Science & Education 8: 525–541, 1999.

Developmental and Educational Perspectives on Theory Change: To Have and Hold, or To Have and Hone?

RICHARD A. DUSCHL,[1] GEDEON O. DEÁK, KIRSTEN M. ELLENBOGEN[1] AND DOUGLAS L. HOLTON[2]

[1]*Department of Teaching & Learning,* [2]*Department of Psychology and Human Development, Vanderbilt University, Peabody College, Nashville, TN 37203, USA*

ABSTRACT. Eric Schwitzgebel presents an attractive argument for the use of affective indicators to both assess and extend the 'theory theory' research agenda. A key component of his argument is an account of explanation that can be applied to both children and adults, few of whom possess the attributes and behaviors that warrant being called scientists. The core features of his account include 1) *regarding* a set of propositions as a theory and 2) *subscribing* to a theory by accepting and employing this set of propositions to explain events within the theory's domain. We will argue that this account, while potentially helpful for guiding research on the affective content of explanations, requires elaboration because it (1) does not fully characterize what is distinctive and important about theoretical and scientific thinking, (2) raises questions about different kinds of explanations, such as seen in transitions from common-sense explanations to theoretical explanations; (3) favors individual theorizing to the exclusion of socially mediated theorizing, and (4) raises developmental questions about the nature of explanation-seeking and the capacity to apply evidence to evaluate theories.

Our response begins with a short section connecting the theory theory to the conceptual change research in science education. In particular, we examine the 'theory theory' position as presented by Alison Gopnik (1988; 1996a; 1996b) because Schwitzgebel draws heavily on her account. We then examine Schwitzgebel's defining criterion for theoretical thought, namely, the propensity to seek and hold explanations. This leads us into a discussion of the role of observation in science, and the possibility that a transition from sense perception observation to theory-driven observation is required to cross the boundary from phenomenal common sense explanations to theory-driven scientific explanations. Further, we suggest that an additional component of theoretical thought – bringing evidence to bear for theory *evaluation* – must be considered in any treatment of theoretical thought. This highlights a related issue: the impact of environmental context on the expression of theoretical thought. Here we will argue that social and technological conditions both frame and limit the kinds of explanations children and adults hold, and the manner in which these explanations are honed. We will claim that science as a way of knowing in children and adults depends on mechanisms and venues that enable private knowledge to 'go public'. It is in public forums that the environment transmits and shapes epistemological standards and rules for deciding 'what counts' as rational and legitimate observations and explanations. We conclude with discussions of explanation-seeking affect as evidence of a human theory-building trait, and implications of cognitive developmental evidence for this trait as Schwitzgebel conceives it.

THEORY THEORY CONSTRUCTIVISM

Gopnik (1996a) writes that the 'theory theory' 'is the most influential contemporary constructivist theory . . . . [based on] the idea that cognitive development is the result of the same mechanisms that lead to theory change in science' (p. 221). The 'theory theory' is grounded in rules and representations *qua* cognitive science: Theories are held to be representations which contain rules that can be used to make new representations. Gopnik explains 'the theory theory proposes that these . . . representations and rules are responsible for at least some kinds of cognitive development and . . . for theory changes in science' (p. 212).

The link between cognitive processes and structure and theory processes and structure is not new to the field of science education. One of us (Duschl) has explored with psychologists and philosophers the tensions that arise when cognitive schema are treated as theories (Duschl, Hamilton & Grandy 1990; Duschl & Hamilton 1998). Over the last 20 years researchers have been documenting and examining children's alternative theories, models, and explanations in the hope of better understanding the process of conceptual change (Pfundt & Duit 1994; Smith, Carey & Wiser 1985). The intellectual foundations of conceptual change theory (Posner, Strike, Hewson & Gertzog 1982) and of the theory theory each owes a commitment to Thomas Kuhn's mechanism for theory change and Jean Piaget's structuralist/constructivist model of cognitive development. The structural similarities between cognitive schema and scientific theories have been a topic of debate since a seminal article by McCloskey (1983). The core issue is whether the cluster of concepts children coordinate to comprehend their world have theory-like permanence or merely knowledge-in-pieces that adapt quite naturally to different situations (diSessa 1993). Put otherwise, we may ask whether the analogy between children's and scientists' thinking is superficial or deep, and where it breaks down. The theory theory position as advocated by Gopnik (1996b), Karmiloff-Smith (1988), Schwitzgebel and others holds that the metaphor is deep.

