtraction, and Siegler's "rule assessment" studies. My own studies with problem solving on the TOH, Sharon Carver's work on debugging, and Fay's and Mayer's work on children's LOGO misconceptions are further examples of the power of detailed analysis of high density data. These examples illustrate the basic premise of this feature of soft-core approaches: Careful analysis of error patterns provides a window into the child's mind.

I don't have time to say much about feature 7, other than to note that the more formal information processing approaches require a detailed specification of the task and its context. I believe that IP approachs can be naturally extended to what is now being dubbed the study of "situated knowledge."

So much for the soft core. I think it is clear that we are *all* sinners. Now let me turn to the three hard core features.

Perhaps the distinctive feature of the hard core is the use of computer simulation models. Over 25 years ago, Herbert Simon (1962) suggested the general form of an information-processing approach to cognitive development:

> If we can construct an information processing system with rules of behavior that lead it to behave like the dynamic system we are trying to describe, then this system is a theory of the child at one stage of the development.
> Having described a particular stage by a program, we would then face the task of discovering what additional information processing mechanisms are needed to simulate developmental change -- the transition from one stage to the next. That is, we would need to discover how the system could modify its own structure. Thus, the theory would have two parts -- a program to describe performance at a particular stage and a learning program governing the transitions from stage to stage [Simon, 1962, pp. 154-155].

This is an interesting quotation. First of all, it probably represents Herb Simon's one and only foray into the field of developmental psychology. Secondly, it seems a bit old fashioned in its uncritical presumption of stages and in the separation of learning from performance. The third point is one of personal interest to me, for I found this to be a very intriguing idea when I first came upon in a few years later in graduate school.

I have echoed it many times since, and it has prompted various criticisms from some of my developmental colleagues. So in my remaining comments, rather than set forth a tutorial on computer simulation models, I will attempt to respond to some of the issues that have been raised with respect to them.

One question about computer simulation models is the issue of constraint. It might seem that computer simulation models are totally unconstrained, and therefore a poor medium in which to state theories of cognitive development. Rather than belabor the obvious point that verbal theories are certainly less constrained than computation ones, let me mention two clear constraints. The first is that the model must fit the data. For high-density data, this is a challenging task. There is an additional constraint that -- in the past was *not* applied to such models, but which will have to be brought to bear on models of the future. This constraint is based on what is known about the physiology of the nervous system, in particular, its processing rates.

For many years, computer simulators simply ignored the physiological constraint, while acknowledging that, ultimately, symbol systems were grounded in a neural substrate. This is not to say that their models were inconsistent with what was known about physiology, only that there was no consistency check at all. However, a recent analysis by Allan Newell suggests how one might go about applying this constraint. The path is indirect: It occurs through consideration of the different hierarchical levels of the human cognitive system and time scale of operation of each level. Each level is comprised of organized assemblies of the level below it, and it runs more slowly. Newell uses very rough approximations for the operational time scale of each level: 1 ms for neurons, 10 ms for neural circuits comprised of neurons, 100 ms for a deliberate cognitive act, 1 sec for a cognitive operation. Newell (1988) puts it this way:

> The *real-time constraint on cognition* is that the human must produce genuine cognitive behavior in ~ 1 s, out of components that have ~ 10 ms operation times. The significance of such a mapping, however approximate, should not be underestimated. For years, cognitive psychology has enjoyed the luxury of considering its analysis to be one that floats entirely with respect to how it might be realized in the brain ... The floating kingdom has finally been grounded.

How to apply this constraint: suppose we have a model of human behavior in a domain in which the model passes the sufficiency test: that is it can do the behavior that humans do. We can then apply the temporal constraint imposed by physiology by determining if their is a plausible mapping between basic operations in the model and in human performance. In extreme cases, this is easily done, but the extreme cases illustrate the general method.

Consider an AI chess playing program called Hitech, developed at CMU, that is rated at the Master level for chess. Hitech gets its power by generating a massive search (about 100 million positions per move). It does this at the rate of about 175,000 positions per second. In other words, Hitech can generate and evaluate a complex representation for chess position in about 5 microseconds. However, the order of magnitude of neural firing rates is only about 1 ms, so the 5 *micro*seconds per position rate for Hitech violates the temporal constraint, and rules it out as a plausible theory of human cognition.

Even if we posit a massively parallel computation (indeed, Hitech is comprised of a set of simultaneous processors), this does not make Hitech any more plausible as a human model, for, even connectionist models require time for "bringing the results of computations in one part of the network into contact with developing results in other parts of the network." (Newell, 1988).

