method of testing theories of representation. Nativist approaches underestimate change by characterizing the infant as a fully formed adult masquerading in diapers. Connectionist theories eliminate directionality because the end point is arbitrary.

The demise of Piagetian theory posed yet another problem. Without commonality in processes or destinations, there is no developmental analysis. The overthrow of Piagetian theory is analogous to the dissolution of the Soviet Union. The current cognitive map consists of fractionated territories, each inhabited by processors who use specialized and untranslatable languages which prevent them from assimilating potentially useful contributions from other cultures. If each domain is acquired in unique ways and each representation is inaccessible to others, there is no development to describe, only a list of changes.

Beyond modularity is a response to these concerns. Karmiloff-Smith proposes a theory that maintains the defining characteristics of a developmental approach while linking it to two seemingly incompatible paradigms: cognitive science and connectionism. She tries to persuade the cognitive scientist that directed change exists and is revealing. She also suggests that early developments can be modelled by a network. Later qualitative transformations towards an end state arise through a reorganization of hidden layers during the course of learning. She tells developmentalists that attributing innate special-purpose biases and procedures to the infant does not preclude directed developmental change towards a more general and accessible cognitive system.

Her bold strategy is to redescribe the end state and the change process in terms compatible with cognitive science. She then translates the architecture of the cognitive processor into an associative neural network. The redescription of development ought to appeal to many developmentalists because it captures elements of the Piagetian credo. Development moves from specificity to generality, from the implicit to the explicit, from stereotyped procedures to creativity, and from what Piaget (1978) termed "success to understanding." The path of development is constrained. Although the timing of change varies across tasks and environments, development always involves rewriting initial representations into more flexible formats. The impetus for rewriting is the need to reflect on accomplishments. Thus, the organism is not a collection of modules because there is an implicit, unified self, seeking to understand its own operations.

The reader of *Beyond modularity* will inevitably ask whether the rewriting is successful. Karmiloff-Smith may not convince cognitive scientists of the existence of development. The translation of each code into the next level requires that the two languages be compatible but that the new code be more abstract, dissociable, and accessible. The cognitive scientist will doubt that complex codes can originate from simpler ones.

Developmental psychologists acknowledge qualitative change but note the anomalies of a fully developed redescriber existing in an organism working with primitive codes and a general-purpose redescriptive device coexisting with all-purpose modules. They will also be dissatisfied with the vague analysis of the nature of modules, representations, and redescriptions. Karmiloff-Smith postulates innate constraints or attentional biases for domains as diverse as perceptual organization, mathematics, and drawing. She lacks a principled way to separate modules immediately available to the infant from domains where attentional biases quickly produce encapsulated procedural knowledge and from domains that are never modularized. Yet a theory of the architecture of cognition must be precisely situated.

Even in innately structured domains, the structure is often underspecified. The infant intuitive physicist quickly understands that two objects cannot occupy the same place and that dropped objects fall until they hit a surface. These notions guide the baby's search for missing objects, but what is the representation? Is it a search routine or an image schema? How is understanding formatted? Without answers to these questions we do not know whether and how the representations of the infant physicist lead to adult knowledge of the world.

The first phase of growth translates implicit procedures into explicit codes. Without a rich model of the implicit and early explicit codes we will remain ignorant of the redescriptive process and difficulties of translation. This problem is serious because in some areas, such as understanding the referents of nouns, the initial biases are discarded for new principles. Moreover, the requirements of translation may differ so extensively across domains that it would be hard to assign translation to a common processor. Similarly, the conversion from implicit to explicit knowledge differs radically from the redescription of representations into verbal and conscious forms. In addition, not all knowledge reaches this final state. Karmiloff-Smith needs to specify the limits of cognitive transfer and conscious access to cognitive structure, as well as constraints on the format of mature representations. Precision about the re-representational device is important. The "redescriber" must be equipped with skills or knowledge that will allow rewriting from a simpler and qualitatively different format to the more abstract and more organized representation. Where does this knowledge come from? The role of culture and social experience as a source of knowledge is underemphasized. She also offers a skeletal explanation for change. Mastery of a field may be necessary for change, but it may not prompt further reanalysis unless redescription satisfies some goal.