By adopting an evolutionary account of the selection and development of theory-like cognitive processes the theory theory camp distances itself from some of the traditional difficulties confronting other conceptual change researchers. That is, the story goes, the biological struggle for survival has forged the human mind over countless generations and through myriad conditions to be innately capable of theory building and theory revision. 'In fact, science may be successful largely because it exploits powerful and flexible cognitive devices that were designed by evolution to facilitate learning in young children' (Gopnik 1996b, p. 485).

Intriguingly, the traditional cognitive research programs that examine how children do or do not think like adults (c.f., Carey 1985; Karmiloff-Smith 1988) are turned upside down: '[t]he moral of my story', Gopnik writes, 'is not that children are little scientists but that scientists are big children' (p. 486). This appealing point-of-view is consistent with the trend away from science-for-scientists curriculum approaches toward science-for-all approaches.

Because theory theory constructivism aligns itself with recent trends in evolutionary psychology (Carey & Gelman 1992; Pinker 1997), accordingly it must be examined against the tenets of evolutionary theory. In evolutionary theory the expression of a trait, be it six webbed toes, chromatic vision, or theoretical thought, depends on adaptation to changes in the environment. A competitive advantage goes to those individuals and populations who possess the traits favored by new environmental factors. This is Giere's 1492 argument; namely that the explosion of modern science in the last 500 years can't be explained by evolutionary selection of cognitive traits (Giere 1996). Equally important is the environment in which cognition occurs. Moreover, trait variability is an essential aspect of evolution (Mayr 1982), thus raising questions about the various ways a cognitive trait like theory-building expresses itself both between and within individuals. Finally, it is crucial to bear in mind that traits emerge epigenetically, not just genetically (e.g., Gottlieb 1991; Greenough 1991). That is, '. . . what is inherited is [not only] the genes [but] developmentally relevant aspects of the organism's stimulative environment . . . . [Any] phenotypic trait . . . must be constructed in individual ontogeny' (Lickliter & Berry, 1990, p. 355–56). Thus, even if a theory-building trait resulted from natural selection, this would hardly support Schwitzgebel and others' assumption that the trait is universal and present in children and even infants, (Gopnik, 1996b), as well as scientists. Giere (1996) writes:

> [I]nstruments, symbolic notation, printed documents [and] experimental methods . . . are not necessary for a child to develop into a fully functional adult, [but] they are necessary . . . for a child to become a modern scientist (p. 540).

Is Explanation Enough?

The claim of a deep, abiding similarity between young children's and scientists' thinking may seem unlikely to some, but we agree with Schwitzgebel that the claim can only be fairly evaluated using criteria that encompass adults' naive theories. This requires an examination of what counts as a theory, such as Schwitzgebel has provided. The results of such an examination are critical because they will partly determine whether researchers conclude that theorizing occurs in neonatal infants (Gopnik 1996b; Gopnik & Meltzoff 1997), children between ages 4 and 10 (Carey & Spelke 1996), or only adolescents and adults (Inhelder & Piaget 1958). These results could therefore have substantial impact on our goals and practices in science education.

Schwitzgebel attempts to be inclusive in his definition of 'theory', to find the common denominator of axiomatic and semantic approaches, as well as informal reasoning by naive adults. Given the heterogeneity of this set, we admire the challenge Schwitzgebel has taken up. Does he succeed – that is, does he distill a well-defined 'kernel' of theoretical thought, to be sought in young humans?

