CHAPTER 14

Cognitive Science and Cognitive Development

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The interdisciplinary field of cognitive science represents an important way to study cognitive development. It offers insights on the mind in development that are not always apparent when considering cognitive development more narrowly from the perspectives of one of the main constitutive domains of cognitive science: psychology, linguistics, computer science, neuroscience, anthropology, and philosophy. This chapter examines several ways in which a cognitive science approach has helped frame and address questions about cognitive development that either would not have been posed at all, or would have been posed in different ways when emerging from each of the disciplines. There are clear benefits to this approach, but there are also major challenges imposed by the need for researchers to master methods and theories across several disciplines. As the depth of knowledge in each local discipline increases rapidly, how can researchers who stay abreast of these new developments also take advantage of scholarship that is much farther afield from their usual area of work? This chapter illustrates ways to combine the necessary depth in any single field with the benefits of breadth as well.

The most powerful contribution of cognitive science lies in the ways in which convergences across disciplines offer insight not available from the perspective of just one. By building on insights, paradigms, methods, and models in other disciplines that are focused on the same or similar problems and questions, a cognitive science approach repeatedly offers new ways of understanding familiar phenomena. It also helps us see new phenomena through its unique lens. The idea of the benefits of research that incorporates diverse viewpoints is hardly new. At least since the time of Bacon, the value of converging forms of evidence was seen as important to induction (cf. Heit & Hahn, 2001). More than 150 years ago, just as the different sciences were starting to become recognized as distinct, the British polymath William Whewell discussed the insights offered by the consilience that occur when widely divergent forms of evidence for a common pattern emerge (Whewell, 1840/1999). The recognition of cognitive science, however, as an arena in which important convergences could occur is far more recent, having gained serious attention roughly 30 years ago (Bechtel, Abrahamsen, & Graham, 1998; Keil, 1991, 2001). While relatively new, the benefits from this convergence have been among the most impressive of any interdisciplinary effort.

Developmental research has been the most prominent area of cognitive science in which theories and research have come together to yield powerful new insights. What
is it about the study of the development of cognition that brings together theory and empirical research in psychology, linguistics, neuroscience, computer science, anthropology, and philosophy in ways that are rarely seen in studies of the mature form? This chapter focuses on how the study of the developing mind tends to bring together ideas in the cognitive science disciplines in especially fruitful ways. In particular, it illustrates how patterns of change over time in developing organisms are more likely to foster awareness of common problems across the disciplines.

The analogous chapter, “Cognitive Science and the Origins of Thought and Knowledge,” which appeared in the previous edition of this Handbook (Keil, 1998), approached the topic by considering fundamental questions about the mind and how they are best informed by considering them from the vantage points of several distinct disciplines. Questions such as how to quantify entities, recognize individuals, or communicate successfully were considered. This way of understanding what cognitive science is and its impact on development has been highly effective and continues to be a prominent way of motivating and conducting research. One need only look at current research on the development of quantitative understanding (e.g., Dehaene, 1998; Wynn, 1998), object tracking and individuation (e.g., Leslie, Xu, Tremoulet, & Scholl, 1998; Munakata, 2001; Scholl, 2004), and communication (e.g., Bloom, 2000; Gleitman & Bloom, 1998; Lightfoot, 1999; MacWhinney, 1998; Yang, 2004) to see the lively and productive benefits of a research strategy that poses questions in ways that draw on several disciplines at once.

This chapter could easily be an incremental review of those basically interdisciplinary questions and an update of the dramatic advances in research in each of these areas. The earlier chapter, however, provides a road map of sorts that would easily enable readers to make such extensions on their own. Instead, I have taken a different approach here. This chapter focuses on basic questions about cognitive development that have been posed in psychology for many decades, often for more than a century. It then explores how those questions have changed so as to be more inclusive of insights from other disciplines that make up the cognitive sciences. These changes occur both because of an emerging awareness of related questions in those other disciplines and because of a recognition of the limitations of posing them in their traditional narrow terms. The result has been a shift both in how the questions are posed and in the nature of the likely answers. The strategy of the prior chapter was to start with developmental questions that were intrinsically interdisciplinary and show how different disciplines converged to answer them, whereas the strategy here is to focus on long-standing developmental questions that have traditionally been seen as centered in psychology and to show how their scope and breadth have changed. In the end, there is a convergence from both strategies on similar kinds of questions, but this account tends to reflect more closely the historical pattern from the perspective of psychologists. In addition, the questions addressed here are meant to be distinct from those of the earlier chapter so as to consider different perspectives. They are all posed in domain-general terms as opposed to the domain-specific format that governed the prior Handbook chapter. This shift does not mean that domain specificity is irrelevant to the answers to these questions; it merely uses a point of departure to organize this material. The final section of this chapter confronts domain specificity versus generality directly and, in doing so, links this chapter more closely with the prior one.

The questions addressed here are shown in the Chapter Contents. Ten questions are addressed here:

1. What is the initial state?
2. Is there an adapted mind?
3. Does development proceed from the concrete to the abstract?
4. What is the nature of conceptual change?
5. What is the difference between learning and development?
6. What are the representational formats underlying developmental change?
7. What is the role of implicit and explicit cognition in development?
8. What is the role of association and rules in development?
9. Are there developmental universals?
10. What constitutes a cognitive domain and how does domain structure influence development?

BEGINNINGS

The earliest periods of cognitive development are of great interest to scholars from a wide range of disci-
plines. A focus on these periods leads naturally to questions about initial states and about the ways in which the mind might be adapted for learning.

**What Is the Initial State?**

At least since the writings of Plato and Herodotus, scholars have asked about the “initial state” of the human child. What is the best way to characterize the newborn’s cognitive architecture and capacities? In one sense, questions about the initial state at the moment of birth seem arbitrary and misleading. The particular moment of birth does not seem to be particularly important and can be influenced considerably by pharmacology and apparently random environmental triggers. Moreover, children are frequently born preterm, sometimes by more than 2 months, and as the viability of younger and younger preterm infants increases, the moment of birth becomes ever more blurred. With children surviving birth at times as early as 4 months prior to the typical due date, why talk about the normal birth date of 9.5 months postconception as the “initial state”?

There are several good reasons for continuing to focus on the question of the cognitive nature of the newborn delivered at the normal due date. First, despite clear evidence that learning can occur prenatally (DeCasper & Spence, 1986; Moon, Cooper, & Fifer, 1993; Nazzi, Bertoncini, & Mehler, 1998), there is little doubt that the opportunities to learn new information expand enormously after birth. Not only are all the sensory systems suddenly bombarded with dramatically new and much richer information, the event of birth, which places the newborn outside the womb, triggers a host of new interactions and inputs from caregivers and others around the infant (e.g., Fernald, 1992, 1993). Second, birth itself may coincide with new cognitive capacities, as is illustrated by comparisons of developmental capacities of full-term and preterm infants (Rose, Feldman, & Jankowski, 2001; Roy, Barsoum-Homsy, Orquin, & Benoit, 1995; Weinacht, Kind, Monting, & Gottlob, 1998). Birth may help accelerate or trigger cognitive capacities and abilities. Finally, even newborns are capable of a wide variety of actions on their environment that bring new experiences to them and that, in their own right, constitute important areas of learning.

From the perspective of developmental psychology, questions about the initial state were vague and largely ill formed until the past decade or two, when they have become sharpened by work in other disciplines. From linguistics, the notion of learnability has been important. From computer science, learnability and massive parallel processing have become influential, as have ideas about architectural configurations of the initial state. From neuroscience, we now have precise neural accounts in other species of initial states and their modifications through experience as well as new paradigms for how endogenous experience, as well as exogenous experience, might structure the brain. From philosophy, there has been a considerable sharpening of ideas about initial states, and from anthropology, the notion of backward convergence with decreasing age toward a common mental structure has emerged. Each of these can be considered in more detail.

In one sense, the problem of learnability is straightforward. It asks what sorts of knowledge structures are learnable given a particular form of learning, a set of environmental inputs, and some notion of what it means to successfully achieve learning (Pinker, 1989, 1995). In many cases, it is impossible to learn a unique pattern given a limited set of data. A classic example involves trying to figure out what sort of function describes the curve that goes through a finite set of points. It is not possible to derive a unique function in most such cases, and even appeals to parsimony and simplicity are often not adequate to solve these riddles of induction (Goodman, 1965). This problem became especially evident in language acquisition where Chomsky’s notion of the “poverty of the stimulus” was used to motivate the idea that many learning systems could not identify the grammar of a language given the normal “impoverished” inputs that those systems would encounter (Chomsky, 1975). Building on more formal demonstrations of the inability of some learning systems to identify a given language from a larger possible set (Gold, 1967; Wexler & Culicover, 1980), a number of scholars argued that the same formal approach could be applied to many other areas of learning and cognitive development (Jain, Osherson, Royer, & Sharma, 1999).

The learnability approach and the “poverty of the stimulus” argument, however, has not been accepted uncritically (e.g., Fodor & Crowther, 2002; Margolis & Laurence, 2002; Pullum & Scholz, 2002). It has been argued that the stimulus is far richer than previously thought and that much more convergent learning is therefore possible (Pullum & Scholz, 2002). The point here is not to evaluate what aspects of grammar in particular, and knowledge more generally, are learnable with a particular learning system. The critical message
is that the learnability debate has helped sharpen questions concerning the initial state. Psychologists now are more likely to acknowledge that some forms of knowledge may only be learnable with certain kinds of architectures and that it is therefore important to develop precise ways of characterizing the knowledge representation, the learning strategy, the information provided, and the meaning of satisfactory levels of learning.

