6

Domain–Specific Causal Knowledge and Children's Reasoning about Possibility

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Before children enter elementary school, they appear capable of making predictions about causal relations in the physical (e.g. Bullock, Gelman, & Baillargeon, 1982), psychological (e.g. Wellman, 1990), and biological (e.g. Inagaki & Hatano, 1993) domains. Young children can also generate explanations of observed events across these domains as well (e.g. Schult & Wellman, 1997; Shultz, 1982; Wellman & Liu, 2007). Some have argued that these predictive and explanatory abilities indicate children possess multiple domain-specific mechanisms of causal reasoning, which develop independently (e.g. Gopnik & Meltzoff, 1997; Wellman & Gelman, 1998).

Young children also appear capable of engaging in various kinds of counterfactual inference (e.g. Beck, Robinson, Carroll, & Apperly, 2006; German & Nichols, 2003; Harris, German & Mills, 1996; Kavanaugh & Harris, 1999; as well as various chapters in this volume). These abilities also undergo particular developmental changes. These differences are often explained in terms of the development of more domain–general mechanisms or reasoning processes (e.g. Beck et al. 2006; Beck, Riggs, & Burns, this volume; Riggs, Peterson, Robinson, & Mitchell, 1998; Woodward, this volume). Some have even argued that such development can subsume apparently domain-specific knowledge (e.g. Riggs et al. 1998, suggest that the development of counter-factual reasoning abilities accounts for the development of false belief).

I would like to argue that in addition to the development of particular domain-general mechanisms that allow children to engage in kinds of causal and counterfactual inferences, there is another influence on their reasoning: their domain-specific causal knowledge. I will examine the relation between children's existing causal knowledge within a domain and their ability to make various kinds of inferences about possibility. I will explore this hypothesis across three kinds of inferences: (1) Children's use of a causal inferential mechanism based on Bayesian inference (which involves forming and reasoning about potential hypotheses); (2) Children's judgments about fictional and real entities; and (3) Children's ability to reason about counterfactuals. Each line of evidence will suggest that the way in which children represent their causal knowledge supports the kind of inference they can make.

1 Physical and Psychological Knowledge in Reasoning about the Possibilities in Interpreting Ambiguous Causal Evidence

In previous work, my colleagues and I (Sobel, Tenenbaum, & Gopnik, 2004) introduced 3- and 4-year-olds to a machine that lit up and played music when particular objects were placed on it. We explained that objects that activated the machine were called 'blickets' (and that the machine was a 'blicket machine'). We showed children a set of identical wooden blocks and that of the first twelve blocks placed on the machine, either two or ten activated it (between subjects, in the *rare* and *common* conditions respectively). Children were also shown that the machine activated if at least one object placed on it was a blicket. Children then saw a test trial, in which two new (but still perceptually identical) blocks (A and B) activated the machine together, followed by object A activating the machine by itself. We asked children whether A and B were each a blicket.

Object A is clearly a blicket, and all children categorized it as such. The more interesting question concerns the status of object B. If we make certain assumptions about the way the blicket detector works (which I will describe below), what's demonstrated in the test trial provides no evidence about the causal status of object B—object B activates the machine with another object, which independently has the power to activate the machine. One could argue that the probability that object B is a blicket is equivalent to the base rate of blickets in the world. If children recognize this possibility, their treatment of object B should depend on whether they observed that blickets were rare or common. This is a different pattern of response based on just recognizing associations among events—object B has only ever been associated positively with the machine's activation; on this view of the world, it should be a blicket regardless of the base rate. 4-year-olds responded that object B was a blicket ~80% of the time in the common condition, but only ~20% of the time in the rare condition (registering the base rate). 3-year-olds, in contrast, were insensitive to the training, and

stated that object B was a blicket ~80% of the time in both conditions. Using a similar procedure, adults respond in a qualitatively equivalent manner as 4-year-olds (Griffiths, Sobel, Tenenbaum, & Gopnik, in press).

These data have been used to suggest that 4-year-olds (and adults) possess a causal inference mechanism that is well-described by Bayesian inference, constrained by particular pieces of prior knowledge (Griffiths et al. in press; Griffiths & Tenenbaum, 2007; Sobel, 2009; Sobel et al. 2004; Tenenbaum & Griffiths, 2003). These researchers do not suggest that children are engaging in explicit Bayesian computations; rather, these investigations suggest that Bayesian inference is a computational-level description (cf. Marr, 1982) of children's causal inference: a description of how the child integrates the data they observe with the causal knowledge they possess.

One aspect of this description is the idea that children make inferences over a hypothesis space of possible causal models that could explain the data they observe. For example, in the Sobel et al. (2004) procedure, when children observe the test trial, there are four hypotheses potentially consistent with these data:

h_1) that neither object is a blicket
h_2) that only object A is a blicket
h_3) that only object B is a blicket
h_4) that both objects are blickets.

The data children observe are equally inconsistent with hypotheses h_1 and h_3 because object A has to be a blicket. The data, however, are equally consistent with the other two hypotheses (h_2 and h_4). Bayesian inference rationally describes how the prior probability of blickets affects children's inferences. I will not describe the full computation model in detail here, but refer the reader to Tenenbaum & Griffiths (2003) and Griffiths et al. (in press) for a short and more detailed version of this description respectively.