We agree that explanation seems, by any account, a necessary feature of theorizing. But it is less clear that it is sufficient. If it is, it seems to include all informal causal reasoning. Consider the hypothetical beliefs (1) 'My car stalled because it ran out of gas', and (2) 'We exist because God made us'. In reducing theorizing to explanation, *quality* of explanation has been sacrificed. Both causal explanation (1) and tautology (2) are attributed to the same explanation-seeking instinct. Yet they are fundamentally different: the holder of the causal explanation (1) could be convinced by evidence that her theory was wrong (e.g., after filling the tank the engine still does not start), without detailed knowledge of mechanisms but simply awareness that evidence can force out an existing hypothesis. The tautological explanation (2), in contrast, is impervious to evidence. Tautological beliefs may change, but not systematically in response to evidence. Can a plausible definition of theorizing exclude evidence evaluation (see below) or weighing alternative explanations as necessary criteria? From within Schwitzgebel's explanatory framework – evolutionary theory – the capacity to theorize without these adjunct tendencies would seem to confer little advantage in reproductive fitness.

Including all explanation under the rubric of theoretical (protoscientific) thought thus cuts too broad a swath. Not all explanation is theoretical. At minimum, some capacity to apply standards of evidence, or weigh alternative explanations, is also necessary. We advocate a shift away from the hypothetical options illustrated in Figure 1, in which adults are conceived as consistently theoretical/scientific thinkers, and children either sometimes are, or (as in Piaget's theory) never are. The options represented in Figure 2 are more veridical: adults *sometimes* (seldom?) engage in theoretical thought, and at issue is whether or not children (of a given age or level of ability) are also capable of theoretical thought: By the theory theory, children at any age have similar *fundamental* capabilities as adults. This is in contrast to the view (bottom of figure) that children (prior to some lower limit level of development) lack outright the capacity for theoretical thought. Of course, there should be intermediate positions in which children have some, but not all, of adults' theoretical skills. As we shall see, understanding the nature of theoretical and atheoretical thought in children will depend on an examination of children's developmental status and history of communication with a community of knowers and learners.

Learning to Learn – Observation in Science

Even if children in a given age range can evaluate explanations against evidence, such explanations might be quite heterogeneous. Furthermore,

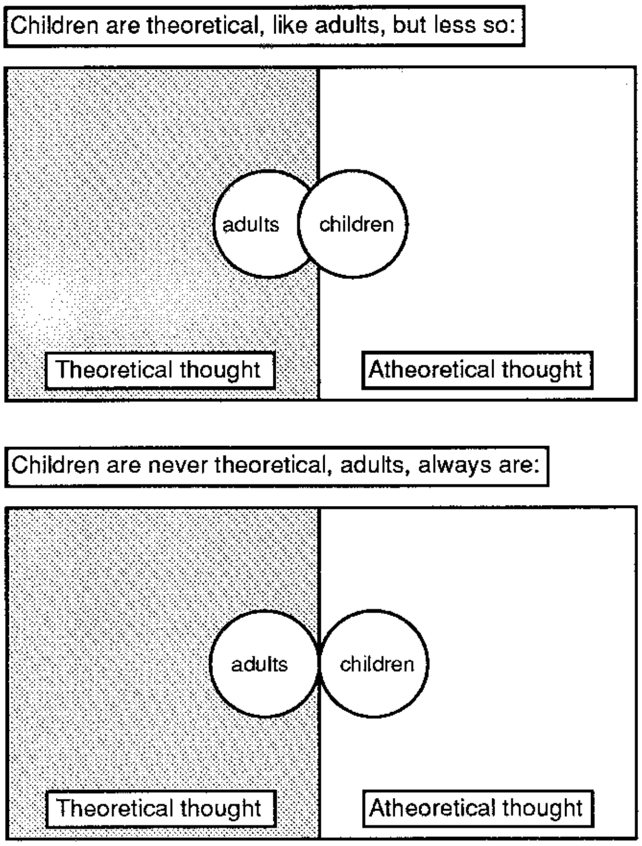

Fig. 1. Outmoded view of the possible distributions of theoretical and atheoretical thought across children and adults.

particular *kinds* of explanations might predominate at different levels of the development of theoretical thought. One distinction involves the kinds of data and phenomena 'covered' by two kinds of explanations. This distinction mirrors the historical relationship between observation and theory in the sciences.