It would be a gross exaggeration to imply that formal learning procedures are foremost in the minds of most developmental psychologists, but there is a greater appreciation of the need to specify the relevant components of a learning system. At the same time, the challenge of using formal approaches to better delimit that initial state has become much larger than initially envisioned by many. Some workers, from a computer science perspective, have argued for dramatically different architectures to get around learnability issues, such as architectures that use massively parallel processing systems and radically different learning procedures. It has been argued that many aspects of category learning and conceptual change that seemed “unlearnable” in older, simpler associationist systems can be modeled nicely by these parallel architectures (Rogers & McClelland, 2004). Thus, computer science advances, both in more traditional learning architectures and in newer parallel ones, have refocused the study of the initial state.

Rapid advances in neuroscience have made it possible to look in detail at the initial state of some portion of a neural network and then examine how it changes as the organism learns. One of the most elegant and detailed analyses along these lines has been done with perceptual motor learning in the barn owl (Knudsen, 2002). It is possible to show how the barn owl learns to auditorily localize by tuning sets of neurons to inputs from both the eyes and the ears that appear to be gated in a complex manner related to timing of input (Gutfreund, Zheng, & Knudsen, 2002). In auditory localization learning in the barn owl, it is possible to describe, at the neural level, considerable prewiring that seems necessary to enable auditory learning but also considerable plasticity to allow for dramatic tuning and recalibration, which can be demonstrated experimentally by putting prisms on the owls’ eyes or plugs in their ear holes. There is a still a long way to go from these neural models to formal learning models, but it is possible now to see potential benefits of the convergence of these different approaches. One can, for the first time, start to computationally model initial states and their tuning functions based on neural data (Kardar & Zee, 2002). This is a great leap forward from earlier claims that Parallel Distributed Processing (PDP) networks were modeled after the nervous system. These claims were largely based on loose analogies rather than on data-driven mappings from neural architecture to computer architecture.

Neuroscience has also helped shape questions about initial states through discoveries about how endogenous cycles of activation can create an internal experience that must be acknowledged as much as external experience. Thus, in addition to externally driven patterns of neural activity, there are endogenously driven ones that appear to be critical in guiding the tuning and sharpening of neural circuits (Zhang & Poo, 2001). For example, in both the retina and the thalamus, spontaneous cycles of endogenously generated electrical activity of neurons are thought to be causally involved in helping refine and sharpen orientation-specific circuits in the lateral geniculate nucleus and the visual cortex. These circuits then become further tuned after birth by visual experience. Apparently, molecular genetic specifications of structures must interact with these endogenous waves of activity, perhaps conserving an activity-dependent mechanism of tuning of neural architecture both pre and postnatally (Zhang & Poo, 2001). Discussions of initial states and poverty of the stimulus must now take into account the influences of internal cycles of this sort. More broadly, tremendous advances in the neurobiology of development are now helping constrain in much richer ways discussions of initial cognitive states (Marcus, 2004).

We have talked about computer science influences arising from the debates about architectures that are massively parallel versus serial. A different contrast concerns systems that are modeled by central cognitive control patterns as opposed to “behavior based” systems that are built up out of simple perception/action routines (Brooks, 2001). The idea was immortalized in an excerpt from the film Fast, Cheap and Out of Control (1997), in which the computer scientist Rodney Brooks waxes at length about the virtues of engaging in artificial intelligence research in a way that he sees as recapitulating phylogeny. By starting with relatively simple perception action circuits of the sort found in insects, it is possible to model behaviors in ways that seem to pay little attention to central cognitive control mechanisms (Brooks, 1997). Consider two ways of explaining the moth’s behavior of flying toward flames. One might at-
tempt to model that behavior by starting with a central
cognitive system that recognizes bright light sources
and then links that recognition routine to a motivational
system that wants proximity to the light source and then,
based on the interaction of these two systems outputs, a
series of commands to a perceptual motor guidance sys-
tem. Alternatively, one might ask about the crudest pos-
sible connection between the sensory inputs and actions.
A simple version is shown in Figure 14.1. Imagine that
the eye of the moth that is closer to, or more directly
faces, a light source fires neural outputs more rapidly.
Assume further that those outputs go to the wing on the
opposite side of the moth from the eye, which will then
flap more rapidly than the wing on the same side as the
eye. As a result of this difference in wing flapping, the
moth will turn toward the flame and fly toward it until
both eyes receive equal stimulation; it then flies in a
straight line toward the flame.

The actual story for most moths is probably consider-
ably more complex (e.g., Hsiao, 1973); but this “toy” ex-
ample illustrates the basic point: Complex goal-directed
behavior may sometimes emerge from surprisingly sim-
ple noncentral perceptual motor mechanisms. The argu-
ment made by Brooks and his colleagues is that we
should think of much of the complexity of human behav-
or as bottom-up concatenations of such insect-like rou-
tines. Analogously, one might think of learning in
development as the concatenation of such routines (cf.
Thelen, 2000). We may feel compelled to infer much
more elaborate central control processes to certain beh-
vior patterns but perhaps often inappropriately. An endearing
robot known as Kismet provides an example. Kismet has
several routines built into it for tracking eye gaze and
body and head movement of humanoid faces and making
automatic reactions back (Adams, Breazeal, Brooks, &
Scassellati, 2000; Scassellati, 2001, 2002). The circuits
that make up each of these face-responding routines are
all seemingly simple and distinctly nonhuman like; and
yet in real time, human observers see the behaving robot
as having far more cognitive, motivational, and emo-
tional structure than it really does.

Human infants may be nothing like Kismet, but re-
search in that tradition has influenced thinking about
possible initial states and has helped psychologists real-
ize that highly interactive social behaviors might not on
their own indicate rich internal cognitive processes or
the rich initial states that those processes seem to entail.
As demonstrations of ever more sophisticated social
tracking and contingency responding routines occur in
younger and younger infants (e.g., M. H. Johnson, 2000),
debates in computer science about the appropriate archi-
tectures are ever more relevant.

In philosophy as well, recent discussions of initial
states and the related issue of nativism have influenced
more traditional views in developmental psychology.
Philosophers have focused on classic ideas in psychol-
ogy such as triggering and canalization (Ariew, 1999),
domain specificity (Cowie, 1999; Samuels, 2002), and
modules and their precursors (Carruthers, 2005), just as
advances in developmental psychology have reinforced
the relevance of these topics to philosophers interested
in nativism. Philosophers have pointed out the chal-
enges of adequately describing either representations,
learning, or the available information in the environ-
ment. Philosophy has also often been the first vantage
point from which interconnections are apparent between
psychology, computer science, linguistics, and neuro-
sience.

The contributions of anthropology to characterizing
the initial state are more tentative but there are exciting
developments in this area as well (Sperber & Hirschfeld,
1999). As cognitive science techniques are used with
more sophistication in cross-cultural research, patterns
of interaction between cultural structures and cognitive
structures become more accurately described. One pat-
tern that can strongly inform questions about the initial
state is seen in cases where adult diversity of cultures,
when considered in younger and younger ages of a cul-
ture, tend to converge on a common format in the young
child or infant. This convergence starts to make sugges-
tions about initial states (Medin & Atran, 2004). A dif-
ferent tactic has been to argue that the ability of
information to propagate through a culture depends on
all members of that culture having a sufficiently shared

Figure 14.1 A noncognitive way to explain the moth’s ten-
dency to fly toward light sources is to hypothesize a cross-
connection between the moth’s eyes and wing muscles, such
that the eye on the side of moth that is closer to a light source
fires excitatory patterns to the contralateral wing, making it
flap more rapidly and turn the moth toward the light source.
In this manner, the moth will continually adjust its behavior
until it is heading directly toward the light source.
cognitive common ground to act as a medium of transmission (Sperber & Hirschfeld, 2004). That common ground in turn leads to suggestions about initial states.

Given the complexities of characterizing the initial state, it is tempting to declare it irrelevant, just as others have declared the nativist/empiricist controversy as a nonissue. In neither case is this move correct. One of the major advances in recent years in cognitive science has been to flesh out in detail different facets of the problem of initial states across the disciplines, giving new insights to those engaged in developmental psychology research with the youngest of humans. Thus, questions about initial states have become considerably more refined as they have been considered across the disciplines.

Is There an Adapted Mind?

