(i.e., number of featural changes) of one set of objects X are mapped onto those of another set Y according to the principles of mathematics (Rothbart 2007).

In this regard Sarah is perhaps not alone in her formal analogical abilities, given the ability of other primates and birds to match entropy levels regardless of the physical icons used to instantiate this mathematical property (e.g., Fagot et al. 2001; Wasserman et al. 2001; Young & Wasserman 1997). However, Sarah's performance on functional analogy problems (Gillan et al. 1981) provides for now – the authors' concerns notwithstanding – the sole evidence of a nonhuman recognizing a *material* analogy by, "observing similarities between materials or types of phenomena" (Rothbart 2007, p. 24).

Is the relational matching-to-sample task exemplary of analogical reasoning? There is compelling evidence of relational conceptual capabilities in nonhuman animals (for reviews see, eg., Wright & Katz 2006, Zentall et al., in press). Macaque rhesus monkeys, for example, exposed to the same "symbol" training procedures as chimpanzees in a RMTS task (Thompson et al. 1997) learned to generalize their responses to a circle whenever the two items in the discriminative cue matched (e.g., AA, etc.), and to a triangle whenever they did not (Washburn et al. 1997).

Flemming et al. (2007) also found that rhesus monkeys (*Macaca mulatta*) not only correctly chose novel identical/nonidentical relational pairs in the presence of discriminative color cues, but they also correctly chose the color itself in the presence of the relational pairs. Importantly, however, unlike chimpanzees (Thompson et al. 1997), none of the monkeys in these experiments (Flemming et al. 2007; Washburn et al. 1997) responded above chance on the RMTS task over literally thousands of trials.

The authors argue that, "a cognizer could pass a classic S/D [same-different] task by calculating an analog estimate of the variability between items in the sample display and then employ a simple conditional discrimination to select the appropriate behavioral response to this chunked result" (sect. 2.2, para. 4). But, given that monkeys can learn two-item conditional relational judgment tasks as described earlier, should they not then also acquire the relational matching task if judgments of sameness and difference may be reduced to the discrimination of between-item variability or entropy? Yet, clearly the monkeys do not.

Moreover, results obtained by Flemming et al. (2007) from rhesus macaque monkeys further suggests that categorical same/different judgments, although not necessarily prevalent in early stages of relational discriminations, can be learned and applied through the implementation of entropy-infused displays. Monkeys were not only successful in making a two-choice discrimination between sets of six identical or nonidentical stimuli, but also with *pairs* of novel stimuli. When the number of items in the display was systematically reduced to two, the monkeys' performance levels neither declined nor revealed asymmetric effects (on same vs. different trials), as would be expected if the animals' judgments were still under perceptual control of entropy. Flemming et al. (2007) argued that same/different judgments are not entirely based on entropy-infused displays, but rather that conceptual categorical judgments can emerge and overcome the initial dominance of perceptual-based responding.

A conditional cue is proto-symbolic. Nevertheless, as noted, these same monkeys still failed to acquire the RMTS task. Why might this be? As described by Thompson and Oden (1996; 2000), conditional S/D tasks can be "solved" following application of a single matching operator, whereas for success in the RMTS task the animal must not only apply the matching operator to the sample and alternatives, but also to the abstract encoded outcomes.

The "profound disparity" in the performance of chimpanzees and monkeys in the RMTS task lies then in the chimpanzee's capacity – like that of children (Rattermann & Gentner 1998b) – to symbolically recode abstract relations into iconically equivalent symbols, thereby reducing relational matching to a task that is functionally equivalent to physical/perceptual matching (Thompson & Oden 1996; 2000; Thompson et al. 1997; 2001), a process, "akin to acquiring a new perceptual modality" (Clark 1998, p. 175).