This relationship has been one of the most examined problems in philosophy of science. Today we recognize the observational-theoretical distinction as false but this was not always the case. Turn of the century philosophers sought to develop a syntax for the language of science that would separate theoretical from observational terms. The members of the Vienna Circle seeking unambiguous meaning of scientific claims advocated that all theory terms be defined by observational terms. Historically, the activity of science was principally driven by sense perception observations employing the naked eye. The relatively recent innovations of optical (e.g., light microscope), mechanical (e.g., balances), and electronic (e.g., CAT scan

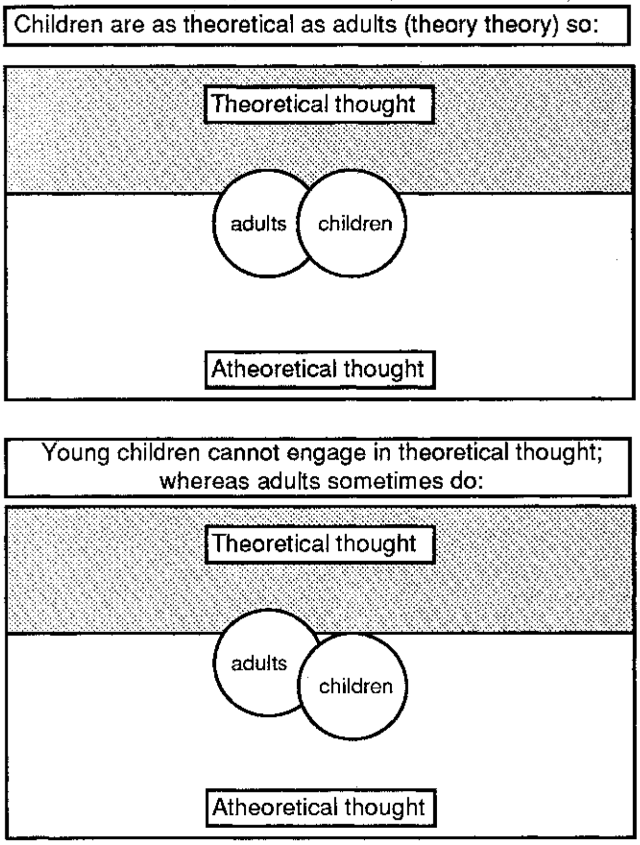

Fig. 2. More accurate view of the possible distributions of theoretical and atheoretical thought across children and adults.

or MRI) devices exponentially expanded the scope of observation, and, in turn complicated the relation between observation and theory and evidence and explanation (Ackerman, 1985). While recognizing that sense perception observations are still an important part of science and are not atheoretical, the historical record makes very clear that the practices of science with respect to evidence gathering, data acquisition, and observation have moved steadily away from sense perception observations and common sense explanations toward theory-driven observations and scientific explanations (Nagel, 1961; Shapere, 1982; Ackermann, 1985). Science is the domain of inquiry that goes beyond what our senses tell.