In one sense, the answer to this question is obviously “yes.” Human brains have a large number of adaptations that all would agree on. Glial sheaths are an adaptation that occurs more prominently in organisms with complex cortices requiring transmission of larger packets of information over longer distances. Larger brains have ventricles filled with cerebrospinal fluid that help control and maintain the chemical environment of the brain. The convolutions of the cortex in primates are thought to be an adaptation to enable the packing of more cortical surface layer in a constrained volume. In all these functional and physiological senses, the brain is adapted. The more provocative question, however, is different and is at the core of evolutionary psychology (Tooby & Cosmides, 2005). To what extent are there adaptations for distinct cognitive faculties, and at what levels of processing? It is noncontroversial that there are adaptations of the sensory receptors such as the eyes and the ears, for different kinds of information. There is some disagreement, but mostly a consensus, about there being adaptations for modules that track objects (Mitroff, Scholl, & Wynn, in press), social agents (Leslie, 2000), depth (Sakata et al., 1997) and language (Hauser, Chomsky, & Fitch, 2002; Pinker & Bloom, 1990). But there is far more disagreement about whether humans or other species have evolved cognitive adaptations for detecting cheaters (Cosmides, 1989), picking attractive mates (Buss, 1994), or thinking about the living world (Atran, 1998; Bailenson et al., 2002). Although evolutionary psychology is a relatively new term, questions about an adapted mind were part of Darwin’s thinking shortly after his proposal of the idea of evolution by natural selection. He discussed at length the adaptive function of the early emergence of emotions and their corresponding facial expressions (Darwin, 1872).

The debate about an adapted mind is making considerable advances as considerations across disciplines start to feed back on psychological questions. One of the most intriguing has occurred in computational biology, where scholars explore the adaptive value of modular versus general structures and ask under what sorts of environments and mechanisms of architectural change modules will appear (Calabretta, Di Ferdinando, Wagner, & Parisi, 2003; Wagner, Mezei, & Calabretta, 2004). Consider a line of work that asked about the optimal way to evolve a system that performs both “what” and “where” computations on objects in the visual array. Although earlier work had shown that it was possible for a single kind of architecture with one learning algorithm to “learn” to have two distinct modules (Jacobs, 1999), later research suggested that hybrid architectures using both a genetic algorithm and a variant of learning through back propagation, show a considerable advantage in the development of functionally specialized modules (Wagner et al., in press).

Networks were designed that could change their structures in two ways, either by production of variants of the initial network through random mutations (the genetic algorithm) or through a form of instructed learning in which weights were changed as function of task performance (back propagation). It was found that a hybrid network of this sort would rapidly create distinct functional modules for “what” and “where” tasks when the genetic algorithm preceded learning through back propagation. Moreover, the advantage occurred primarily in cases where the network first learned the simpler task (where) before the complex one (what). One way of interpreting these results is to argue that the genetic algorithm mimicked evolutionary change while the back propagation learning represented learning within a single organism’s life span (Calabretta & Parisi, in press).

It is far too early to conclude that hybrid architectures modeling evolved modularity and learned modularity together have an advantage over those that only incorporate learned modularity. Indeed, many continue to argue that gradually learned modularity during infancy, through a competition process between networks subserving two distinct tasks, is the way to understand the emergence of distinct domains of cognition (Dailey & Cottrell, 1999; M. H. Johnson, 2000). By such accounts, there is no adapted mind in the sense of a priori domain-specific specializations for different kinds of
information patterns corresponding to real-world categories such as social agents, living things, and faces. Instead, those specializations arise from channeling of information caused by much lower-level perceptual cues. The debate continues as other groups argue for strong evidence for evolutionarily adapted modules (Duchaine, Cosmides, & Tooby, 2001) and for a general progression in evolution of the replacement of general purpose learning systems with adaptively specialized ones (Gallistel, 2000). Either way, however, computational approaches now allow for the exploration of the relative advantages of domain-specific architectures that occur gradually and postnatally as a result of a single organism's learning experiences as opposed to those that occur through an evolutionary process across a species as whole.

There are profound problems in trying to model the richness of the environment and evolutionary processes. Researchers are forced to use highly idealized and necessarily oversimplified toy systems; but computational approaches of this sort are certainly starting to influence thought about the emergence of functional specializations and the extent to which we have adapted minds. In turn, that computational perspective has also led to new ideas about experimental research by psychologists with human infants (e.g., Munakata, McClelland, Johnson, & Siegler, 1997). As mentioned, in a broader sense, the mind is obviously adapted if one includes the structures of the sensory transducers, which do after all contain part of the nervous system. The debate revolves around whether principled boundaries limit the scope of such adaptations, such as applying only to the sensory transducers, only to lower-level perceptual input modules, or only to the highest levels of cognition. Thanks to computational perspectives, that debate is moving forward with more specificity and a greater effort to empirically support the different positions.

A related research strategy for examining the extent of the adapted mind is to use “reverse engineering.” The idea is often used to describe forms of industrial espionage in which engineers take a competitor’s product and, from its function, try to work backward to figure out how it works and why it was built the way it was. With respect to the mind, the idea is to consider the local functional value of a property or behavior (such as mating, child rearing, or cheating detection), frame that property as a goal, and then see what follows from such an assumption, as one tries to consider a system, its constraints, and the ways it might meet that goal. There is considerable debate about whether there are sufficient constraints to be able to infer with some reliability the structure of the engineering solutions for the human mind (Lewens, 2002); but the strategy represents a new way of approaching questions about the adapted mind that draw on ideas in evolutionary biology.

Some have suggested that the reverse engineering strategy is empty, because it can be used to argue for the presence of anything, that is, if a pattern of thought is observed early in development and is seen in virtually all children in all cultures, it must have been selected for in evolution. Although such misleading inferences can occur, they can also occur in analyses of real engineered artifacts, which has not at all undermined use of reverse engineering as a strategy with devices (Lewens, 2002). It may well be that for more complex interconnected systems of both a biological and artificial nature, the reverse engineering strategy rarely misleads above a certain level of functional complexity. Moreover, cross-species comparisons often suggest common goals. Through broader evolutionary analyses of essential functions for social organisms, a small number of key functions may emerge, such as cooperation in groups, mating, child rearing, and self-protection (Pinker, 1997). Those functions, which are hardly controversial and have cross-species validity, can then be used to frame a wide range of questions about cognitive development.

A new look at individual differences has also arisen from questions about the role of an adapted mind in development. Traditionally, individual differences have been understood as a battleground over gene versus environment effects (e.g., Scarr, 1992); but that way of considering individual differences overlooks the ways in which patterns of variation can highlight foundational domains (Bjorklund & Pellegrini, 2000; Scarr, 1992; Segal & MacDonald, 1998). One precursor of this view comes from the work of Gardner (1983) on “multiple intelligences” that led to proposals of distinct domains of thought, such as logical, spatial, and interpersonal intelligence. Rather than ask whether the degree of manifestation of a trait, such as spatial reasoning skill, is largely a function of experience or genes, an evolutionary psychology approach to individual differences asks if, across patterns of variation among individuals, a common distinct functional architecture seems to emerge. In this way, the analysis converges with that of cross-cultural studies and developmental approaches, to ask if certain “mental organs” are highlighted by an individual-differences perspective. We are only beginning to see hints of this approach because of the large data sets
involved. If, over a wide pattern of variation across individuals, certain aspects of cognition remain both invariant and domain specific, then the cognitive abilities involved should be considered as candidates for being adapted forms of thought.

More extreme forms of individual differences—patterns of pathology—have also been used to argue for an adapted mind. These more extreme forms are distinguished by being maladaptive and likely to threaten survival of those who would have such pathologies, especially if those individuals are living in traditional environments. Thus, one argument for a cognitive faculty being adapted is that, when it is severely damaged, it threatens survival. The domain of folk psychology has been studied more in this respect than any other in individuals with autism. While there remain extensive debates about the extent to which autism is solely the result of a cognitive deficit (Birlen, 1990; Cohen & Volkmar, 1997), in a large number of cases the primary deficit seems to be a specific cognitive problem in thinking about the mental states of others, such as how beliefs and desires can lead to actions, deception, and misunderstandings (Baron-Cohen, 1995, 2004; Leslie & Thaiss, 1992). Moreover, there appears to be a continuum along which individuals can be variably handicapped in their ability to have a “folk psychology,” ranging from severely autistic individuals who have great difficulty understanding almost anything about how mental states lead to actions to more modest deficits, such as Asperger’s syndrome in which individuals are able to understand the mental lives of others, but only to a limited extent and with considerable difficulty (Klin, Volkmar, & Sparrow, 2000).

Patterns of neurological impairment and their resulting deficits in specific areas of thought do not automatically mean that those areas of thought are adapted domains. There have been many demonstrations of how a generalized learning system, such as one that learns through massively parallel processing, might nonetheless show domain-specific deficits with certain kinds of lesions. Thus, differential deficits in the abilities to think about tools or animals have been simulated in such systems (Farah & McClelland, 1991; Rogers & Plaut, 2002). Low-level differences in attention to perceptual and functional features have been argued as able to account for such differences (Borgo & Shallice, 2003). In other cases, however, specific impairments in thought are much more difficult to explain in terms of problems in domain-general learning (Humphreys & Forde, 2001; Keil, Kim, & Greif, 2002; Vinson, Vigliocco, Cappa, & Siri, 2003).

Similar controversies exist about whether humans have specific areas of the brain adapted for perceiving faces (Duchaine, Dingle, Butterworth, & Nakayama, 2004; Duchaine & Nakayama, 2005; Gauthier, Curran, Curby, & Collins, 2003; Kanwisher, 2000; Killman & Arterberry, Chapter 3, this Handbook, this volume). Those debates, in turn, have often brought in key developmental arguments about the possibility that specialized brain regions that are uniquely involved in one kind of task (e.g., face perception) might not have been initially “wired” to only process faces, but because of lower-level perceptual shunts, only received information about faces and thus, over time became organized preferentially for that kind of information (Johnson & Morton, 1991). Thus, development becomes critical to understanding whether cognitive specializations in the brain were selected for in the course of evolution or in the course of learning in a single lifetime, with both possibilities being proposed in several areas of cognition (Elman et al., 1996).