Here I will consider just the following questions: what knowledge is necessary to form this hypothesis space, and do children possess this knowledge? First, children must recognize the temporal relation between cause and effect; placing an object on the blicket detector makes it activate and the detector's activation should not cause the experimenter to place an object on it. Second, any object's location in space should be independent of any other object's locations in space; placing an object on the machine should not cause the experimenter to place any other object on the machine. Similarly, if a blicket is in one location, it does not mean an object in another location is also a blicket. Given research on infants' causal perception (e.g. Leslie & Keeble, 1987; Oakes & Cohen, 1990), and pre-schoolers' causal knowledge (e.g. Bullock et al. 1982; Sophian & Huber, 1984), it seems reasonable to assume that both 3- and 4-year-olds understand these principles. Such knowledge limits the hypothesis space to $h_1 \ldots h_4$.

But children also need to understand that there is a particular kind of causal relation between objects and machine. Sobel et al. (2004, following Tenenbaum & Griffiths, 2003) called this the *activation law*: children must recognize that there is some

mechanism that relates blickets to the detector's activation in a deterministic (or near deterministic) manner. Without this, the test trial is more consistent with object B being a blicket than the base rate—even though object A is a blicket, it might have failed to be efficacious when A and B were presented together. This is how 3-year-olds responded. I do not mean to suggest that 3-year-olds are indeterminists (this seems highly unlikely, and there is some direct evidence against this possibility, e.g. Kuzmak & Gelman, 1986; Sobel et al. 2009). Rather, 4-year-olds appear to interpret the causal relation between a blicket and the blicket detector as indicating there is a stable mechanism by which a blicket causes the detector to activate. It is doubtful that 4-year-olds know what the nature of that mechanism is (indeed, it is doubtful that adults know the nature of that mechanism, see Rosenblit & Keil, 2002). Rather, if children know there is something about a blicket that makes the machine activate, then they will treat the data in the test trial as ambiguous, and resort to the base rate. If they do not understand that such a mechanism must be present, they will be more likely to respond based on the associative information they observed.

There is some evidence that 4-year-olds assume causal relations are deterministic (e.g. Buchanan, Tenenbaum, & Sobel, 2010; Bullock et al. 1982; Schulz & Sommerville 2006). For example, Schulz and Sommerville (2006) demonstrated that 4-year-olds treat apparently stochastic data as indicating the presence of a hidden cause that worked deterministically; after observing stochastic evidence, children preferred to intervene on a novel event that had been hidden during the familiarization than a familiar event that worked stochastically. Further, several investigations suggest that preschoolers struggle with reasoning about various kinds of causal inferences that involve probabilistic contrasts (e.g. Kuzmak & Gelman, 1986; Perner, 1979; Sobel et al. 2009).

A more concrete way of examining what children know about the nature of the relation between objects and their causal efficacy is to investigate what children know about the mechanisms by which objects produce that efficacy. Do children know how a blicket can cause the machine to activate? To this end, I will turn to the study of children's understanding of the relation between objects' causal properties and stable, non-obvious properties of those objects.

Developing Knowledge of Objects' Non-obvious Properties. There is strong evidence that preschoolers relate objects' causal properties with their category membership (e.g. Gopnik & Sobel, 2000; Kemler-Nelson, 1995, Kemler-Nelson, Russell, Duke, & Jones, 2000), but there is also evidence that a robust understanding of this relation develops between ages 3–4 (e.g. Nazzi & Gopnik, 2000). There is also evidence that children believe that objects with shared category membership (indicated by a common label) will share internal properties, and even that 4-year-olds recognize that certain categories are defined by their insides while others are 'inside-irrelevant' (e.g. a jar; Gelman & Wellman, 1991). Again, however, there are some suggestions that a robust understanding of this relation develops between ages 3–4 (e.g. Gottfried & Gelman, 2005).

Are these two sets of findings related? Do children recognize that objects with shared causal properties share insides, and that those insides might be responsible for those
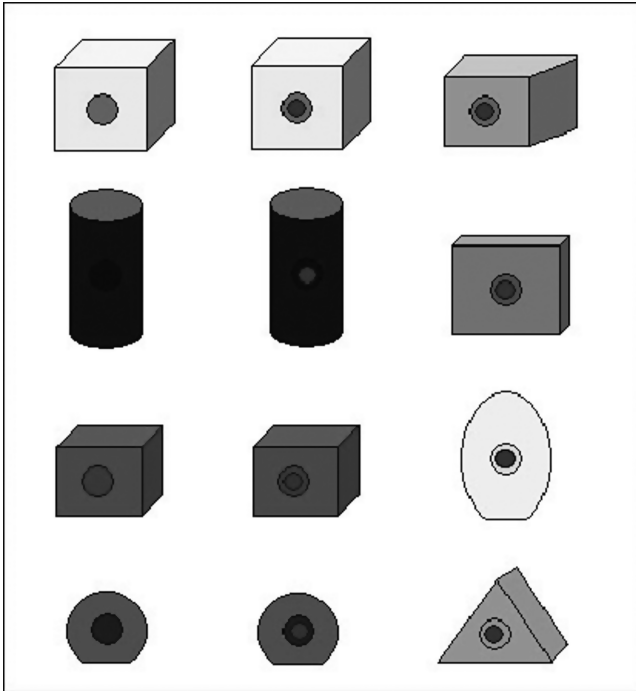
Figure 6.1 Schematic example of the stimuli used in Sobel, et al. (2007).

causal properties? Sobel, Yoachim, Gopnik, Meltzoff, & Blumenthal (2007) demon-strated that 4-year-olds, but not 3-year-olds, connect causes with insides. In one experiment, 4-year-olds transferred the causal efficacy of an object to another when its internal part was moved. In another, 4-year-olds were shown an object with both an internal and external part, and two identical objects, one with only the internal part and one with only the external part. When shown that the object with both parts had causal efficacy on a machine (it made it activate), children chose the object with the common inside as the one that would also make the machine activate.