The crossover from sense-observation to theory-driven observation may require a special curiosity and a special environment. This curiosity leads us to seek and use tools and texts to develop non-obvious 'how and why' explanations. What comes to count as a theoretically-relevant observational event depends largely on our theories about the source, transmission, and reception of information and evidence (Duschl, 1988; Shapere, 1982). So in the case of an MRI scan, our theories of tissues, of electromagnetism, of the non-invasive effect of electromagnetic waves on tissues, of how the absorption and reflection of those waves reveals the structure of different tissues, and of how the digital display of received waves represents tissue sections, all contribute to an observational event. The distinction we are making between sense perception observations and theory-driven observations is akin to Hanson's (1958) distinction between 'seeing as' and 'seeing that' observations. 'Seeing that' observations are mediated by tools, beliefs and knowledge claims, and thus affect the selection of evidence, the location of patterns in evidence, and explanations of selected, patterned evidence.

Perhaps children undergo a similar 'seeing as' to 'seeing that' 'boundary crossing' with regard to the evidence they use to construct and revise explanations (we do not necessarily mean a punctuate transition; a gradual, asynchronous one seems better-supported by developmental evidence). For Schwitzgebel's argument to become a viable developmental theory, he must specify the kinds of explanations and evidence invoked by children, and how these change (e.g., from largely phenomenistic explanations to inferential, abstract theories). Thus, our position is that a complete theory theory must address a possible boundary crossing with respect to rule(s) for evidence. Note that the curiosity drive in and of itself does not mandate a boundary crossing from seeing as to seeing that; individuals could comfortably reside in the domain of common sense phenomenal explanations. Schwitzgebel briefly addresses this in his conclusion.

Our position is that the nature of theory change in common sense 'seeing as' explanations based on sense perception evidence is very different from theory change in scientific 'seeing that' explanations based on theory driven evidence. We require an account of the boundary crossing conditions from sense perception observations to theory driven observations. Thus, while we agree that young children have explanations, the components of which undergo conceptual change, the question is when and how their explanations begin to incorporate non-obvious, abstract theoretical constructs and begin to change as dictated by evidentiary standards.

Let us elaborate on this idea of boundary crossing. Figure 3 depicts two realms of theory development within which boundary adjustments occur. The notion of boundary adjustments is taken from Kitcher (1993). Kitcher thinks of the parade of science as a process of shifting boundaries of scientific claims about beliefs, methods, and aims or goals. We are claiming that such boundary adjustments can occur with common sense explanations and scientific explanations. There is, however, a qualitative difference between the nature of boundary adjustments within each theory

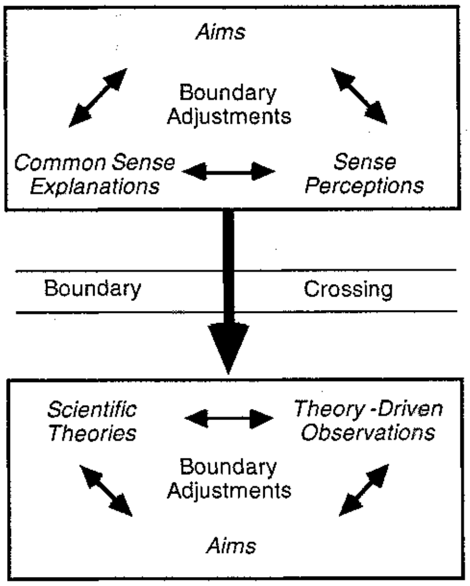

Fig. 3. Boundary crossing from sense perception explanations to theory-based observations, and boundary adjustments within each mode.

building domain and that difference is what comes to count as evidence and what is treated as anomalous data. Science is an activity where consensus opinions are sought and challenged. A critical dimension of scientific reasoning is learning to think about theories. This involves critically examining the boundaries of theories.

Research (Samarapungavan & Wiers, 1994) has shown that children are capable of thinking about the boundaries of theories. Hence, we want to suggest that in addition to Schwitzgebel's recommendation to focus on affect, it is to also essential to examine how young children cope with boundary adjustments and boundary crossings. In particular, examining how children deal with anomalous data and competing theories in social contexts is critically important. The suggestion here is two-fold: one regards the evidence-explanation continuum; the other focuses on the social dynamics of explanation building and evaluation. The complex relationship between evidence and explanation in science warrants an examination of changes or boundary adjustments in three kinds of criteria children have to relate evidence to explanation:

1) criteria for assigning data to one of four categories: fact, artifact, irrelevant or anomalous;
2) criteria for identifying patterns/models in selected data;
3) criteria for theories or explanations created to account for the patterns/models.