Karmiloff-Smith's considerable contribution is the use of the findings and language of cognitive science to redescribe and correct Piaget's theory. Without introducing a new level of specificity, however, it is not easy to understand how cognitive change can be represented in a language common to the purposes of cognitive scientists and developmentalists.

The challenge of representational redescription

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Abstract: Representational redescription (RR) poses a significant challenge to cognitive science; but Karmiloff-Smith underestimates the extent to which some current computational models already engage in RR. Moreover, a large part of the existing challenge is to produce convincing psychological evidence that deserves to be modeled. Finally, task constraints are essential for success in both psychological theorizing and modeling.

One of the most interesting aspects of Karmiloff-Smith's *Beyond modularity* is her notion of representational redescription (RR). RR characterizes how representations change with development, becoming progressively more explicit and accessible to other parts of the cognitive system. She rejects a traditional stage approach to development in favor of a recurrent system in which three phases characterize the mastery of each conceptual domain.

While acknowledging that connectionist models have been particularly successful in capturing the implicit representations and behavioral mastery of her phase 1, Karmiloff-Smith correctly argues that these models generally have not made much headway in simulating the more explicit representations of phases 2 and 3. However, one connectionist approach to modeling cognitive development already implements a recurrent multiphase RR process that might capture some of the data highlighted by Karmiloff-Smith. Cascade-correlation is a generative connectionist algorithm (Fahlman & Lebiere 1990) that has been successfully applied to a variety of developmental domains including the balance scale (Shultz et al. 1994b; Shultz & Schmidt 1991), seriation (Mareschal & Shultz 1993), prediction of effect size, integration of velocity, time, and distance cues (Shultz et al., in press), and acquisition of personal pronouns (Shultz et al. 1994a). Like other generative algorithms, cascade-correlation constructs a network topology as it learns a domain. For cascade-correlation, this construction entails the recruiting of new hidden units whose activations correlate with the behavioral error that the network is experiencing. Such newly recruited hidden units receive input from the network's input units and from any previously installed hidden units, thus effectively redescribing developmentally earlier computations. Because high-level hidden units receive both raw descriptions of inputs and interpreted descriptions from previous hidden units, they permit ever more sophisticated interpretations of problems in the domain being learned. Such cascaded hidden units afford the construction of increasingly powerful knowledge representations that were not available to developmentally earlier instantiations of the network.

Moreover, cascade-correlation goes through two recurrent phases that would appear to capture many of the phenomena cited by Karmiloff-Smith. The network begins in what is called the output phase, reducing behavioral error based on environmental feedback by adjusting output-side weights (those connection weights leading into output units). When this error reduction stagnates, the network enters the so-called input phase, where the focus shifts to building new hidden units. The input phase adjusts input-side weights to candidate hidden units so as to maximize the correlation between network error and candidate unit activation. When these correlations level off, the candidate unit with the highest absolute correlation with network error is installed into the cascade, just beyond the last hidden unit. Then the algorithm reverts to the output phase, in which the network must adjust to this new representation of the problem domain by again training the output-side weights.

Karmiloff-Smith's phases 1 and 3 appear to be analogous to the output phase of cascade-correlation. In both cases, there is concentration on reducing behavioral error. In all but the first output phase of cascade-correlation, there is also focus on reconciling new RR with performance demands, analogous to Karmiloff-Smith's phase 3. Her phase 2 appears to correspond to the input phase of cascade-correlation. In both cases, one sees a focus on RR of current computation.