Most importantly, 4-year-olds but not 3-year-olds relate causes and insides in light of competing perceptual information. Children were shown the blicket machine (although it was not labeled as such—it was only referred to only as a machine) and a set of objects like those shown in Figure 6.1: two identical objects and a unique one. Children observed that one of the two identical objects and the unique object activated the machine and other object did not. They were then shown that the member of the pair that activated the machine had an internal property and were asked which other object had the same inside. 4-year-olds responded based on the causal efficacy, and chose the unique object; 3-year-olds responded based on perceptual similarity.

What these data suggest is that 4-year-olds, but not younger children, understand that objects' causal and non-obvious (and in this case, internal) properties are related. Stronger evidence for this point come from some recent data collected in my lab. We told 3- and 4-year-olds that the blicket detector was a 'blicket machine' and 'things with blickets inside made the machine go'—providing them with strong information about how to relate the insides of the objects with the machine's efficacy. We then showed children that objects with internal parts (that were labeled 'blickets') activated the machine, and objects without internal parts did not activate the machine. We also showed children that the detector activated if at least one object with a blicket inside was on it. We then showed children two new objects (A and B), which activated the machine together. The door on object A was opened to reveal it was empty. Children had no trouble inferring whether each object contained an internal part (they claimed A did not, and B did). The critical question was an *intervention* question—we asked children to make the machine go. They had observed an action that was effective—placing both objects on the machine. But if children recognize that the internal part is responsible for the object's causal property, then they should recognize there is no need to put object A on the detector to make it activate. The majority of the 4-year-olds registered this information, and only placed object B on the machine. They did this significantly more often than the 3-year-olds, who were more likely to imitate what they had observed as efficacious (place A and B on the machine together).

Mr. Blicket and Blicket Machines. The data presented above suggest that children develop an understanding of the relation between causes and insides (and potentially that those insides are responsible for objects' causal properties) between the ages of 3 and 4. More generally, these data suggest that children develop an understanding of the nature of physical causal mechanisms between ages 3–4, consistent with a set of similar findings (e.g. Buchanan & Sobel, in press; Bullock et al. 1982; Gottfried & Gelman, 2005; Shultz, 1982). Is it possible that this developing knowledge allows children to recognize the inherent ambiguity in the rare-common manipulation described above? That is, if 3-year-olds could be made aware of the relation between objects' causal properties and another stable, non-obvious property, would they interpret the data they see as ambiguous and rely on the base rate information inherent in the procedure?

Sobel and Munro (2009) presented 3-year-olds with Mr. Blicket (see Figure 6.2): a blicket machine with cardboard eyes that spontaneously activated contingent on the experimenter as if they were having a conversation (akin to a manipulation used by Johnson, Slaughter, & Carey, 1998 on infants). After the experimenter and child conversed with Mr. Blicket, the experimenter told the child that Mr. Blicket would tell him/her what objects he likes. Drawing from the theory of mind literature, we chose to focus on Mr. Blicket's desires because by the age of 3, most children recognize that their own desires can be different from others' (Repacholi & Gopnik, 1997), that fulfilled and unfulfilled desires have causal consequences (Wellman & Woolley, 1990), and that shared preferences for objects relate to non-obvious properties of those objects (Fawcett & Markson, 2010). These data all suggest that 3-year-olds might understand that

Figure 6.2 Mr. Blicket.
Source: Photograph taken by the author.

Mr. Blicket wants particular objects for some reason, which is stable in the context of the experiment.[2]

Our first experiment with Mr. Blicket was an extension of the Sobel et al. (2007) procedure, in which 3-year-olds were shown the objects from Figure 6.1. For each set, they observed that Mr. Blicket liked one member of the identical pair and the unique object, but not the other member of the identical pair. They were then shown that the inside of the object in the pair that he liked had an internal property and were asked which other object had the same insides. The majority of 3-year-olds in this condition chose the unique object. To ensure that children were not just more engaged by this task than by a task involving a blicket machine, a control group of 3-year-olds was given the same procedure using a blicket machine that spontaneously activated at the beginning of the experiment, while the experimenter talked to the child. The machine's activation had a similar pattern, but it was not contingent on the experimenter. In this condition, 3-year-olds responded based on the external perceptual features of the objects.

Given the possibility that 3-year-olds recognized that Mr. Blicket's desires were related to a stable, non-obvious property of objects, we wondered if 3-year-olds would be sensitive to base rate information if the Sobel et al. (2004) procedure was replicated with Mr. Blicket's desires as opposed to a blicket machine. A new group of 3-year-olds

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[2] Of course, an individual's desires can change over time. However, in this procedure, we were concerned with whether children recognized that if an agent liked two things at a particular moment in time, those two things might share some non-obvious feature (given that the external perceptual features of the objects did not offer a guide to Mr. Blicket's desire for those objects).

participated in this procedure: they were introduced to Mr. Blicket in the same manner, trained that he either liked few or many things (two or ten of the first twelve identical blocks in a box, the *rare* and *common* conditions respectively) and that he 'activated' if at least one thing that he liked was on him. They were then shown analogous data from the test trial: that he liked objects A and B together and he liked object A by itself. All children stated that he liked object A. Ninety-three per cent of 3-year-olds in the common condition stated he liked object B compared to the 44% who said so in the rare condition.

Three controls were critical. First, we wanted to ensure that children were not relying on the spontaneous activation of the detector, but rather understood that there was a difference between the causal relations indicated by Mr. Blicket's desire towards an object and an object making the blicket machine activate. Another group of 3-year-olds were introduced to a spontaneously activating blicket machine. They received a procedure analogous to the rare condition of this experiment, using that machine. These children categorized object B as having efficacy 72% of the time, significantly more often than children in the Mr. Blicket desire condition. This suggests that when the same data are presented as a machine activating, children respond associatively, and do not use the base rate information.