Within this epistemological framework for deciding what evidence counts, asking what is the unit or agent of theory change is important. Schwitzgebel seems to treat the individual as the unit. The broadening of science studies in this century, from the exclusive domain of philosophy of science to an integration of perspectives from philosophy, history and sociology of science, has challenged perspectives about what should count as the basic unit for doing science. The established view of the individual scientist as the unit or agent of conceptual change is being supplanted by a view that places communities of scientists as the fundamental unit of change. Thus, the social and technological environment that frames the doing of science is extremely relevant to the crafting of explanations. Hull captures the essence of the changes that are taking place among philosophers when he writes, '[t]he objectivity that matters in science is not primarily a characteristic of individual scientists but of scientific communities' (Hull 1988; p 4).

We feel Schwitzgebel still needs to address the role of social context in explanation development and evaluation. The differences between the explanations of young children and scientists are due in part to differences in the structure of their social contexts. For scientific explanations to count as knowledge, they must pass through publicly recognized forums for criticism, forums which share standards for evaluating theories, responding to criticisms, and distributing intellectual authority (Longino, 1990). Similarly, what counts as a valid explanation from a child is socialized, typically in informal contexts of everyday conversations with adults and peers. This is illustrated by the following example (Callanan & Oakes, 1992; p. 221–222):

[Bedtime conversation, child age 4; 2]

Child: Why does Daddy, James, and me have blue eyes and you have green eyes?

(*Mother* explains that the child got her eyes from Daddy)

Child: I like Pee Wee Herman and I have blue eyes. Daddy likes Pee Wee Herman and he has blue eyes. James likes Pee Wee Herman and he has blue eyes. If you liked Pee Wee Herman you could get blue eyes too.

(*Mother* explains that it would take more than liking Pee Wee Herman to make her eyes blue. Also states that God gave her green eyes and they couldn't be changed.)

As this example shows, there are conventional ways in which we shape children's ideas about which explanations are valid and which are not, even in informal settings.

Thus, to address questions about humans' theoretical curiosity and explanation-seeking we must understand how different environments promote and socialize forms of explanations. Until there are opportunities to take one's explanations 'on the road', to go public with ideas, to subject your evidence, methods, and assumptions to criticism – that is, to have one's criteria for forming and evaluating explanations 'honed' – the means for revising explanations are limited.

SUMMARY: EXPLANATION AND LEARNING TO LEARN

Schwitzgebel's theory of explanation contributes to the interdisciplinary dialog between cognitive psychology and philosophy of science. While both domains take issues about the growth of knowledge as central concerns, there are subtle and important differences between them. Schwitzgebel's principal recommendation is to focus on children's affective responses as evidence for a specialized curiosity: engaging in behaviors to generate and regard theories. Such a focus, he contends, can serve as a viable context to test the theory theory.

The theory theory perspective of constructivism has significant implications for our images of learning and of learners. In particular, the theory theory challenges deficit models of learning proposed for young learners. Taking a stance that young children, even infants, are theory builders challenges conventional ideas about what children can and cannot do. With respect to science learning contexts, our reading of the theory theory implies that the goal of learning should shift from sense perception descriptions of nature and the recognition of patterns to theory driven observations of nature and the explanation of patterns.