The transition between Karmiloff-Smith's phases 1 and 2 appears analogous to the increase in error typically observed in cascade-correlation nets just after the transition from input phase back to output phase, following the installation of a hidden unit that represents the network's output in a novel way. In both cases, new representations temporarily interfere with previous performance. The transition to Karmiloff-Smith's phase 3 is likewise similar to cascade-correlation's adjustment of output-side weights after hidden unit installation. Error decreases and the network's representation of the problem being learned is better tuned than ever.

A major difference between the two approaches is that the redescription in Karmiloff-Smith's phases 2 and 3 is driven by an as yet unspecified analysis of earlier procedures. In contrast, both the input and output phases in cascade-correlation are driven by the necessity to reduce error. Karmiloff-Smith may be underestimating the extent to which RR in children is motivated by the need to reduce error on newly posed tasks that differ from the original behavioral task. Another difference between the approaches is that standard cascade-correlation may not create the explicit awareness that is often credited to children, for example in Karmiloff-Smith's phase 3. It is unclear how or whether connectionist networks can model such awareness. Nonetheless, available simulations display some important aspects of RR and suggest that phase transitions in development may occur continuously.

A second point is that much of the psychological evidence for RR offered by Karmiloff-Smith could be attributed to either phase 2 RRs or to phase 1 behavioral adjustments. For example, the tendency to balance off-center-weighted blocks at their geometric center (pp. 84–87) would be a natural characteristic of networks trained to balance large numbers of center-weighted blocks. Likewise, decreased reaction time on conservation tasks (p. 110) could just as easily be simulated by networks doing mere weight adjustment as by networks doing RR. Most cognitive modelers believe that it is unproductive to successfully model nonexistent phenomena. A significant part of the challenge of RR must be borne by those purporting to document it psychologically. Verbalizations may be quite easy to document as RR, but nonverbal explicit representations seem to be more challenging.

A final point concerns Karmiloff-Smith's criticism that connectionist efforts suffer from modeling individual tasks, rather than modeling development. This is unfair, because virtually all developmental research, including that cited by Karmiloff-Smith, is restricted to individual tasks. At the present state of the art, task constraints are necessary for success, whether doing modeling or empirical psychology. Surely the next reasonable step is to deal with multiple tasks rather than venturing into task-free development.

Modal knowledge and transmodularity

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Abstract: Necessary knowledge is modal knowledge. The modal features of the phase model of representational redescription (RR) in Karmiloff-Smith's *Beyond modularity* are not squarely addressed. First, one main epistemological problem is to explain the temporal construction of atemporal knowledge. The RR model is silent here. Second, the RR model is primarily domain-specific. Yet the construction of modal knowledge is a universal, though not a general, process. Third, truth-value is distinct from modality, yet the RR model pays more respect to the former than to the latter, even in its account of the construction of novel knowledge.

Necessary knowledge is one main form of modal knowledge. How does the transmodular model in Karmiloff-Smith's (1992a) *Beyond modularity,* (henceforth, *Modularity*) deal with the development of such knowledge?

Consider three features of the representational redescription (RR) model outlined in *Modularity.* First, this is a *phase model* and so carries no implications about the simultaneity of age-related changes (pp. 6, 173). Second, the model operates through reiterative cycles *within a domain,* where a domain is taken to be a set of representations bound to a specific area of knowledge, such as number and language (p. 6). The RR process is stated to be domain-specific (p. 11). Third, the model characterises the capacity of the human *mind to enrich itself* (pp. 28, 190). My argument will be that each of these three features has modal implications which are not squarely addressed in *Modularity.*

1. Phase model. There may be stage models which make age claims (Demetriou et al. 1992) but Piaget's (1960) model is not one of them; his five stage criteria (constant order, overarching structure, integration, consolidation, and equilibration) do not include age. This point was not lost on Brainerd (1978). Age is an indicator, not a criterion, of developmental level (Smith 1993, sect. 18). Unlike a criterion, which must be exceptionless, an indicator has relative utility, for example, in sample selection or education. *Modularity,* denies that age claims have scientific interest (p. 28), but exactly why such a position is incompatible with Piaget's model, which is stated to be "likely wrong" (p. 167),