Another feature of the hard-core approach is HC2: that is, to view the basic elements of the simulation as theoretical entities. This is also a controversial, and somewhat misunderstood, aspect of the hard-core approach.

First of all, it is important to distinguish between the theoretical content of a program that runs on a computer and the psychological relevance of the computer itself. Hard-core information-processing theories are usually sufficiently complex that it is necessary to run them on a computer in order to explore their implications, but this does not imply that the theory bears any resemblance to the computer on which it runs. Computer simulations of hurricanes do not imply that the atmosphere works like a computer.

Failure to make this distinction between model and computer leads to the common misconception that information-processing approaches can be arranged along a dimension of "how seriously they take the computer as a model" (Miller, 1983). It would be counterproductive for a developmental psychologist to take the computer at all seriously as a model for cognition, because the underlying computer does *not* undergo the crucial self-modification necessary for cognitive development. However simulation *models* can undergo self-modification, and later in this talk, I will mention some.

The hard-core information-processing approaches are serious, not about the similarity between humans and computers, but rather about the extent to which intelligent behavior -- and its development -- can be accounted for by a symbol-processing device that is manifested in the physical world. So it is not the computer that is important here, but the model that runs on the computer. For example, if one adopts a production system approach, then the program and the computational architecture that interprets it jointly comprise a theoretical statement about the general organization of the cognitive system and the specific knowledge that is required to do the task at hand. Both the production-system interpreter and the specific productions are proposed as theoretical constructs, not just programming conveniences.

In production-system models, the productions and the architecture bear the same relation to cognitive behavior as a particular molecular structure and general laws of chemistry are taken to jointly explain the behavior of a substance. It is no more appropriate to argue that productions are only functionally equivalent to some "real" mental item, than it is to say that molecules are only functionally equivalent to some real chemical entity.

An important consequence of building simulation models, is that they turn the theoretical enterprise into something somewhat more tractable and concrete. For one can go from developmental principles, with no grounding in computational implementation, to theory as design, in which one constructs a self-modifying production system by making a series of design decisions.

In this slide I have contrasted a collection of principles, whose interaction is extraordinarly difficult to understand, with a series of design points, dealing with very specific and well-understood mechanisms.

Change mechanisms. What are the basic change mechanisms that lead to new productions? Examples are generalization, discrimination, composition, proceduralization, and strengthening.

Conditions for change. What are the conditions under which these change mechanisms are evoked: when an error is noted, when a rule is applied, when a goal is achieved, or when a pattern is detected?

The formalization of cognitive architectures and the implementation of models in the form of production systems enables us to directly confront and resolve many of the issues that otherwise remain hopelessly intangible and unresolveable.

It should be clear by now that the hard/soft labels are not distinct categories so much as they are ends of a continuum. The hard core features can be viewed as the extreme points of soft-core features, as this mapping illustrates, and I see a trend along the continuum.

Where have we been, and where are we going?

The fundamental question in cognitive development is "what is the transition mechanism." I have tried to make the case that hard-core information processing approaches may provide some answers. Is there any evidence for progress along this frontier? I think so.

First of all, there has been a resurgence of interest in the fundamental question. People have stopped avoiding it. For example, in the past few years we have seen Sternberg's (1984) edited volume *Mechanisms of Cognitive Development*, MacWhinney's (1987) edited volume *Mechanisms of Language Acquisition*, a volume I co-edited on *Production system models of learning and development*, and Siegler's (1989) *Annual Review* chapter devoted to transition mechanisms.

Until recently, most developmental psychologists have avoided moving to computationally-based theories, attempting instead to attack the profoundly difficult question of self-modification with inadequate tools. But I see a trend in the direction of hardening the core.

Only a few of the chapters in the 84 Sternberg volume specify mechanisms any more precisely than at the flow-chart level, and most of the proposed "mechanisms" are at the soft end of the information-processing spectrum. However, only five years later, Siegler, in characterizing several general categories for transition mechanisms (neural mechanisms, associative competition, encoding, analogy, and strategy choice) is able to point to computationally-based exemplars for nearly all of them (e.g., Bakker & Halford, 1988; Falkenhainer, et al, 86; Holland, 1986; MacWhinney, in press; Rumelhart & McClelland, 1986; Siegler, in press).

The future of the hard-core approach

But what about the future?

Over the next ten years, I expect to see theories of cognitive development couched in terms of cognitive architectures. Perhaps PS, perhaps PDP. The writers of those papers will be able to assume that readers need no more of a tutorial in the underlying system than current writers assume that they have to explain the conceptual foundations or computational details of an ANOVA.