Second, we wanted to ensure that children did not simply find Mr. Blicket more interesting, and thus brought more cognitive resources to the task. Another group of 3-year-olds were introduced to Mr. Blicket in the same manner and given the identical procedure to those in the rare condition, except that they were told that Mr. Blicket's activation indicated that he was 'thinking about' an object. 3-year-olds have a much more difficult time understanding the causal structure of thought than of desire (e.g. Flavell, Green, & Flavell, 1995; Wellman, Cross, & Watson, 2001), and the data were consistent with these findings: again 72% of the children stated object B had efficacy, significantly more often than children in the desire condition.

Third, we also wanted to ensure that 3-year-olds were not confused when asked to relate Mr. Blicket's activation with his thoughts as opposed to his preferences. Desires tend to be based on fairly stable dispositions, while thoughts might be more fleeting and why an individual thinks about an event might not always be stable (e.g. Eisbach, 2004), particularly with regard to properties the objects might have. In a final experiment, we introduced a new group of 3-year-olds to Mr. Blicket (we called him Mr. B. in this experiment to avoid confusion), and told them that he knew which of the objects were 'blickets' and his activation indicated that a blicket was on him (i.e. he just acted like a blicket machine). Again, knowledge is a mental state that is not as well-understood by 3-year-olds as desire (e.g. Gopnik & Slaughter, 1991), so we predicted that children would not understand this particular activation law, and not use the base rate information. Indeed, they did not, categorizing object B as a blicket 80% of the time even though blickets were rare.

In each of these controls cases, our hypothesis was that children would not register the relation between a stable property of the objects and those objects' efficacy (i.e.

whether they activated the spontaneously activating machine or Mr. Blicket/ Mr. B agent). However, a critical prediction of this account is that small subsets of 3-year-olds would register these relations. We performed a post-test on children in the rare conditions of the Mr. Blicket desires procedure, and all three of the control procedures (ninety children in all). After their participation in the procedure and a delay, all children received the same internal properties procedure, using the stimuli shown in Figure 6.1. Across the procedures, the higher the percentage of responses in which the child related the internal properties of the objects to their causal properties, the more likely children were to respond consistently with the base rate (and thus to have interpreted the data from the test trial as not revealing anything meaningful about the causal status of object B). This correlation was significant even when unrelated measures of general cognition were factored out. 3-year-olds who understood that the causal efficacy of the objects was related to a stable, non-obvious property were more likely to observe the ambiguity in these procedures, and potentially use the base rate information appropriately.

An important facet of these data is that across the 'rare' conditions, children were shown the same data; what differed was the way in which the experimenter described the data, which we assumed tapped into (or not) children's existing causal knowledge. Because 3-year-olds knew a great deal about the relation between desire and non-obvious properties, children were able to interpret the data they observed as ambiguous. In contrast, 3-year-olds do not appear to understand the relation between objects' properties and the working of a physical machine or why people think or know about certain things but not others, and as such failed to interpret the present data as ambiguous in the base rate experiment.

The final point worth making here is about the definition of 'domain'. Concepts like *desire, thought,* and *knowledge* are all part of the psychological domain, and seem ontologically different from the physical mechanisms involved in how a blicket detector might activate. I do not want to suggest that the domain-specific knowledge necessary to engage in the kind of hypothesis formation for Bayesian inference means that *any* psychological inference will emerge before *any* physical inference. Rather, what is critical to children being able to engage in this kind of causal reasoning is their understanding of particular causal mechanisms within a domain of knowledge.

2 Physical and Biological Knowledge in Judgments of Fantasy

The previous section suggested that 3-year-olds understand certain aspects of the causal structure in the psychological domain before they understand certain aspects of causal structure about the physical world. In this section, I want to examine children's general causal knowledge about the physical world compared to the biological world, focusing on a particular kind of judgment: about what is and is not possible. Judgments of

possibility are clearly based on experience—usually if we experience something, we believe it is possible. However, there are many objects and entities with which children might not have had direct experience that they still believe are possible. Similarly, numerous experiments in cognitive development present children with scenarios that actually are impossible (through various kinds of sleight of hand, for example, the 'shrinking machine', see e.g. DeLoache, Miller, & Rosengren, 1997). Because a child's causal knowledge makes a set of ontological predictions regarding what is and is not possible in the world, broad differences across these domains might interact with children's judgments about the possibility or impossibility of objects or events.

There are many studies of children's judgments of the fantasy/reality difference (e.g. Harris et al. 1991; Morison & Gardner, 1978; Samuels & Taylor, 1994; Shtulman & Carey, 2007; Subbotsky, 1994). Most of these suggest that children generally recognize that impossible events are impossible and real events are not. However, most of these studies do not consider judgments across domains of knowledge, or how children's developing causal knowledge in a domain might affect their judgments.

Biological vs Physical Knowledge. Infants understand various violations of causal structure in the physical environment (e.g. see reviews by Baillargeon, 2002; Spelke et al. 1992), and although paradigms that use action instead of looking time show a delay in children's understanding (e.g. Keen, 2003), there is little doubt that by age 4, children have a good understanding of certain aspects of physical causality. Further, the previous section detailed 4-year-olds' sophisticated causal reasoning abilities about certain kinds of physical events such as whether and what makes a machine activate (see Gopnik et al. 2001; Siegler 1976; Sobel et al. 2004; Sobel et al. 2007). Four-year-olds can also generate various mechanistic explanations for relations among physical events (Bullock et al. 1982; Shultz, 1982).