Penn et al. suggest that, in part, the ability to label relational information is unique to the human mind and responsible for the discontinuity implicated by the relational reinterpretation (RR) hypothesis. In fact, we believe there is comparative evidence to suggest that similar symbolic systems also apply to our nearest primate relatives. In the case of other animals, like monkeys, however, no evidence as yet indicates that a conditional cue can acquire the full status of a symbolic label, although it would seem that symmetric treatment of a conditional cue lays the foundation for a recoding of relational information as set forth by the RR hypothesis.

Monkey see, monkey do: Learning relations through concrete examples

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Abstract: Penn et al. argue that the complexity of relational learning is beyond animals. We discuss a model that demonstrates relational learning need not involve complex processes. Novel stimuli are compared to previous experiences stored in memory. As learning shifts attention from featural to relational cues, the comparison process becomes more analogical in nature, successfully accounting for performance across species and development.

Penn et al. present an encompassing argument on why nonhumans are not able to reason relationally. Their point is well made, yet they fail to adequately address the basis of performance in the relation-like reasoning tasks in which animals do succeed, such as same-different learning (Young & Wasserman 1997), match to sample, and primitive grammatical learning (T. Q. Gentner et al. 2006; Hauser & Weiss 2002). Although these tasks do not necessarily require a relational reasoning system, they are instances of relational responding. If animals do not possess a perceptual symbol system, how do they respond relationally?

We offer an explanation for the ability of animals in the form of a computational model that learns to respond to categories defined by relations by making structured comparisons to concrete examples stored in memory. The model, BRIDGES (Building Relations through Instance Driven Gradient Error Shifting), provides an account of how animals (and people) learn to respond relationally. The model does not posit elaborate processes or representations.

BRIDGES combines two popular approaches to cognition, exemplar-based category learning (Kruschke 1992) and structure mapping theory (D. Gentner 1983). Exemplar-based models store every experienced stimulus in memory. When a novel stimulus is encountered, the similarity between the stimulus and each stored exemplar is calculated. The novel item is assigned to the category whose members have the highest summed similarity. A learning process adjusts the attention allocated to the various stimulus dimensions, which affects the model's notion of similarity. For instance, if small red stimuli and big red stimuli belong to category A, and small blue stimuli and big blue stimuli belong to category B, the model will learn to weight color more than size.

Structure mapping theory expands on this notion of similarity. The similarity between two scenes is determined by aligning the objects and relations present within one scene with the objects and relations in the other scene (Markman & Gentner 1993). The quality of the alignment determines similarity.

BRIDGES extends the notion of similarity used in exemplar models to an attention-weighted form of structure mapping theory. This allows relational similarity, the degree to which mapped objects play the same role in their corresponding relations (Jones & Love 2007), to play a variable role in the alignment process. Attention can shift between the features (e.g., red) and the relations (e.g., redder). This allows for abstraction away from the features and toward the relations, but only so far as the statistics of the environment warrant. Attention is updated according to a supervised or unsupervised gradient descent algorithm. The result is that BRIDGES is able to learn to respond differentially to the presence of relations, but that responding is still affected by the features of the stimuli.

BRIDGES has successfully simulated (Tomlinson & Love 2006) relational responding in a number of situations, including same-different learning in pigeons (Young & Wasserman 1997) and infant grammar learning (Marcus et al. 1999). Like the participants in these experiments, BRIDGES generalizes to presentations of the relations with novel objects. Also, these relations are still clouded by the featural similarity of the individual stimuli since attention shifting is rarely complete. BRIDGES's operation is consistent with observed relational shifts (from concrete to abstract) in children and experts (Chi et al. 1981; Gentner & Rattermann 1991).

In contrast to BRIDGES, Penn et al. explain the match-to-sample tasks and same-different learning as a result of entropy detection (see Young et al. 2003), which does not require a relational competency. Entropy explanations and BRIDGES both do equally well in accounting for a number of phenomena. However, BRIDGES is distinguished from an entropy explanation by its sensitivity to experienced examples (i.e. attention does not fully shift to relations). In support of BRIDGES, Gibson and Wasserman (2004) found that pigeons adjust their responding when the featural similarity of the test arrays is put at odds with the relational similarity of the arrays.