To summarize and speculate:

1. Some important aspects of cognitive development have been captured in IP models. The first models described different states, and the more recent models describe both states and transitions.

   The approach to theory as design has allowed us to formulate self-modifying I.P.S.

2. But we need much more work on theory. As John Flavell put it recently: "Serious theorizing about basic mechanisms of cognitive growth has actually never been a popular pastime."

3. So my view of the future is a normative one: We should train our students not only in experimental design and statistical methods, but also in simulation models. Not only with soft core tools, but also in the hard core.

If we really respect the complexity and richness of children's minds, then we should approach their study with tools equal to the task.

As Flavell and Wohlwill said 20 years ago: "Simple models will just not do for developmental psychology."

References

Ashcraft, M.H. (1987). Children's knowledge of simple arithmetic: A developmental model and simulation. In J. Bisanz, C.J. Brainerd, & R. Kail (Eds.), *Formal methods in developmental psychology: Progress in cognitive development research* (pp. 302-338). New York: Springer-Verlag.

Bakker, P.E., & Halford, G.S. (January 1988). *A basic computational theory of structure-mapping in analogy and transitive inference* (Tech. Rep.). . Centre for Human Information Processing and Problem Solving, University of Queensland, Australia.

Brown, J.S., & Burton, R.R. (1978). Diagnostic models for procedural bugs in basic mathematical skills. *Cognitive Science, 2,* 155-192.

Brown, J.S., & VanLehn, K. (1982). Towards a generative theory of 'bugs'. In T. Romberg, T. Carpenter, & J. Moser (Eds.), *Addition and subtraction: A developmental perspective* . Hillsdale, NJ: Erlbaum.

Case, R. (1985). *Intellectual development: Birth to adulthood.* New York: Academic Press.

Case, R. (1986). The new stage theories in intellectual development: Why we need them; What they assert. In M. Perlmutter (Ed.), *Perspectives for intellectual development* (pp. 57-91). Hillsdale, NJ: Erlbaum.

Chi, M.T.H. (1981). Knowledge development and memory performance. In M. Friedman, J.P. Das, & N. O'Connor (Eds.), *Intelligence and learning* . New York: Plenum Press.

Deloache, J.S. (1988). The development of representation in young children. In H.W. Reese (Ed.), *Advances in Child Development and Behavior* . New York: Academic Press. In press.

Falkenhainer, B., Forbus, K.D., & Gentner, D. (1986). The structure-mapping engine. In *Proceedings of the American Association for Artificial Intelligence* . Philadelphia: American Association for Artificial Intelligence.

Fay, A.L., & Mayer, R.E. (1987). Children's naive conceptions and confusions about LOGO graphics commands. *Journal of Educational Psychology, 79*(3), 254-268.

Fischer, K.W. (1980). A theory of cognitive development: The control and construction of hierarchies of skills. *Psychological Review, 87,* 477-531.

Flavell, J.H. (1982). Structures, stages, and sequences in cognitive development. In W.A. Collins (Ed.), *The concept of development* (pp. 1-28). Hillsdale, NJ: Erlbaum.

Flavell, J.H., & Wohlwill, J.F. (1969). Formal and functional aspects of cognitive development. In D. Elkind & J.H. Flavell (Eds.), *Studies in cognitive development* (pp. 67-120). New York: Oxford University Press.

Groen, G.J., & Parkman, J.M. (1972). A chronometric analysis of simple addition. *Psychological Review, 79,* 329-343.

Halford, G. S. (1970). A theory of the acquisition of conservation. *Psychological Review, 77,* 302-316.

Holland, J.H. (1986). Escaping brittleness: The possibilities of general purpose machine learning algorithms applied to parallel rule-based systems. In R.S. Michalski, J.G. Carbonell, & T.M. Mitchell (Eds.), *Machine learning: An artificial intelligence approach* (pp. 593-624). Los Altos, CA: Kaufmann.

Kail, R. (1988). Developmental functions for speeds of cognitive processes. *Journal of Experimental Child Psychology, 45,* 339-364.

Klahr, D., & Carver, S.M. (1988). Cognitive objectives in a LOGO debugging curriculum: Instruction, Learning, and Transfer. *Cognitive Psychology, 20,* 362-404.

MacWhinney, B. (1988). *Competition and cooperation in language processing.* . In press.

Miller, P.H. (1983). *Theories of developmental psychology.* San Francisco: Freeman.