Children's biological knowledge, in contrast, is not as well developed. Children recognize differences between animate and inanimate objects, and assign psychological traits only to the former (e.g. Gelman & Opfer, 2002; Saxe, Tenenbaum, & Carey, 2005). But, most research on children's biological concepts proposes that biological knowledge is still developing during and after the pre-school years (e.g. Carey, 1985; Hickling & Gelman, 1995; Inagaki & Hatano, 1993, 2002; Rosengren et al. 1991; Springer, 1995). In general, these investigations suggest that during the preschool years, children appear to have a richer understanding of the physical than the biological domain.

A notable exception comes from a set of studies on children's explanations of impossible events. Schult & Wellman (1997; see also Wellman, Hickling, & Schult, 1997) investigated how preschoolers apply knowledge of folk physics, psychology, and biology to provide explanations of various types of human action. They found that 3- and 4-year-olds explained impossible physical events—such as a character wanting to float in the air—in terms of physical principles (e.g. gravity), and impossible biological events—such as a character wanting to hang from a tree branch forever—in terms of biological principles (e.g. limb fatigue). They concluded that young children have at least three basic

explanatory systems for providing explanations about physical, psychological, and biological events. Critically, Schult & Wellman (1997) asked children to explain why impossible events were impossible (i.e. could not happen). They found few domain differences between explanations of impossibility in the physical and biological domains.

These investigations suggest that young children have a relatively firm understanding of what is and is not possible across domains of knowledge. More importantly, these data suggest that children also understand the nature of the causal structures within these domains at around the same time. This is somewhat inconsistent with the conclusion from the previous section: that children's understanding of causal structure differs across domains and affects various inferences they make—in this case about the nature of possibility. At issue might be how children conceptualize *impossibility*. Shtulman & Carey (2007) found that 4-year-olds had little difficulty judging impossible and ordinary possible events as such, but also tended to judge improbable (but possible) events as impossible. They suggested that young children make judgments of impossibility based on whether they can 'imagine circumstances that would allow an event to occur' (2007: 1015). Such an ability potentially relies on children's experience with the world (or memory of that experience), but also should rely on children's developing causal knowledge. If this were the case, then we would expect to see differential judgments based on both of these pieces of information. Judgments about known possible events might be based on experience (children would presumably judge a microwave as real, even if they don't know how one works). In contrast, judgments about unknown or impossible events (including whether the event is impossible) might be based more on the child's existing causal knowledge.

The Ontology of Machines. Cook & Sobel (2011) examined this hypothesis by investigating children's judgments about whether various kinds of machines were possible. We were interested in machines because young children are clearly exposed to the category, but the increasing prevalence of technology suggests that judgments about the possibility of various kinds of machines reflect deep ontological commitments about what causal relations are possible.

We asked 4-year-olds, 6-year-olds, and adults about four categories of machines: (1) machines that exist in the world and we believed were familiar to children (e.g. a *radio*: a machine that plays music); (2) machines that exist in the world and would only be familiar if the child had a particular experience that introduced him/her to the machine (e.g. a *metal detector*: a machine that beeps if metal is nearby); (3) machines that were impossible because they violated an aspect of physical causality (e.g. a *shrinker*: a machine that makes a big crayon into a small crayon); and (4) machines that were impossible because they violated an aspect of biological causality (e.g. a *plant speaker*: a machine that makes flowers talk). Figure 6.3 shows the percentage of times children and adults judged each of these types of machines were real.

All three groups judged the familiar possible machines as real and both categories of impossible machines as make-believe more often than chance. However, 4-year-olds showed a difference in their categorization of the physical and biological impossible
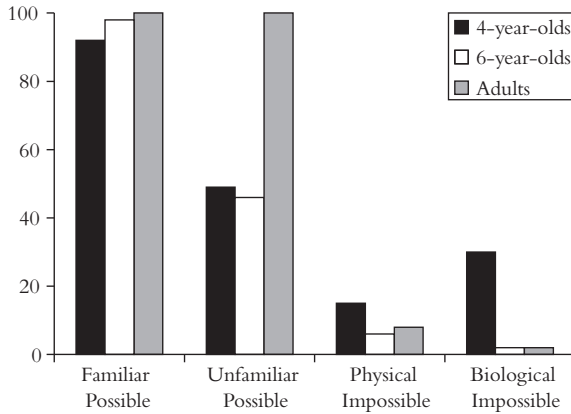
Figure 6.3 Percentage of machines in each category judged to be real (as opposed to impossible).
Four-year-olds, but not 6-year-olds, judged impossible machines differently across the physical
and biological domains.
Source: Data from Cook & Sobel (2011).

machines, saying the latter were more likely to be real than the former. Older children
did not show this difference, possibly because their understanding of causal knowledge
in the biological domain is more developed.

   Both 4- and 6-year-olds responded at chance levels about unfamiliar machines.
There are a number of possibilities for this pattern of performance. Because we could
not standardize the experiences children had prior to coming into the lab, some
children might have had experience with some of these items. If children recalled
their experiences with the machine in question (e.g. metal detectors at an airport), they
should say that it is real. If children did not recall the experience or never had the
experience in the first place, they might treat the machine as Shtulman & Carey's
(2007) improbable items, categorizing it as make-believe because they can't access a
situation in which it is real.[3] It could also be possible that both age groups might lack
specific pieces of causal knowledge necessary to recognize that the mechanisms for
some of these machines are possible. The present data cannot discern between these
possibilities. Finally, as children got older they tended to categorize more of the
biologically impossible items as make-believe. Judgments in no other category signifi-
cantly correlated with age. This correlation was present even just among the 4-year-old
sample, suggesting that some biological knowledge develops during this time. In
general, these data are problematic for the idea that experience alone constrains

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[3] A detailed examination of these data found that the variance in the unfamiliar machine condition was
greater than that of the familiar machine condition (and either impossible category as well). This suggests a
greater level of individual differences of responses in this condition, consistent with the analysis described in
the text.

children's fantasy judgments (clearly, children do not observe the physical or biological violations we asked them about in the real world). Rather, we suggest that children's causal knowledge constrains what they believe is impossible. This is consistent with the arguments from the previous section about Mr. Blicket. In that investigation, for a child to reason in a manner consistent with Bayesian inference (a domain-general judgment), they needed a particular piece of specific knowledge within a domain crucial to understanding something about the causal laws of that domain. Here, children need similar domain-specific knowledge to make a judgment about whether something is real or make-believe. They need to know that impossible entities are ones that violate a causal law.