The potential insights of an evolutionary perspective, however, go far beyond arguments for specialized domains of thought and modularity. Questions about an adapted mind can also lead to insights about specific developmental trajectories and rates of development. Why, for example, do the three classes of cues for depth—three-dimensional dynamic cues (e.g., motion parallax), binocular cues (e.g., binocular disparity), and pictorial cues (e.g., linear perspective)—emerge in infancy in that order? (Killman & Banks, 1998). One appealing explanation is that it makes adaptive sense for 3-D dynamic cues to emerge first because they are most robust under conditions of degradation common in young infants, such as low acuity and weak binocular coordination. Such dynamic cues might then form feedback for other sorts of cues that are used later. Similarly, earlier emergence of some cognitive skills relative to others can be understood in adaptive terms and then considered as a largely maturational pattern.

Arguments about adaptive developmental sequences in turn raise questions about whether a sequence of development is preordained or is an inevitable unfolding of cognitive and perceptual systems in which some components must necessarily precede other ones. Thus, although one might argue that addition precedes multiplication in the development of mathematical thought because of a maturational program, it is much more
plausible to argue that addition logically precedes multiplication and that the latter cannot be understood without a sense of the former (National Research Council, 2001). There is, therefore, a danger in being excessively promiscuous in adaptive explanations, a bias that is seen in much of biology (Gould & Lewontin, 1979). Nonetheless, although asking about developmental patterns in adaptive terms may sometimes be misleading, such a strategy often helps focus research on new sets of questions for empirical exploration.

Adaptive questions about developmental patterns can also be a fruitful way of asking about cross-species differences. Why are some organisms much more precocial with respect to some cognitive and perceptual skills than others that are more altricial with comparable or analogous skills? Why do young human infants, while clearly able to see objects in depth, show no fear or tendency to avoid the deep side of the visual cliff while other species show such a linkage at birth (Campos et al., 2000). One answer might focus on the mobility of newborns of other species and the need that mobility creates for a neonatal linkage of fear and avoidance with depth perception. That answer might further be supported by arguments for how, in the absence of mobility, it is advantageous for a fear-depth linkage to take time to develop.

More broadly, there are repeated trade-offs between the advantages of having precocious but inflexible cognitive perceptual systems as opposed to less precocious but more flexible systems. Again, adaptive explanations are not always going to inform questions about developmental sequences in the acquisition of knowledge in domains such as mathematical skills, folk psychology, folk biology, and folk physics; but they are likely to be part of the story in many of those domains and will often help frame questions that motivate more focused research. Other examples might include the use of object files and estimation skills in number knowledge before calculation-based methods (e.g., Wynn, 1998) or use of continuity, no action at distance, and solidity principles in object concepts before those of gravity and momentum/trajectory (Spelke, Breinlinger, Macomber, & Jacobson, 1992).

**Patterns of Change**

Cognitive development intrinsically involves various notions of change. It has, however, been difficult to unambiguously characterize distinct patterns of change. Debates occur both about the representational formats involved and about the degree and kind of change involved. Work across the cognitive sciences has greatly helped to sharpen some of these distinctions.

**Does Development Proceed from the Concrete to the Abstract?**

Few things seem more commonsensical than the idea that development must proceed from the concrete to the abstract. This view has been discussed in different ways throughout much of the history of developmental psychology (e.g., Bruner, 1967; Inhelder & Piaget, 1958; Vygotsky, 1962; Werner, 1940). Yet, a cognitive science perspective on this question has started to raise serious questions about the ubiquity of this pattern. From the perspective of linguistic theory, a major shift in views of language acquisition was launched by Chomsky (1957, 1965, 1975). This shift was so major that it is now presupposed by most scholars in the area even as they might vigorously dispute many or all the details of how Chomsky describes the capacity for a natural language (e.g., Bresnahan, 1982; Gazdar, Klein, Pullum, & Sag, 1985; Manning & Sag, 1995). The common presupposition is that there are abstract ways of characterizing language competence that are far above more concrete levels of analysis such as word tokens, simple word order patterns, or sentence-size. At the concrete level, languages appear to be so dramatically different from each other as to suggest near infinite variation and little or no common structure. But with a more formal and abstract way of describing linguistic competence, as developed so powerfully by Chomsky, it was possible to see strong universals on structure that all languages share and that might be understood as guiding constraints on language acquisition (e.g., Anderson, 2004; Lightfoot, 1999; Pinker, 1994).

At an early age, children throughout the world seem to learn ordering relations based on abstract syntactic categories such as subject and object and not on number of words or word tokens. They appear to have abstract parameters that are "set" in ways that allow them to unpack the structure of a particular language (e.g., Lust, 1999; Yang, 2004). Again, this perspective can be debated (e.g., Seidenberg & Macdonald, 1999), but there is no doubt that a dominant model of language acquisition is that children start out with abstract skeletal expectations about a grammar of a language that they then fill in with more concrete
language-specific details of tense marking, subject-verb agreement, and sentence embedding.

From a computer science perspective, there has been a surge of interest in whether concrete to abstract progressions are inevitable parts of systems that learn. While such a progression might seem to be necessary in simple systems that do little more than perform first-order tabulations of feature frequencies and correlations, it is striking how more contemporary models of learning often allow for, and even vigorously embrace, systems in which more abstract representations of the environment can have developmental precedence. Consider how advances in connectionist modeling can show this seemingly paradoxical result. Since many connectionist models work by tracking feature frequencies and correlations, they might seem especially good cases of concrete-to-abstract patterns of development. It is possible, however, to design architectures in which a system quickly abstracts away from lower-level feature frequencies and correlations in a manner that does not initially emphasize concrete categories but instead gives developmental priority to more abstract ones (e.g., Rogers & McClelland, 2004). Thus, there have been arguments for developmental patterns in which children first master abstract categories such as living thing, nonliving natural kind, and artifact and then gradually differentiate downward to knowledge of more specific categories (Keil, 1979); connectionist models have been designed to model such patterns (Rogers & McClelland, 2004). Or, very young children might show category clustering by categories such as vehicle and animal before clustering by categories such as car, boat, dog, and cat (Mandler, 2004). Again, there are now computational explorations of how to model such patterns (Rogers & McClelland, 2004). A related computational approach might construct a learning system that approximates the statistical process of factor analysis (Ohahramani & Hinton, 1998), a process in which abstract factors might emerge in a computational analysis long before more local patterns have any meaning.

Abstract performance might also precede concrete knowledge in a system in which a priori weights on an architecture embody some higher-order property in a domain. Thus, some connectionist approaches augment learning algorithms and node structures with predetermined weights on some links, or “clamps,” on weight change. The aggregate structure of such clamps and weights might then embody an abstract cognitive principle such as a general principle of syntax (Yang, 2005).

There may still be profound limitations on many of these connectionist architectures (Marcus, 2001), but their evolution in recent years makes possible consideration of a wide range of patterns in which development proceeds from the abstract to the concrete. A rich array of psychological patterns that suggest abstract to concrete change (e.g., Ingaki & Hatano, 2002; Keil, Smith, Simons, & Levin, 1998; Mandler, 2004; Simons & Keil, 1995) have motivated newer computational models that now in turn feed back on and motivate further psychological questions (Goldstone & Son, in press).

In philosophy, the abstract versus concrete contrast has been a topic of active discussion in many forms. There are several levels of explanation of any system and there are complex discussions about which ones are most fruitful and how they should be characterized. As part of these discussions, it is commonly assumed the lowest level, most reductionist characterization of a process is often inappropriate and unfeasible (Fodor, 1974, 1975). Moreover, functional levels of analysis, far above levels of concrete mechanism are often embraced for their distinctive nature and importance in both science and daily thought (e.g., Block, 1980; Cummins, 1983; Lycan, 1996). Similarly, abstract notions of causal powers have been argued as more fundamental to natural science than mechanisms (Harre & Madden, 1975). All these discussions have served to provide different ways of instantiating what it means to be concrete versus abstract.

These philosophical discussions have powerful implications for developmental studies of the progression of thought. By illustrating the distinctive, and sometimes privileged, role of levels of explanation in modern science as well as in the history of science, philosophers help constrain discussion of how such structures might emerge in children.

Philosophical discourse also allows one to see more clearly not only why some patterns of abstract to concrete change might occur, but also why the opposite pattern often might seem to be more obvious. If one characterizes abstract thought in terms of the ability to explicitly describe an abstract relation in language, one is inclined to see thought as progressing from the concrete to the abstract. For reasons that may have little to do with underlying cognitive capacities (Bloom & Keil, 2001) it can be much more difficult to verbally describe a principle such as randomness than it is to label a concrete category such as dog or a concrete relation such as push. Yet, it is ever more evident that adults, children,
and even infants can be sensitive to, and cognitively employ in everyday thought, highly abstract categories and relations that they cannot verbally describe (e.g., Csibra, Biro, Koos, & Gergely, 2003; Gelman, 2002, 2003; Gergely, Nadasdy, Csibra, & Biro, 1995; Keil, 2003b; Newman, Keil, Kuhlmeier, & Wynn, 2005). Young children may be hard pressed to articulate any version of essentialism directly but appear to show assumptions about essentialism extensively in their daily cognitions (Gelman, 2003; Medin & Ortony, 1989). Similarly, young children might see certain teleological modes of interpretation as especially resonant with living kinds (Greif, Kemler-Nelson, Keil, & Guiterrez, in press) yet be unable to articulate that notion at all.