BRIDGES suggests that animals and humans at various stages of development can be understood as lying along a continuum. When modeling the simple behavior of animals or infants, attention shifting is rarely complete and a representation with only simple features and a type-token relation is sufficient. The type-token relationship assumes that the individual is able to recognize objects present in the input as members of a larger category. In other words, when pigeons are presented with an array of shapes, they are able to represent the squares as members of an abstract type, square. In contrast, when modeling more complex behavior, in children or adults, a representation using other relations (e.g., cause) or high-order relations (i.e., relations between relations) is often required. Additionally, attention shifting occurs faster and is more complete. BRIDGES provides a tool to talk about these and other differences in a quantitative way.

Animals might not be able to succeed at complex relational reasoning tasks, but they can compare current examples to previous examples in a structured way, and from this respond in a manner consistent with an understanding of abstract relations. BRIDGES is a computational model of how this relation-like behavior can be learned. By comparing concrete examples of the relations in a structured manner, one can learn to respond in a manner consistent with the relations, without true abstract knowledge.

On possible discontinuities between human and nonhuman minds

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Abstract: The history of comparative psychology is replete with proclamations of human uniqueness. Locke and Morgan denied animals relational thought; Darwin opened the door to that possibility. Penn et al. may be too quick to dismiss the cognitive competences of animals. The developmental precursors to relational thought in humans are not yet known; providing animals those prerequisite experiences may promote more advanced relational thought.

They cannot speak. Their movements are limited and clumsy. And, their sensory systems are barely functional. Evidence of habituation and associative learning can be obtained only when the most sensitive and creative behavioral testing methods are deployed. Of course, there are no signs that they reason about higher-order relations between events. Should the absence of evidence of reasoning about higher-order relations be counted as incontrovertible evidence of absence in these creatures?

This is a trick question! We might be talking about a newly hatched pigeon or we might be talking about a newborn human infant. These two organisms traverse dramatically different developmental trajectories to adulthood. As adults, pigeons fail some of the tests of higher-order relational cognition – like the forming of analogies – that humans pass. Why? Penn et al. point to the inherited information processing systems of the respective organisms; humans are born with neural systems which pigeons lack.

Penn et al.'s proposal is certainly plausible. But precisely what are these neural systems? Do these systems merely mature as the child approaches adulthood? Or must these systems be carefully cultivated by enriching experiences to fully flower? Suppose that these experiences are not a part of pigeons' usual upbringing; could providing pigeons with these experiences promote still loftier levels of cognitive achievement? Is it not reasonable to take these questions seriously before yet again proclaiming an evolved human uniqueness?

The history of comparative psychology is replete with confident proclamations of human exclusivity. Most famous and germane here is that of John Locke, who in his 1690 volume, *An Essay Concerning Human Understanding*, assuredly opined: "I think, I may be positive … That the power of Abstracting is not at all in [Brutes]; and that the having of general Ideas is that which puts a perfect distinction betwixt Man and Brutes; and is an Excellency which the Faculties of Brutes do by no means attain to" (Locke 1690/1975, p. 159).

Nearly two centuries later, the faculty of abstraction was a focal point of Charles Darwin's consideration of animal and human intelligence in *The Descent of Man*: "[T]he greatest stress seems to be laid on the supposed entire absence in animals of the power of abstraction, or of forming general concepts" (Darwin 1874/1896, p. 83). Unlike Locke, Darwin left the door open to abstraction in animals. Darwin observed that:

> It is generally admitted, that the higher animals possess memory, attention, association, and even some imagination and reason. If these powers, *which differ much in different animals*, are capable of improvement, there seems no great improbability in more complex faculties, such as the higher forms of abstraction, and self-consciousness, &c., having been evolved through the development and combination of the simpler ones. (Darwin 1874/1896, pp. 83–84, emphasis added)

Hence, abstract thinking might only emerge in species possessing a requisite ensemble of other, foundational cognitive skills.