Children's Fictional World Construction. The experiment described above suggests that children might use their understanding of causal structure to recognize that certain physical violations are make-believe, and that children are more credulous towards violations of biological structure. If this is the case, then we might expect children to treat violations of physical and biological causality differently in other tasks that require them to make judgments about fantasy worlds. To examine this, we focused on how children constructed fictional worlds in the context of writing a novel story.

Intuitively, constructing a fictional world involves more than just recognizing the difference between what is real and what is not. Skolnick & Bloom (2006a) point out that children must appreciate the causal structure of the fictional world in question, and what kinds of causal violations (if any) that world can support. In a set of empirical studies (Skolnick & Bloom, 2006b), they found that children do not treat all fiction as one possible world. Rather, they suggest that children appreciate particular boundaries among fictional worlds—for example, children believe Batman and Spongebob come from different fictional worlds, and that each believes the other is fictional. Batman, however, thinks Robin or the Joker is real.

This argument suggests that if children are asked to construct their own fictional world, then that construction will be relatively coherent in the kinds of causal laws that exist in the world. We (Sobel & Weisberg, in preparation) investigated this question by asking 4-year-olds to construct a novel story through a set of picture choices. Children were told that they were going to write a story about a novel character. Children saw six pairs of pictures. One picture in each pair depicted the character engaging in an ordinary event. The other picture showed the character engaging in an event with the same outcome, but in which the character violated some aspect of physical or biological causal structure. There were an equal number of physical and biological violations across the task. For example, in one picture pair, children could choose to make the protagonist live with his mom and dad, brother and sister, or make him live with his fifty-two mothers and fathers and sixty-seven brothers and sisters (an example of biological violation). In another picture pair, children could choose whether the character walked outside to play through an open door or through a wall (an example of a physical violation).

We coded three aspects of children's story construction: (1) How many fantasy choices children made; (2) How consistent each child was in his/her choices; (3) Whether responses differed between the physical and biological items. For the most part (79% of the time), children chose the ordinary pictures. Individual children were also relatively consistent in their choices. We considered the number of times children switched from an ordinary response to a fantasy response (or vice versa) over the course of the trial. For any given picture pair, the probability that children would switch their response type was only 23% (well under chance levels) and the majority of children (69%) made zero or one switch. Thus, once a child made an ordinary response, he/she was likely to continue making ordinary responses, and once a child made a violation response, he/she was likely to continue making responses of that type. When children did differ in their responses, they systematically did so across domains: they were more likely to have the character violate aspects of physical causality than biological causality, even though the overall level of such responses was rare.[4]

Are these data consistent with the previous findings about children's ontological commitments about machines? I suggested above that 4-year-olds recognized more impossible physical machines than biological machines as such because at this age, they understood the causal structure of the physical world more generally than the causal structure of the biological world. Here, when given the choice between constructing a story featuring an ordinary physical or biological event and a corresponding one that violates an aspect of causal structure in that domain, children made more physical violations than biological ones. If children misunderstand the biological violations as possible, they might be more inclined to choose biological violations more often than physical ones, which would be inconsistent with these data. However, this is not necessarily the case, as the ordinary options were clearly possible (and presumably would be recognized by children as possible). Thus children's failure to select the biological violations in the construction of a fictional world is not informative since there is always a possible alternative that could be seen as a safer choice to maintain coherence. Critically, it is important to remember that children are doing so in the context of generating a story—a *fictional* world. If children are generating such worlds coherently (as suggested by Skolnick & Bloom, 2006a, among others), then their causal knowledge should guide this construction. Overall, these data suggest that children's developing causal knowledge across domains influences their reasoning on the same kind of task.

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[4] One other aspect of these data was interesting. We also contrasted two types of protagonists—a human character on Earth with an obvious alien character from another planet (Zoltron from the planet Zolnar, who was a purple carrot). Our goal was to suggest that one character might be more likely to violate real-world causal knowledge. However, children were completely insensitive to the difference between these conditions (and made mostly ordinary choices across both conditions). This finding, however, might indicate another way in which children's immature causal understanding manifests; at age 4, it would appear that children do not recognize that different contexts influence what is possible (consistent with Beck's research discussed in the section on counterfactuals below).

3 Counterfactual Reasoning across Domains[5]

The previous sections have suggested that children's causal knowledge influences their judgments about ambiguity and about fantasy, both in judging fantasy from reality but also in constructing novel pieces of fiction. This section will consider the relation between children's causal knowledge and their ability to engage in types of counter-factual inference. Harris and colleagues (Harris, German, & Mills, 1996; Harris, 2000; Kavanaugh & Harris, 1999) proposed that children's ability to learn new causal relations is not only related to their ability to engage in counterfactual thinking, but more strongly, following Mackie (1974), that counterfactual reasoning plays a primal role in determining whether a causal relation is present. On this view, children develop the ability to engage in counterfactual reasoning quite early on, use this ability to learn about causal relations in the world, and this ability is present across domains of knowledge.