Philosophical discussions of language and thought and of the nature of language without thought bear closely on these issues (e.g., Fodor, 1975; Weiskrantz, 1988). They stand to help empirical researchers get a better handle on the ways in which the ability to articulate a concept in language might not be seen as the sole basis for making inferences about the presence of abstract versus concrete concepts.

Even neuroscience is relevant in such discussions. Certain patterns of brain damage resulting in difficulty in thought about categories, such as living things, might be best characterized as impairments at abstract levels of thought rather than more concrete ones (Keil, 2003c; Keil et al., 2002; Laiacona, Capitani, & Caramazza, 2003; Martin & Weisberg, 2003). A vigorous debate exists about the appropriate level of abstraction for describing the basis of a “living kinds deficit,” including discussions of how a normal ability to encode living things might be represented at a genetic level. For example, in one analysis of an individual who had a congenital deficit in thinking about living things, it was concluded:

> Prior to any experience with living and nonliving things, we are destined to represent our knowledge of living and nonliving things with distinct neural substrates. This in turn implies that the distinction between living and nonliving things, and the anatomical localisation of knowledge of living things, are specified in the human genome.

(Farah & Rabinowitz, 2003, p. 408)

Although this result contrasts with other claims in the literature, it illustrates how explorations of this controversy in neuroscience are offering new refined insights into how to understand the abstract versus concrete contrast in cognitive development.

Anthropological studies are brought to bear on this question because of frequently erroneous claims that members of a certain “primitive” (and usually non-Western) culture think in more concrete terms than those of another. Such claims have time and time again been debunked by careful analyses (e.g., Cole, Chapter 15, this Handbook; this volume; Cole & Means, 1981). More recently, cross-cultural studies have shown how quite dramatic patterns of variation in thought might reflect different but equally abstract characterizations of a domain, such as construing biology in ecological versus more taxonomic ways (Bailenson et al., 2002; Medin et al., in press).

In short, the notion of concrete and abstract forms of thought and the developmental relations between the two has been a frustrating and often ill-defined problem in developmental psychology. It has been greatly informed by discussions in several other disciplines of cognitive science that converge to make sense of them.

**What Is the Nature of Conceptual Change?**

Psychologists have long been concerned with ways in which children’s concepts change over the course of development (e.g., Baldwin, 1895; Piaget, 1954; Vygotsky, 1962). More commonly, anyone who engages in casual conversations with a 5- and 12-year-old about concepts as diverse as density, zero, or reproduction, soon becomes convinced that typical 5-year-olds often have very different concepts of certain things than 12-year-olds, with the obvious implication that powerful patterns of conceptual change occur during that period. This much seems straightforward. Much less straightforward, however, is the question of the type of conceptual change that is occurring. We have already seen how abstract to concrete progressions, and the reverse, are one way of talking about conceptual change, but another level of analysis is more structural in manner. It is at this level of analysis that work in other areas of cognitive science has been extremely influential, especially in more recent years.

In the philosophy and history of science, there have been extensive discussions of forms of conceptual change. One of the mostly widely discussed is Kuhn’s original notion of scientific revolutions (Kuhn, 1962), a form of change in which a slowly building body of contrary evidence to a particular theory, or paradigm, ultimately reaches a critical mass that launches a dramatic shift to a new way of understanding some aspect of the
world. That notion of revolutionary change powerfully influenced views of cognitive development. For example, young children have been regarded as initially understanding much of the biological world (especially animals) in psychological terms and not biological ones (Carey, 1985). Similar arguments have been made for children’s shifting concepts of weight and mass (Smith, Carey, & Wiser, 1985) and force and motion (Tao & Gunstone, 1999). This is a particular view of conceptual change with intriguing predictions. For example, concepts in a prerevolutionary system of thought might be completely incommensurable with those in a later system such that individuals from the two systems would largely be talking past each other or mistakenly think they were referring to the same things when in fact they were not. This prediction in its strongest form seemed troubling in that communication with children often does not seem to create such impasses.

Later developments in philosophical discussions of conceptual change refined Kuhn’s early ideas in ways that in turn informed models of what is happening with respect to conceptual change in children. Thus, notions of local incommensurability were introduced to deal with global incommensurability and thereby allow more effective communication as well as more gradual patterns of change (Kitcher, 1978, 1993). Others more directly challenged the entire notion of conceptual revolutions (e.g., Laudan, 1990), leading to more nuanced models of conceptual change in children (e.g., Carey & Spelke, 1994).

In computer science, attempts to model conceptual change in various systems motivated quite different models that naturally arose from certain architectures. Wholesale conceptual revolutions were often more difficult to model than gradual incremental differentiation of concepts that might ultimately drift to quite different patterns of thought but not have a revolutionary flavor (Moorman & Ram, 1998; Roschelle, 1995; Shultz, Mareschal, & Schmidt, 1994; Thagard, 1992).

In psychology, other models of conceptual change have existed for many years. These might include gradual differentiation of a set of conceptual distinctions or procedures. Here, too, computer science implementations were sources of inspiration. Thus, models of children’s developing understanding of tasks such as balance beams as a differentiating set of rules were closely linked to work in artificial intelligence on production systems (Klahr, Langley, & Neches, 1987; Langley, 1987; Newell & Simon, 1972; Siegler, 1976, 1981). The development of the microgenetic method in psychology (Siegler, Chapter 11, this Handbook, this volume) was certainly influenced by incremental logs of scientific discovery in computational systems (Newell & Simon, 1972; Simon, 2000).

Beyond differentiation and conceptual revolutions, however, recent work in psychology has drawn on several other models of conceptual change, and frequently through inspiration from other fields of cognitive science. The question of whether change is qualitative versus quantitative has been informed by formal discussions of such contrasts in both philosophy and linguistics (Briscoe, 2000; Christiansen & Chater, 1999).

More specifically, several different structural models have emerged through commerce with other disciplines in cognitive science. Consider two such examples that have emerged as alternatives to the ideas of conceptual revolutions and gradual incremental change: increasing access and shifting default biases (Inagaki & Hatano, 2002; Keil, 1999).

The notion of increasing access was initially proposed in the context of comparative considerations of how development varied across species (Rozin, 1976). A cognitive routine might be largely automatized and relatively encapsulated and then gradually become more and more available for use in other domains in some species, but not others. In development, Rozin suggested that increasing access to a phonological code might be the basis for major advances in learning to read (Rozin, 1976). In philosophy, notions of increasing access during the course of development figured prominently in accounts of modularity and conceptual change (Fodor, 1975, 1983; Karmiloff-Smith, 1992). In such accounts, a cognitive capacity might be present early on, in a narrow range of contexts, but then become available for deployment in a wider and wider range of situations. In anthropology, it is common to talk about how an innovation might initially be sequestered within a small group and then spread through a culture as access increases. The notion of increasing access to a cognitive skill or competency is an account of conceptual change that is starkly different from both gradual differentiation and revolutionary change. The mental structure or computational routine might be present and unchanged throughout the relevant developmental period but simply be unavailable for use in many tasks in younger children. A sharp increase in access can look like dramatic concep-
tual change even as the underlying conceptual structure changes little.

The notion of differing default biases suggests that children might have two quite different ways of understanding a system with the primary changes being which one first comes to mind or is seen as most relevant in particular tasks. Unlike increasing access, two different forms of thought may be fully accessible throughout a developmental period, but there may be a dramatic shift in which one is normally used first. Thus rather than seeing young children as only able to understand animals in psychological terms, this view might argue that, throughout much of development, children have both biological and psychological ways of understanding organisms but that younger children tend to default more to the psychological form (Gutheil, Vera, & Keil, 1998). In some tasks, slight reframings of contexts can get young children to use the lesser default (biology) in reasoning (Gutheil et al., 1998). This idea of shifting default biases was heavily influenced by cross-cultural work in anthropology showing that people in other cultures often did not simply have a radically different way of viewing the world, but rather had multiple ways of making sense of situations that might overlap closely with people in other cultures. What differed was which ways of thinking were first elicited in certain sets of contexts. Forms of reasoning about moral situations in terms of sacred violations, or interpersonal harm, or authority conformance, might all be available to people in all cultures, but have different default hierarchies as to which is elicited first in local contexts such as family, community, or peer interactions (Haidt, 2001; Shweder, Much, Mahapatra, & Park, 1997; Turiel & Perkins, 2004).

Shifting default biases are also informed by discussions in philosophy and linguistics of relevance and how it is determined in discourse (Sperber & Wilson, 1995). In those fields, a rich discussion has focused on principles guiding inferences about the relevance of various topics and propositions to situations and prior discourse. Those discussions in turn influence how psychologists think about how children might adopt one frame of reference versus another (Keil, 2003a).

Linguistic approaches to the study of language acquisition afforded unusually specific accounts of different patterns of conceptual change. Thus, debates about whether the very young child understood ordering relations in a language in radically different ways from older children, led to vigorous debates about how the nature of natural grammar might change over time (Brown, 1973; Ingram, 1989; Lightfoot, 1999; Pinker, 1994). The precision of those different accounts and the ways in which evidence is brought to bear on them strongly influenced models of conceptual change in psychology.

