Analogy and conceptual change in childhood

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Abstract: Analogical inferences are an important consequence of the way semantic knowledge is represented, that is, with relations as explicit structures that can take arguments. We review evidence that this feature of semantic cognition successfully predicts how quickly and broadly children's concepts change with experience and show that Rogers and McClelland's parallel distributed processing (PDP) model fails to simulate these cognitive changes due to its handling of relational information.

Rogers & McClelland (R&M) have presented a powerful response to the theory-theory of concepts (Carey 1985; Keil 1989; Murphy & Medin 1985), the view that knowledge of causal and other abstract relations among entities influences learning, memory, and reasoning. Against this view, R&M have shown that an artificial learner (their parallel distributed processing, or PDP, model) need not represent concepts within a theory to show many classic phenomena of cognitive development, including category coherence, context-sensitive generalization, conceptual reorganization, and the causal status effect.

Despite its ability to simulate these aspects of child cognition, R&M's approach has a fundamental limitation: Their PDP network does not process relational structure the way that children do. That is, within R&M's PDP model, relations (like *ISA, can,* and *has*) allow the model to learn the difference between being a predator, being capable of chasing, and actually having prey, much as children do when recognizing that a kitten, even when it hasn't chased any mice, is a miniature predator-to-be. So far, so good, but children, unlike a PDP network, can represent these relations and their fillers in a manner that preserves *relation-filler independence* (i.e., relations and their fillers are represented independently), while simultaneously representing the bindings between roles and fillers in an explicit and dynamic fashion. Thus, children can appreciate how "Fido chases Felix" is like "Felix chases Fido" (same elements involved in the same relation) and how they differ (role-bindings are reversed; e.g., Richland et al. 2006). This capacity requires (1) that relations and objects be coded with the same sets of units regardless of their specific configuration (i.e., the same unit[s] should code for the *chase* relation and for the object Fido regardless of whether Fido is chasing Felix or Felix is chasing Fido), and (2) that the system can create and destroy bindings dynamically. That is, it must be able to bind the units representing the chaser role of the chase relation to the units representing Fido (and explicitly encode that binding) when Fido is doing the chasing, and then bind the same units that represented the chaser role to Felix when Felix is doing the chasing.

Consequently, although the R&M model can simulate some important aspects of cognitive development, it fails to account for several developmental phenomena that entail relational reasoning, such as transitive inference and analogy. These capacities are important because they account for rapid and broad changes in semantic cognition, such as developing the *living thing* concept. For example, Opfer & Siegler (2004) have shown that children can quickly learn abstract categories like goal-directed agent by comparing goal-directed actions (e.g., cats turning toward mice, caterpillars turning toward leaves, and plants turning toward sunlight). Moreover, just as adults interpret ambiguous blobs turning toward goals to be living things (Opfer 2002; Schultz et al. 2004), kindergartners who learned that plants – like animals – are goal-directed also spontaneously induced (without feedback) that plants – like animals – are living things, too (Opfer & Siegler, 2004). This zero-trial learning is inconsistent with the hundreds of epochs of direct training required by the R&M model. Further, errors that children actually make during learning – such as assuming that only animals are living things – are consistent with their idea that life requires some kind of goal-directed movement (normally visible only in animals), but this error is never made by the R&M model; moreover, errors made by the model – such as honoring a categorical distinction between sunflower/rose/robin/salmon versus sparrow/pine/flounder – have never been reported in the many studies investigating development of the living things category (for review, see Opfer & Siegler 2004). Thus, while R&M's PDP model can simulate *feature-based learning* of the living thing category, it does not actually simulate children's *relation-based learning* of the living thing category.

Children make analogical inferences such as those found in Opfer & Siegler (2004) because they can process relational structure. Relational structures allow us to make alignments between otherwise dissimilar systems (e.g., Gentner 1989; Holyoak & Thagard 1995) and to make inferences based on relational – rather than only featural – commonalities (Opfer & Bulloch 2007). Thus, having learned a predicate like *goal-directed agent,* children can align otherwise dissimilar objects (cats, potted plants) and generalize the properties of cats and other goal-directed agents (e.g., living-thing) to plants as well. These kinds of problems pose a difficulty for R&M's model precisely because it represents neither relations (e.g., goal-directed) nor relation-filler bindings explicitly. Consequently, R&M's PDP model cannot use relational information to drive inference (see also Hummel & Holyoak 2003).

A recent model by Doumas et al. (2008), called DORA, provides a solution to these problems. DORA is a connectionist model that, by virtue of its solution to the dynamic binding problem, can represent relations as explicit symbols that can take arguments. Starting with unstructured representations of objects as simple feature vectors, DORA learns explicit representations of object properties (and later relational roles) via comparison-based intersection discovery. These representations are effectively single-place predicates (represented as collections of nodes) that can be bound to arguments. DORA then links sets of these single-place predicates to form complete multiplace relations (where each of the linked predicates serves as a role of the relation). Importantly, these relational roles can be dynamically bound to arguments. Like its predecessor LISA (Hummel & Holyoak 2003), DORA uses time to carry binding information. Roles are bound to their fillers by systematic asynchrony of firing, where bound roles and fillers fire in direct sequence. For example, to bind Fido to the role chaser and Felix to the role chased, DORA will fire the units representing chaser followed by the units representing Fido, followed by the units representing chased, followed by the units representing Felix.

Unlike R&M's PDP model, successful models of semantic cognition must be able to learn explicit representations of properties and relations from examples and must bind these representations to novel arguments. By exploiting the strengths of structured relational thinking, successful models can make analogies based on common relations and thereby generalize over shared relations, just as children do when learning that, by virtue of being goal-directed agents, plants – like animals – are living things.

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