Testing and Applying the Explanation-Seeking Drive

Because Schwitzgebel grounds his argument for an innate theorizing capacity in the affective concept of explanation-seeking curiosity, an in depth inquiry into the nature of this drive is in order. 'Drive' describes a specific type of phenotype-environmental interaction. Drives such as hunger tend to be periodic and cyclical, as opposed to affective states (e.g., sadness) which are more flexible and context-responsive (Smith & Lazarus 1990). Construing explanation-seeking as a drive implies cyclical, sequential manifestations. Further, it remains to be explained why some people (e.g., scientists) do not simply accept every reasonable explanation they hear, even if there is no immediately obvious disconfirming evidence. Science often progresses when an existing theory which accounts for a lot (e.g., Newtonian physics) turns out to not account for some esoteric or even hypothetical cases dreamed up by an intrepid scientist (e.g., Einsteinian relativity). Do scientists who seek esoteric cases to disconfirm seemingly-satisfactory theories suffer from a drive 'gone wild', analogous to sex addicts or compulsive overeaters?

As Schwitzgebel notes, people often do not act upon a need for more and better explanations. Given this behavioral variability, how can we test the hypothesized drive? Even when people *do* want to know something about their environment, this might not always stem from a desire for an evidence-dependent, theoretical explanation as described above. Sometimes people might simply want to control their environment (e.g., to have a good crop every year), but not really care about the underlying theories (of, e.g., nitrogen uptake, soil acidity, etc.). Thus, explaining, 'sprinkle this stuff on your soil so your plants will grow tall' might satisfy many people. So if some people want an explanation but others don't really seem to care (i.e., show no evidence of curiosity), can we conclude that there is an innate explanation-seeking drive?

Schwitzgebel conceives of a drive to be assessed via affective states. Yet affect is responsive to situations and an organism's *interpretation* of that situation, which adds the practical problem of deducing the organism's theory's before assessing its affective responses. That is, to predict an affective response to (e.g.) anomalous data, we must first understand the organism's knowledge and beliefs. These of course will differ between ages as well as between individuals. This does not make predicting an affective response impossible, but adds the burden of assessing cognitive historical and social environmental factors to predict expression of explanation-seeking curiosity. Furthermore, it remains to be established *which* behaviors and affective signals are responses to explanation-seeking curiosity. Affective states are inferred from phenomenological (i.e., self-report), expressive, and physiological measures. These behaviors and signs are developmentally specific. Thus, to apply explanation-seeking curiosity to test Gopnik's (1996b) assertion that newborns have a theoretical capacity, we would need to first establish the kinds of affective responses (e.g., to anomalous data) predicted in newborns.

As an example, consider what is perhaps the earliest evidence of causal sensitivity in children: discrimination of mechanical causality (note that knowledge about causality implies an implicit *explanation*). Imagine that infants hold a theory (of sorts) about how objects can interact, move, impact one another, etc. If so, they should respond in a particular manner to evidence that is anomalous from within their 'theory'. Leslie and Keeble (1987), in fact, showed that infants respond differently to expected and unexpected mechanical events. Specifically, they do not look very long at events where an object moves toward and hits another object which is then propelled forward. If, however, there is a delay between impact and propulsion of the second object, or if the two do not touch before propulsion, infants look for a long time at the display, as if puzzled – perhaps as if seeking new information; a new explanation. Yet this is notoriously difficult to interpret. Simply because an infant appears to *us* to be puzzled by an anomalous event, we cannot assume that they are 'puzzled', or that they hold an implicit explanation which has just been challenged. We cannot assume that they look longer because they seek more evidence. Rather, infants might look longer at anomalous events because they violate perceptual expectations: they are novel. No explanation is required. After all, the giant sea slug responds differently when its foot muscle is poked than when it is not poked, yet it has no brain so we cannot imbue it with a cognitive explanation for anomalous foot-poking events. Such an organism might have routines describable as drive states, but we assert that any drive state which exists without the capacity to explain should not be called an 'explanation-seeking drive'. The upshot is that we await convincing evidence that organisms such as neonates hold explanations or theories. Gopnik, Schwitzgebel and others might charge us with chauvinism against preverbal organisms. Of course they would be right that we cannot assume young infants lack a cognitive ability simply because they lack verbal expression. Yet we believe that it is equally or more problematic to make rich and unsubstantiated interpretations of perceptual-motor data such as looking time. Thus, even if we can differentiate affective or behavioral states in very young organisms, it will be difficult to unambiguously attribute them to an explanation-seeking drive.