In summary, as patterns of change are considered across a broader range of disciplines than just psychology, we start to see sharply contrasting ways in which change might occur. These patterns can then be used to motivate studies that directly explore which changes are actually occurring in cognitive development. Several studies now suggest that a much greater diversity of highly explicit models of conceptual change is needed to adequately model the changes we see in children. For example, as the microgenetic method offers more fine-grained images of developmental change, it also reveals how superficially similar patterns of change can have quite different underlying bases.

What Is the Difference between Learning and Development?

It has long been a controversy in developmental psychology as to whether the patterns of learning seen in adults are of a different kind from those found in children (see chapters by Siegler, Chapter 11; Kuhn & Franklin, Chapter 22, this Handbook, this volume). Consider, for example, the patterns of qualitative change that occur as adults progress from novice to expert forms of knowledge and whether those patterns are essentially the same patterns as qualitative change in children (Brown, Bransford, Ferrara, & Campione, 1983; Chi, 1978). The debate has become considerably more sophisticated as a result of converging discussions in other disciplines that contribute to the cognitive sciences.

In computer science, there have been attempts to model increasing expertise in ways that have invoked both local and global aspects of cognition (Anderson, 2000; Ericsson, 1996; Gobet, 1997; Larkin, McDermott, Simon, & Simon, 1980; Schunn & Anderson, 2001). This contrast in turn informs the refined question as to whether children differ from adults primarily because they are universal novices rather than more local ones. Perhaps only those with local novice states can use analogies to grow knowledge in other domains because only they have expertise in another domain that they can use as a basis for an analogy. Adults might find it much easier to learn about computer programming by using
analogies arising from domains where they are more expert, such as recipes in cooking, whereas children may not have such domains to use as launching pads for analogies. Computer scientists and psychologists in collaboration have, in turn, built simulations of how structure mapping might allow transfer of analogical relations to a new domain (Falkenhainer, Forbus, & Gentner, 1989, Gentner, in press). These simulations enable researchers to assess more precisely the benefits of expertise in one domain on a novice to expert transition in another.

At the level of neuroscience, changes in anatomy and functional status of brain regions postnatally start to place constraints on the learning versus development contrast. It is commonly assumed that considerable physical and functional maturation of the prefrontal cortex might influence development of cognition in domains as diverse as moral reasoning and intuitive physics (Zelazo, 2004; Zelazo, Muller, Frye, & Marcovitch, 2003). It is always risky to infer too much about psychological change from neurological change, but as techniques become ever more sophisticated in neuroscience, at the least, loose constraints emerge that might indicate how development would differ from learning. If there are global, brain-based limitations on executive processing that apply across all domains in young children, then no amount of learning in any of those domains in childhood will be the same as a novice-to-expert transition in one of those domains as an adult.

From anthropology, the influences may be more subtle but are still present. As one considers patterns of cognition across cultures, it is common to ask how a domain that has a long cultural tradition in one culture differs from cases in which it is relatively novel in another. People in one culture might well be considered experts in an area, because of their cultural heritage, while those in a different culture without that heritage might be considered novices. When scholars ask about how a culture came to a certain set of beliefs over time, they may ask about the extent to which that pattern of historical development was analogous to the pattern of development that might occur in individuals who are going from novice to expert states in one lifetime. There has been considerable discussion of how individuals in cultures such as China and Russia are learning, as adults, about capitalism, a kind of cultural novice-to-expert transition. It is natural, then, to contrast those patterns of change with those that gradually occurred as capitalism developed over many generations in other cultures (Asland, 2002; Cornia & Popov, 2001, Guthrie, 1999). Are the two ends the same, or are there intrinsic differences between how a practice develops over many generations in a culture and cases in which it emerges in less than one generation? These discussions may not have yet influenced issues of learning versus development in psychology, but they are likely to do so in future years as psychologists confront many of the same issues.

In linguistics, there has been a particularly focused approach to questions of learning versus development by exploring questions about first (L1) versus second (L2) language acquisition (Bialystok & Hakuta, 1994; Ellis, 1994; Gregg, 2001). The nature of L1 acquisition may be different from that of L2. Contrasts range from the influences of L1 on L2, thus drawing parallels to the universal versus local novice issue, to issues involving maturational and critical period effects (Johnson & Newport, 1989; Newport, 1990). Detailed structural comparisons about the precise nature of the two forms of acquisition shed considerable light on how to think more broadly about the learning versus development controversy. Thus, because formal linguistics enables language-acquisition researchers to carefully track structural change over time, it is possible to document differences in novice-expert shifts in adult L2 learning and child L1 learning. A key question is whether those differences will be unique to language because of special domain-specific properties or whether some aspects of those differences will shed broader light on the learning versus developmental controversy.

REPRESENTATIONAL FORMATS

Questions about cognition often involve questions about the formats of mental representations. In considerations of the development of cognition, questions about representational formats become central, especially when considered in a cross-disciplinary manner.

What Representational Formats Underlie Developmental Change?

In some ways, questions about representational formats underlying developmental change overlap with those just considered with respect to conceptual change. Thus abstract-to-concrete shifts are partially ones about for-
There remain vigorous debates about the merits of both approaches and about the nature of the formal computational limitations of each (Marcus, 2001), but there has also been intriguing feedback from such debates to models of the representational states of children and infants. There have been connectionist models of the object concept in infants that have led to novel predictions about performance on object search and retrieval tasks (Munakata, 2001; Munakata et al., 1997). Connectionist considerations of how past tense forms and word order might be learned have led to predictions as well (McClelland & Patterson, 2002). Similarly, as discussed earlier, attempts to model abstract patterns of conceptual change in terms of connectionist architectures (Rogers & McClelland, 2004) have led to new suggestions about how conceptual change might occur.

From a different computational perspective, there has been a surge of work on computational systems based on Bayesian approaches that are designed to track causal structure in the world (e.g., Gopnik et al., 2004; Sanjana & Tenenbaum, 2002; Tenenbaum & Griffiths, 2001). These approaches have afforded powerful new insights into how causal patterns might be apprehended and then elaborated on. In cases in which such simulations are successful, they can then be used as a basis for speculations about underlying representational formats. Thus, one key question is whether certain network graphs of probability relations can do away with any explicit use of the notion “cause” in a representational system.

Finally, from neuroscience, there has been impressive progress in describing neural circuits in ways that suggest how information might be represented and modified in the course of development (Gallistel, 2000). One of the best worked-out examples is seen in discussions of the neural structures underlying pattern recognition in various regions of the visual cortex. Some visual illusions, such as illusory contours, can be found to be computationally present in the first levels of processing of the visual cortex (e.g., Ramsden, Hung, & Roe, 2001). This finding in turn has led to computational models of development that include interactions between higher-order visual processes and more feature-based ones throughout all periods of development, rather than as a sequence from feature representations to those embodying illusions (Grossberg, 2003).

Questions about representational formats are at the very heart of much of cognitive science and have been
the focus of intensive study in many different fields. Those lines of work are now intersecting more and more and, as a result, are refining views in developmental psychology of how to characterize the representational bases of developmental change.

What Is the Role of Implicit and Explicit Thought in Cognitive Development?

In one form or another, developmental psychologists have long embraced the idea that some aspects of cognition develop outside awareness while others are very much part of our phenomenal experience. Freud’s discussion of unconscious thought and its role in development (Freud, 1915) has been considered an early cognitive science theory of representations in development (Kitcher, 1992). Sensorimotor (Piaget, 1952) and enactive (Bruner, 1967) representations might be thought of as examples of implicit thought in early development. It is, in fact, common to think that a major part of infancy may be dominated by implicit thought, which yields to more explicit thought with the onset of language. But these older discussions in psychology were often quite vague in defining the two forms of thought. In more recent years, work in other areas of cognitive science has helped to refine the senses of these contrasts. In neuroscience, patterns of brain damage such as the classic case of HM, who had hippocampal regions removed to cure epilepsy (Corkin, 2002; Scoville & Milner, 1957), have illustrated how implicit learning can proceed while explicit learning seems blocked. Thus, amnesics like HM can show marked improvement on many tasks, such as the tower of Hanoi, while not explicitly remembering the task at all. Other work on visual processing streams, showed that the dorsal stream seems to be involved in explicit processing of visual information while the ventral stream is involved in more explicit processing (Goodale & Milner, 2002; Goodale, Milner, Jakobson, & Carey, 1991). That neuropsychological work has in turn been invoked to explain developmental changes in how infants regard the trajectories of objects (Mareschal, 2000; Von Hofsten, Vishton, Spelke, Feng, & Rosander, 1998).

In linguistic theory, there has long been a contrast between implicit linguistic knowledge in the form of a natural language grammar, and explicit understanding of the structure of a language, which may be largely absent in most normal users. Even though children and adults can show precise and powerful intuitions about grammaticality of sentences, they may have little or no explicit access to those grammatical rules. In some cases, perhaps the grammar of language, it has been argued that the implicit nature of the knowledge arises from it being a module that is informationally encapsulated and cognitively impenetrable (Fodor, 1983).