This hypothesis has some difficulty, as both German (1999) and Guajardo & Turley-Ames (2004) found that young children differed in their ability to generate counter-factuals when explaining events, depending on the valence of the event (whether the outcome was positive or negative) or whether the counterfactual added or removed antecedent events. Other researchers have challenged the hypothesis that young children can engage in counterfactual inferences early in development more directly. For instance, Riggs et al. (1998) suggested that counterfactual inferences place certain demands on executive functioning, which might be difficult for young children. They told 3- and 4-year-olds a story about a character (Peter) who was sick in bed. Another character (Sally) went off to the drugstore to get him medicine. While Sally was away, Peter received a call to go to the post office to help put out a fire. Children were asked where Peter would have been had there not been a fire. They found that 3-year-olds in particular did not perform well on the counterfactual questions and suggest this is due to children having to inhibit where Peter actually was. In contrast, young children had less difficulty with a similar prediction about a future hypothetical (i.e. predicting what would happen given a hypothetical antecedent). Such an inference does not have the same executive demands; the counterfactual requires the child to inhibit the present reality in favor of alternate events, while the future hypothetical does not require this inhibition. Riggs et al. (1998) further argued that such executive functioning might mediate reasoning on a false belief task; they found a correlation between children's counterfactual reasoning abilities and success on a standard false belief measure (see also Perner, Sprung, & Steinkogler, 2004).

Beck et al. (2006) followed up this study by considering a slightly different hypoth-esis. They found that while 3–4-year-olds might have some difficulty with standard

future hypothetical or counterfactual questions, what they really struggle with is a more general concept of possibility (consistent with the conclusions made by Shtulman & Carey, 2007, described in the previous section). In their experiments, 3- and 4-year-olds could reason about events that could occur in the future or events that could have been different in the past had antecedent events been different. But at this age, children struggled when asked to make an open-ended response to a similar counterfactual question that required they recognize two different outcomes of an event as both possible (and plan accordingly for either). They suggested that preschoolers might make future hypothetical and counterfactual inferences, like the ones described by Riggs et al. (1998) above, 'by thinking about the counterfactual event in isolation, without recognizing its temporal relationship to the actual event' (1998: 423). They conclude that children develop a general understanding of possibility that underlies their ability to engage in counterfactual reasoning.

There is clear merit to this account. For example, it nicely explains a finding presented by German & Nichols (2003), who showed that preschoolers were better at making counterfactual inferences about a direct causal relation as opposed to a more indirect cause of an event. They argue that this difference results from the complexity of the inference and not from difficulties with counterfactual reasoning *per se*. Beck et al.'s (2006) account suggests that in longer causal chains, children must recognize that there are multiple possibilities that lead to the particular consequent, while in a short causal chain, children only have to consider the relation between the antecedent and consequent, regardless of any other possibilities. This appears to be a more parsimonious interpretation of these data[6] (Perner and Rafetseder, this volume, generate a similar analysis of these findings).

Consistent with the points made in the previous sections, the hypothesis that I would advocate here is a slight modification to Beck et al.'s (2006) argument: that children's existing causal knowledge might interact with their developing concepts of possibility. For instance, Beck, Riggs, & Gorniak (2010) argue that after age 4 children are still developing

> the understanding that the alternative world was once a possibility that could have happened instead of what really did happen (at around 5 or 6 years; Beck et al. 2006),

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[6] Beck, Riggs, & Gorniak (2010) failed to replicate the German & Nichols (2003) findings using similar stories. An interesting difference in these findings is that German & Nichols tested their participants in Greek while Beck et al. tested children in English. Beck et al. believed that this should not have affected the results. However, an examination of Greek morphology concerning counterfactual utterances (Iatridou, 2000) suggests that Modern Greek has a rich morphological structure regarding counterfactual utterances (presumably richer than English). Children might be sensitive to that difference when learning their language, and thus children learning Greek might understand counterfactual questions earlier than their English-speaking counterparts. This is not to say that children with Greek as their native language can reason about counterfactuals earlier than children whose native language is English; rather they might understand the complicated morphology necessary to elicit adult-like responses about hypothetical questions at a younger age, because competency in their language requires sensitivity to this morphology. This is an open question, but this interpretation is consistent with Beck et al. (2006)'s hypothesis that what is developing is a broad understanding of possibility.

and the understanding of the emotional consequences of considering these counterfactual worlds, such as regret or relief at around 7 years (Guttentag & Ferrell, 2004; see also Beck & Crilly, 2009). (pp. 14)

My reasoning for modifying Beck et al.'s (2006) argument starts from the minor discrepancy mentioned here. Why might children understand possibility at age 5–6, but not the emotional ramification of considering those counterfactual worlds until age 7? Perhaps this difference is not meaningful, but could this be because understanding the *causal* relations between outcomes and their emotional ramifications, particularly about emotions that require metacognitive awareness, does not develop until relatively late (around age 7, e.g. Berti, Garattoni, & Venturini, 2000; Harris, Olthof, Terwogt, & Hardman, 1987)? More generally, children's ability to make counterfactual inferences might depend on the specific causal knowledge they possess about the inference they are asked to make.

To illustrate this point, consider the following experiment by McCormack, Butterfill, Hoerl, & Burns (2009; McCormack, Frosch, & Burns, this volume). They presented children with similar test trials to those used by Sobel et al. (2004), but without the training. They were interested in whether children could answer counterfactual questions about whether the machine would activate. They found that 5-year-olds responded accurately to both predictive and counterfactual questions,[7] and suggest that, 'whatever account is provided of the processes and/or representations underpinning children's causal learning on the blicket detector task must be one that can explain children's ability to make not only causal judgments, but also counterfactual ones' (McCormack et al. 2009: 1573). Paralleling the work I presented above, I would suggest that if their experiment were replicated using Mr. Blicket and asking about his desires, younger children would also show the ability to answer correctly on counterfactual questions.