Newell, A. (1988). The 1987 William James Lectures: Unified theories of cognition. Departments of Computer Science and Psychology, Carnegie-Mellon University.

Rumelhart, D.E., & McClelland, J.L. (1986). *Parallel distributed processing: Explorations in the microstructure of cognition.* Cambridge, MA: The MIT Press.

Siegler, R.S. (1988). The perils of averaging data over strategies: An example from children's addition. *Journal of Experimental Psychology: General.* In press.

Siegler, R.S. (1989). Mechanisms of cognitive development. *Annual Review of Psychology,* pp. . In press.

Simon, H. A. (1962). An information processing theory of intellectual development. *Monographs of the Society for Research in Child Development, 27*(2), Serial No. 82.

Sternberg, R.J. [Ed.]. (1984). *Mechanisms of cognitive development.* New York: Freeman.

Wallace, J.G., Klahr, D. & Bluff, K. (1987). A self-modifying production system of cognitive development. In D. Klahr, P. Langley & R. Neches (Eds.), *Production system models of learning and development*. Cambridge, MA: MIT Press.

TWO KINDS OF INFORMATION PROCESSING APPROACHES TO COGNITIVE DEVELOPMENT

Soft-Core Approaches

Theoretical Features

- ☞ SC 1: Symbol structures
- ☞ SC 2: A symbol processing IPS
- ☞ SC 3: A self-modifying IPS

Methodological Features

SC 4: Formalization
SC 5: Mental Chronometry
SC 6: High-density data
SC 7: Analysis of task environment

Hard-Core Approaches

HC 1: Computer simulation
HC 2: Simulation as theory, not metaphor
HC 3: Self-modifying simulation programs

Theoretical features of soft core approaches

Soft-Core 1: Symbol structures

The child's mental activity can be described in terms of processes that manipulate symbols and symbols structures.

DeLoache, 1987: Symbolic objects
Case, 1986: Figurative schemes, state representations, short term storage space
Chi, 1978: Domain specific knowledge acquisition

Soft-Core 2: A symbol processing IPS

These symbolic processes operate within an IPS with identifiable properties, constraints, and consequences.

Canonical system: LTM, STM, Iconic memory, acoustic buffers, etc.

Soft-Core 3: A self-modifying IPS

Cognitive development occurs via self-modification of the IPS.

Piaget: Equilibration via Assimilation and Accommodation

Case, Halford, Fischer: Structural reorganization

Siegler: Learning - Performance interactions

Methodological Features of Soft Core Approach

Soft-Core 4: Formalization
Use of formal notational schemes for expressing complex, dynamic systems.

- **Flow charts:** Sternberg & Rifkin on Analogical Reasoning
- **Scripts:** Nelson & Gruendel on Event Representation
- **Tree diagrams:** Siegler's rule assessments
- **Story Grammars:** Stein & Glen, Mandler

Desirable criteria for formal schemes:

- **Mapped to behavior**
- **Multiple-levels of analysis**
- **Meet processing constraints**
- **Developmental tractability**

Soft-Core 5: Mental Chronometry
Modeling the time-course of cognitive processing over relatively short durations.

- **Mental arithmetic:** Groen & Parkman, Ashcraft, Siegler, et al.
- **Memory Scanning:** Bobbit
- **Quantification:** Chi & Klahr
- **Development of mental processing rates:** Kail (88)

Soft-Core 6: High-density data
Use of high-density data from error-patterns and protocols to induce and test complex models.

e.g., Piaget, Siegler, Fay & Mayer

Soft-Core 7: Analysis of task environment
Use of highly detailed analyses of the environment facing the child on specific tasks.
Features of Hard-Core approaches

HC 1: Use of Computer simulation

If we can construct an information processing system with rules of behavior that lead it to behave like the dynamic system we are trying to describe, then this system is a theory of the child at one stage of the development. Having described a particular stage by a program, we would then face the task of discovering what additional information processing mechanisms are needed to simulate developmental change -- the transition from one stage to the next. That is, we would need to discover how the system could modify its own structure. Thus, the theory would have two parts -- a program to describe performance at a particular stage and a learning program governing the transitions from stage to stage

H. A. Simon, *Monographs of the Society for Research in Child Development,* 1962

HC 2: Simulation as theory, not metaphor

Commitment to elements of the simulations as theoretical entities, rather than just as metaphor or computational convenience.

HC 3: Self-modifying simulation programs

Goal of creating a complete self-modifying simulation that accounts for both task performance and development.