Philosophical work on modules (e.g., Fodor, 1983) in turn inspired newer psychological approaches asking if automatization of skills might be related to transitions from implicit to explicit and the opposite (Karmiloff-Smith, 1992). In particular, several of those psychological approaches attempted to explain how implicit domain-specific forms of representation and processing might emerge in an organism that had minimal innate biases for those forms of representations (Karmiloff-Smith, 1992). Thus, notions of implicit and explicit in developmental psychology have been considerably sharpened by philosophical proposals about how and why some aspects of cognition might work outside awareness.

Computational approaches that directly target the implicit/explicit contrast have been less prominent. Again, the rise of connectionism was accompanied by claims that processing at the subsymbolic level might also often be implicit (Churchland, 1990). It remains unclear, however, as to how explicit cognition can be best modeled as emerging from a connectionist architecture.

The emergence of research on metacognition in developmental psychology is also related to the implicit/explicit contrast. In that work, young children have complex cognitive systems involved in memory and attention yet often seem to be largely unaware of those systems (Flavell, 1979; Wellman, 1985). Many of the researchers studying metacognition turned their attention to “theory of mind” (Flavell, 1999; Wellman, 1992); they became more centrally interested in the question of how one gains an awareness of mental states in oneself and in others. That new focus brought in a rich philosophical literature on what it means to be aware of one’s own mental states (Aydede & Güzeldere, in press).

More broadly, work on epistemology in philosophy has inspired psychological work asking about how children come to have an explicit awareness of their own knowledge states and of the processes of acquiring and evaluating knowledge (Kuhn, 1993, 1999; Kuhn & Franklin, Chapter 22, this Handbook, this volume). Naive epistemology connects to the implicit/explicit contrast because of the clear difference between having and using knowledge and being aware of that knowledge.
Developments in philosophy in the study of social epistemology, that is how knowledge is constructed in social groups (Goldman, 2002), have also influenced psychological work on how children seem to understand the division of cognitive labor in the world around them (Danovitch & Keil, 2004; Lutz & Keil, 2002).

The implicit/explicit contrast in many respects remains a puzzle. A simple noncircular account of explicit cognition continues to elude us, perhaps not surprisingly as it is closely related to the “hard problem” of consciousness—knowing what it is like phenomenally to have a conscious experience (Chalmers, 1996). At the same time, research is moving rapidly forward regarding many of the distinctive features correlated with cases of implicit cognition (instances more like the “easy problem” of consciousness; Chalmers, 1996). Moreover, work across the disciplines is helping inform our understanding of the relations between these two modes of thought in development. One important advance has occurred in work on the development of the self-concept, which might be considered a necessary part of explicit cognition. By breaking down the notion of self-knowledge into five distinct senses, ranging from a perceptual “ecological self” to a highly propositional “conceptual self,” it is possible to see how some sense of self is present throughout development from the earliest moments of infancy (Neisser, 1988). That sort of analysis has helped foster views that no longer involve a shift from the cognitively implicit infant to a cognitive explicit child, but rather examine the ways in which a form of cognition may be manifested throughout the developmental period.

What Is the Role of Association and Rules?

For almost a century, psychologists have been concerned with two very different ways of thinking about how humans might represent reality: in terms of rule-like representations or in terms of associative ones (Sloman, 1996). Associations were traditionally thought to be frequency-based tabulations of environmental contingencies and have a legacy at least as far back as the writings of the British empiricists in the eighteenth century (e.g., Hume, 1975). In developmental psychology, there has long been a suggestion that associative ways of representing information are more developmentally basic, or foundational, and are then later supplemented or replaced by rule-based forms (e.g., Inhelder & Piaget, 1958; Klaczynski, 2001; Kuhn & Franklin, Chapter 22, this Handbook, this volume). Despite the intuitive sense that there is a powerful contrast at work, this notion has been difficult to explore further in developmental psychology until quite recently when developments in neuroscience, linguistics, and computer science began to suggest more detailed ways in which the contrast might, or might not, be implemented in a representational model.

From neuroscience, there emerged claims that rule-based and association-based knowledge of linguistic forms could be dissociated through patterns of brain damage as well as through different activation patterns as revealed by imaging studies. Some people have deficits that make them do poorly with irregular past tense forms, which may be learned in largely associative ways, while doing fine with regular tense forms. Others may show the opposite pattern (Marslen-Wilson & Tyler, 1997; Pinker, 2001; Tyler et al., 2002). This pattern of findings has in turn brought in computational modelers who vigorously debate whether two computational systems are needed (McClelland & Patterson, 2002; Pinker & Ullman, 2002). Those computational debates have subsequently inspired newer psychological approaches that attempt to model the rules versus association contrast in terms of a single system of representation, such as a largely associative one in which rules are single-dimension evaluations at one end of a continuum that invokes more normal multidimensional similarity at other parts of the continuum (Pothos, in press).

The rules versus association debate has also been prominent in other ways in linguistic and philosophical discussions of the existence and nature of rules that are nonetheless implicit (Davies, 1995). One facet of this debate has been the question of whether rule-like properties (such as syntactic compositionality and productivity), can emerge from implicit architectures. For example, techniques for modeling connectionist networks as sets of vectors have been argued as embodying, through those vectors, rule-like properties (Pacanaro & Hinton, 2002; Smolensky, 1990). These modeling projects in computer science have led psychologists to ask about a richer array of representational formats that might be able to underlie behaviors that appear to be based on both rules and associations. One approach has been to argue that symbols and rules are more perceptually grounded than they might appear at first and, as such, are based on analogue representations that might be more easily compatible with connectionist networks while still being able to account for rule-like patterns in...
how people acquire and use concepts (Barsalou, 1999; Prinz, 2002). This line of work has in turn been connected to theories about representations in infancy such as “image schemas” which appear to have at least some perceptual grounding (Mandler, 2004).

It is far too early to tell if abstractions, such as vectors or factors, over connectionist architectures, can fully model rule-like patterns without in the end simply becoming neural implementations of a symbolic system (Marcus, 2001). There is a major difference between views that one can model rule-like patterns without any need for rules or symbols, and whether they are very much a computational reality at the right level of description even in connectionist architectures (Chalmers, 1993; Marcus, 2001). Either way, the debate has been invaluable in sharpening the focus on the roles of rules and associations in development. A central developmental question concerns whether it is appropriate to see younger and younger children as more and more associative creatures, with rules only becoming important at later points (Klaczynski, 2001). Perhaps infants are best understood as largely associative creatures that only acquire rule-like representations after they have gained some mastery with language. Indeed, this account might be considered one facet of Vygotsky’s theory (Vygotsky, 1962). Alternatively, it may be that human cognitions are necessary hybrids of association and more rule-like structures and that both must be present throughout development for learning to ever get off the ground and proceed successfully (Keil et al., 1998). Such hybrid architectures offer a fascinating way to think about the representational basis for development and in turn raise complex questions about how the two formats interact throughout the course of development. Rather than seeing one format in competition with another, it may be much more fruitful to think of them in mutually supporting roles (Farah & Rabinowitz, 2003; Keil et al., 1998; Sun, 2001).

GENERALITY AND SPECIFICITY

Across the cognitive sciences there has been a convergence of interests on questions concerning the generality and specificity of cognitive structures and processes over the course of development. Many longstanding questions about the nature of cognitive development have been greatly informed by increased attention to the kinds of universals and the kinds of domains that are needed to characterize the growth of the mind.

Are There Developmental Universals?

Developmental psychologists over the years have proposed that inevitable patterns of development and knowledge structures might be built on each other in a sequence largely determined by the structure of that knowledge. Thus, Piaget’s concept of epigenetic development included the idea that knowledge structures and cognitive skills developed to a point where their internal structure precipitated change to a new form. Similarly, models of conceptual change as revolutions are often described as the gradual accumulation of evidence that challenges the existing theory until that theory reaches a point when it undergoes a revolution in terms of how some aspect of the world is understood (Carey, 1985; Kuhn, 1962).

These views of development are compatible with an account involving universal patterns of cognitive growth, not because of innate universal constraints, but because there is only one way of developmentally assembling knowledge. As suggested, the knowledge itself, plus simple assumptions about learning in a normal range of environments, might be enough to account for universal patterns of developmental change. By way of analogy, with a certain set of building blocks, there may be only one sequence that enables building a structure above a certain height; with a set of functions, there may be only a certain sequence in which a computer program could be constructed. As noted, even in knowledge domains, such as mathematics, there are arguments for how certain forms of computation, such as addition, must be learned before others, such as multiplication (National Research Council, 2001).

In some cases, therefore, regardless of the instruction or the environment, a complex knowledge system or cognitive skill must be assembled in a fixed sequence. Thus, if development is to happen with respect to that system or skill, it must happen in the same way. The rate of developmental change may be heavily influenced by the environment and the child’s capacities, but not the sequence. In principle, this is an easy point to make with many analogies available in building systems in biology, computer science, and mathematics. That said, it is much more difficult in more naturalistic situations to have a sufficiently detailed and complete description of the representational and computational aspects of a skill
or kind of knowledge to know if it must follow a universal developmental sequence.