While I have not performed the experiment described in the previous paragraph, I have considered this question by looking at the kinds of counterfactuals questions used by Riggs et al. (1998) about different psychological states—whether someone will be happy or sad given a fulfilled or unfulfilled desire and whether someone will be surprised given their knowledge about an event. Understanding the emotional ramification of a fulfilled or unfulfilled desire is understood by almost all 3-year-olds (e.g. Wellman & Woolley, 1990), while understanding the causal relations between knowledge and surprise is typically not understood until age 5 or later (e.g. Hadwin & Perner, 1991).

I (Sobel, 2002) told 3- and 4-year-olds stories about characters (acted out with dolls), which ended with an antecedent and then a consequent event.[8] On one story, the

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[7] Interestingly, they found that 4-year-olds did not respond in a similar manner, inconsistent with my previous work, and the work presented in the section above. They discuss some possible reasons for this difference, which are beyond the scope of the present discussion.

[8] This procedure was done as part of my doctoral thesis, and also considered other kinds of events. For purposes of space, however, I am omitting other aspects of this procedure. Feel free to contact me for more information.

antecedent event fulfilled a character's desire, which resulted in a consequent of the character being happy. Children were asked how the character would feel if the desire was unfulfilled. On the other story, the antecedent established that the character was happy but ignorant of a particular event, which would surprise him (e.g. another character jumping out of a closet), and was surprised when this happened. Children were asked how the character would feel if he was not ignorant of the event that surprised him (i.e. would he feel happy or surprised?). Children were relatively accurate at answering the counterfactual question about another's desire, and relatively inaccurate at answering the counterfactual question about surprise. Further, neither of these responses correlated with performance on a standard set of false belief tasks.

I am not arguing that all counterfactual reasoning emerges early on, or that children's capacity to reason about counterfactuals is the only mechanism (or even, necessarily, *a* mechanism) for causal learning. Rather, I suggest that children develop coherent representations of specific causal knowledge within a domain, which might support counterfactual reasoning abilities. Cases where we see children engaging in counterfactual reasoning early on might indicate that they possess an understanding of the causal structure of the situation. Cases where children might lack that causal knowledge (such as in the ramification relating events with complex emotions) might show a developmental lag from a general understanding of possibility. Children *are* developing domain-general mechanisms related to counterfactual inference. For example, children's understanding of the language used to ask counterfactual questions seems important (see footnote 6).

Like Beck et al. (2006), I also suspect that children's broader understanding of possibility is relevant to generating counterfactual inferences. In another set of experiments (Sobel, 2004), I told 3- and 4-year-olds stories in which a character wanted to perform an impossible task, tried to do so, but could not (because the event was impossible). Children were asked a more 'open-ended' question—what could the character do different—which is similar to the questions that Beck et al. (2006) described were difficult for young children. A small percentage of the time (~30%), children stated that the character could not do anything different because the task was impossible, and there were some differences across stories in the physical, biological, and psychological domains. I also asked the same children to generate explanations of impossible events in the same domains (some cases were violations of a similar causal law; in other cases the causal law was different from what was asked in the counterfactual question, but in the same domain of knowledge). Children explained impossible events appropriately more frequently than they correctly rejected counterfactuals as possible (~40–70% of the time across the domains, with some differences among them). But critically, the frequency with which that child generated correct explanations of why impossible events were impossible predicted how often they generated correct responses on the open-ended counterfactual question. The latter question is potentially more difficult for a pre-schooler; it has an executive demand that the former does not (i.e. from the child's perspective, why would the experimenter ask for an alternative possibility if there is not one?). These data are consistent with Beck et al.'s

(2006) account that such open-ended questions are difficult for young children, but they are also consistent with the possibility that regardless of that domain-general development, these data suggest that children's existing causal knowledge influenced their ability to generate such alternatives.[9]

   An important challenge towards how we understand the development of counterfactual inference in children is to consider how such inferences might be related to causal knowledge. For instance, a nice empirical investigation would be to consider whether Beck et al.'s (2006) approach holds over various domains of knowledge. I suspect that children have difficulty with understanding what is possible, but also that some of this understanding will be mediated by their developing causal knowledge across domains.

4 Concluding Thoughts

Domain-general mechanisms are critical to cognitive development. Bayesian inference over causal graphical models has suggested a long line of computational and empirical studies (see e.g. Gopnik & Schulz, 2007). Imagination and pretense has suggested clear investigations of children's understanding of the fantasy/reality distinction (see e.g. Taylor, 1999). Theories of executive function also make predictions about how children engage in pretense and understanding others' pretending (e.g. Frye, 2000). Executive function is also clearly important to generating and reasoning about counterfactual inferences (e.g. Riggs et al. 1998), as might be children's pretense (Kavanaugh & Harris, 1999). In all cases, it seems critical to integrate these domain-general approaches with the idea that the development of domain-specific causal knowledge might affect these inferences. An open question, critical to this discussion, is where domain-specific causal knowledge comes from. Answering that question, and illuminating how this integration takes place, are clear goals for future research.

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[9] Hitchcock (this volume) gives a particular good example of a view I would endorse, concerning counterfactual inferences about desks made of Jello. We can reason about such a counterfactual, but such a counterfactual's relation to causal inference is not clear. In order to reason about such a counterfactual, one must already possess some causal knowledge (e.g. about the structural integrity of gelatin). Seelau, Wells, & Windschitl (1995) make a similar point.

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