This area seems ripe for future investigation and is an area in which work in computer science, philosophy, and linguistics might be especially fruitful. Computer scientists for years have studied questions of optimality and necessity in the ordering of algorithms when designing large programs in traditional architectures. It is less clear whether the computational limitations of connectionist architectures are sufficiently constrained and shared across different versions as to suggest developmental universals, but this represents an interesting challenge for those working in such architectures. Similarly, in linguistic theory, formal models of acquisition often have a necessary order. One must have a set of parameters of different possible values before they can be set at each value. Similarly, certain abstract syntactic categories must be understood before ordering relations between them can be modeled. Philosophers, as well, frequently talk about necessary steps of an argument. It seems likely that, as work progresses in these fields on cognitive-science-related issues, it will greatly inform questions about universals in cognitive development.

In all discussions of developmental universals, anthropological and cross-cultural perspectives loom particularly large; for it is only in those more dramatic differences across kinds of environments that developmental universals can be explored. Thus, if it is claimed that a particular end-state knowledge structure must have arisen from a specific developmental sequence, the best test of such a claim is to consider the most radically different real-world environments possible and see if the same sequence repeatedly occurs.

In summary, questions about developmental universals are not as well studied as others in this chapter. However, they seem likely to be precisely the sort that will most benefit from a cognitive science perspective.

What Constitutes a Cognitive Domain?

There has been a sea change in the study of cognitive development from talk about global patterns of change to talk about domain-specific ones (Gelman & Kalish, Chapter 16, this Handbook, this volume; Keil, 1981; Wellman & Gelman, 1997). In many cases, development in a particular domain has its own unique path quite different from that found in other domains. Yet, despite an embrace of domain specificity in many quarters, there remains a difficult and confused issue of how to characterize a domain. That issue may well be better understood with the benefit of a cognitive science perspective. Depending on the different ways in which knowledge and cognitive skills are used, quite different senses of domains emerge with the contrasting senses becoming clearer when considered across the disciplines involved in cognitive science. Three different senses seem most common: domains as modules, domains as areas of expertise, and domains as modes of thought (cf. Wellman & Gelman, 1997).

In the sense of modules, we can think of distinct cognitive domains that fit the criteria laid down by Fodor (1983). Modules are relatively independent cognitive and perceptual systems that show properties of informational encapsulation and impenetrability. Thus, the information in a system is bounded and operated on in a manner distinct from other areas of thought and cannot be cognitively examined by more general thought processes. Modules are thought to be activated by particular informational patterns. They then automatically run through their processing routine with little or no control by other aspects of cognition. They are also assumed to have distinct and dedicated neural architectures that are innately predetermined.

The domains of thought corresponding to modules often have a quasi-perceptual nature and, indeed, some of the best worked-out examples involve perception. A common example is the perseverance of visual illusions even as higher-level cognition might state with certainty that they cannot exist. A viewer may know full well that two lines are of the same length or two circles are of the same size but be unable to overrule the phenomenal impression of differing sizes (Pylyshyn, 1999). Comparable properties were assumed to hold for more cognitive kinds of modules such as those that were involved in syntactic processing (Fodor, 1983) and theory of mind (Scholl & Leslie, 1999, 2001). The sense of domains that emerges is one in which there is often a strong perceptual grounding and the domains are often quite small in scope or are only part of a functioning cognitive system. Thus, if there is a theory of mind module, it may only apply to certain aspects of thinking about social beings and their mental states and not others. Similarly the modular component of natural language syntax may not account for all aspects of syntactic structure and certainly not all aspects of language structure.

There have been many discussions of Fodor’s version of modularity, ranging from arguments for massive modularity in which the highest levels of cognition are
modularized (Pinker, 1997; Sperber, 2002) to arguments that modularity should be strongly limited to a relatively small number of cases usually related to perceptual input systems (Fodor, 2000). A different line of criticism has been to suggest that modularity can also emerge through a process of modularization as a function of acquired expertise in a domain (Karmiloff-Smith, 1992). Domains organized around expertise, however, have a different grain and functionality from the original sense of modularity.

Expertise domains, the second possible sense of domain, can vary enormously in terms of the specificity of the domain. Quite young children can be an expert on characters in a particular video game, on dinosaurs (Chi, 1983), chess (Chi, 1978), and on any number of other topics and skills. Moreover, expertise confers cognitive advantages in terms of task performance. This sense of domain differs dramatically from that used in discussions of Fodorian modules. There is massive individual variation with respect to expertise domains, as opposed to relatively uniform performance levels for Fodorian domains. Expertise domains can, on at least some occasions, be cognitively penetrable and not automatic, although emerging automaticity can also occur with some forms of expertise such as reading, typing, and the like. Expertise domains can also be constantly evolving and changing and therefore may not have universal properties across cultures.

Finally, a third sense of domain specificity is based more on the idea of constrained frameworks of thought (Keil, 1981; Pinker, 1997). This sense of domain has sometimes been equated with having a theory (Gelman & Kalish, Chapter 16, this Handbook, this volume; Wellman & Gelman, 1997), but theories can vary considerably across individuals. It is useful therefore to contrast acquired theories (Gopnik & Wellman, 1994), such as those of cosmology, which can often be local and culturally specific and which are more likely to be part of a domain of expertise, with broader foundational ways of understanding the world that may be universal and often more implicit.

Advocates of radical conceptual change are more likely to embrace domains as theories that can vary considerably across individuals and cultures. By contrast, it may be that, even at the highest levels of thought, there are universal domain-specific constraints on the kinds of beliefs and conceptual systems that people develop. This last proposal is highly controversial, as some, such as Fodor (1983), argue against any sort of domain-specific constraints on central cognitive structures. Consider how such constraints might work. There are, for example, different forms of argumentation, such as the teleological and mechanistic. If one associates the teleological with one domain and the mechanistic with another, it may be more difficult to frame arguments in the nonnatural form of argumentation. Thus, people may naturally be predisposed to make teleological arguments about living kinds (Atran, 1998; Keil, 1992) and in doing so may find it difficult to entertain arguments that are not teleological. Similarly, people may assume an essence for living kinds that they do not assume for artifacts (Gelman, 2003; Keil, 1989). That essentialist assumption powerfully constrains theory construction about living kinds versus artifacts.

Work in other areas of cognitive science has shed considerable light on domain specificity and its different senses. Thus, in philosophy and anthropology, there has been discussion of the extent to which there could be modularity at the highest levels of conceptual structure (Sperber, 2002). A particularly intriguing line of argument is that cultural transmission of knowledge may be greatly facilitated by having shared domain-specific constraints on conceptual systems; these constraints paradoxically allow for cultural diversity by providing a common ground that enables the spreading of ideas in an understandable manner (Boyer, 2001; Sperber, 1994). In computer science, a number of approaches have examined sequestering computational routines and data representations into distinct domains with their own unique principles. Thus, it is commonplace to have specialized chip architectures for processing video arrays as opposed to numeric computations. As mentioned, a fascinating series of studies has emerged in neuroscience, asking what senses of domains might be disrupted by damage to neural tissue with an interesting feedback from that work to computational modeling. That particular discussion is informative for the ways it has refined questions about what senses of domains are viable and how domains might get set up in development. In linguistics, there has been a major shift in perspectives regarding whether there are domain-specific constraints governing aspects of language learning as diverse as syntax and word meaning. In contrast to earlier work suggesting that word learning happened because of language-specific constraints on such meanings, it now appears that such constraints emerge from much broader
facets of cognition (Bloom, 2000). In light of that more recent work, the relevant sense of domain shifts accordingly.

There remains a need to refine the different senses of domains and the claims that one wants to make about each in terms of patterns of cognitive development. Further refinements in developmental psychology will almost surely be heavily influenced from work on how different senses of domains are implemented in other areas of cognitive science.

CONCLUSION

Why has the study of cognitive development become linked especially closely to the cognitive sciences in contrast to many areas of cognitive psychology that continue to function as freestanding enterprises largely unaffected by work in other disciplines? It may be because the study of change over time is such a powerful theme in so many areas of research. Whether it is the study of moral beliefs in a culture, a grammatical form in a Celtic language, the history of ideas about species, or the adaptation of a computer network to new inputs, there are interesting stories to tell about beginnings, patterns of change, representational formats, and the generality of the phenomena. These discussions have relevance for the study of cognitive development at levels far beyond those of analogy and metaphor. Repeatedly in this chapter, we have seen how highly explicit ideas in accounts of cognitive development have been inspired by work in other fields on the growth of a cognitive capacity. Developmental questions evoke converging threads from many disciplines in ways that few other questions do.

In this chapter, we have considered 10 questions that have a venerable history in developmental psychology: What is the initial state? Is there an adapted mind? Does development proceed from the concrete to the abstract? What is the nature of conceptual change? What is the difference between learning and development? What are the representational formats underlying developmental change? What is the role of implicit and explicit cognition in development? What is the role of association and rules in development? Are there developmental universals? What constitutes a cognitive domain and how does domain structure influence development? These 10 questions also have had long histories in the disciplines of philosophy, linguistics, computer science, neuroscience, and anthropology. The striking new pattern is how researchers in psychology are starting to provide and receive benefits from work on similar versions of these questions in the other disciplines. A sense of the larger enterprise of cognitive science has fostered interactions between each of these fields in profound ways that were often unimaginable to those who originally posed these questions in their own disciplines in the past. As a result of these interactions, these questions have assumed a much greater precision and predictive value in each discipline, perhaps especially so in psychology. In many cases, the meanings of these questions are not only more precise, they have changed in ways that are different from their original form and, as a result have suggested new kinds of answers. By all indications, the decade ahead will only accelerate this trend.

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