None of this is to disagree with Schwitzgebel (or Piaget, 1952, for that matter) that humans are motivated to seek new information and to resolve inconsistency. We further support Schwitzgebel's points because psychologists too often dissociate cognition from emotion, and integrating affect into the study of problem-solving and scientific thinking would be a positive step. We suspect, however, that it will be extremely challenging to test the intriguing questions and considerations raised by Schwitzgebel's drive hypothesis.

The Emergence of Theoretical Thought

Given the variability of explanations (including variability in their adaptive utility) and the difficulty of employing affective evidence, we advocate a more detailed consideration of the emergence of the kinds of explanations that we care about – that is, 'how and why' explanations addressed by evidence and subject to revision and argumentation. This requires a developmental perspective, because developmental evidence suggests that children's propensity to engage in evidence evaluation, their ability to effectively evaluate evidence, and their acquisition of cultural standards of theory testing change with age and experience.

What is the course of development of these skills? Current best evidence suggests a fairly protracted and variable course of development of theoretical thinking. The first signs, an ability to attribute effects to unseen causes, are evident by 18 to 24 months. Thereafter, until 5 or 6 years children possess organized, abstract causal knowledge but show little or no capacity for the critical reasoning necessary for evidence-driven theory change. Subsequently there is a slow, protracted period (from 5–6 years through adolescence or later) during which children occasionally engage in critical thought about explanations (i.e., scientific thought) when given sufficient scaffolding. During this period it is inappropriate to assert that children do or do not apply evaluative reasoning to theories; rather it is highly situation-specific and dependent on social support and probably a host of factors which have not yet been studied (e.g., cognitive load, individual differences in intellectual abilities and motivation, etc.). Thus, evidence-driven theory evaluation can be understood in terms of a range performance levels contingent on environmental support (see Fischer & Bidell 1991; Rogoff 1982; Vygotsky 1978).

Placing aside evidence evaluation briefly, at what age do children first show evidence of 'how and why' theoretical explanations involving unobservable causal constructs? Bretherton, McNew, & Beeghly-Smith (1981) documented that 18- to 24-month-olds attribute their own and others' behavior to internal states. For example, toddlers say things like 'if I cry I am mad and 'Are you tired?' (to someone who yawned). Such statements suggest a causal connection between external, observable events and hypothetical internal states. This may be the earliest documented evidence of theoretical thought.

Theoretical thought also requires evidence evaluation skills (which most normal adults *sometimes* exercise). When do children first demonstrate these skills? This question has largely been addressed in research on children's scientific reasoning. The evidence suggests that preschool children's scientific reasoning skills are quite limited. Some researchers have argued that even older children do not differentiate theory and evidence (Klahr, Fay, & Dunbar 1993; Kuhn 1989; Kuhn, Amsel, & O'Loughlin 1988). In experimental settings elementary school children seldom look for negative or disconfirming evidence, vary one thing at a time to test causal hypotheses, accurately record or remember the outcomes of studies, or revise theories to reflect evidence (especially negative evidence).

In addition, young children show limited logical and metacognitive sensitivities fundamental to scientific reasoning. For example, they seldom detect indeterminacy in situations where it is readily apparent to older children and adults (e.g., Byrnes & Overton 1986; Pieraut-Le Bonniec 1980). Detection of indeterminacy would seem to be a basic preconditions of scientific thought. Similarly, awareness of how your knowledge has changed seems central to scientific thinking, yet 3- and 4-year-olds show startling failure to reflect on their own past beliefs and lack of awareness of learning a new piece of information (Taylor, Esbensen & Bennett 1994). Apparently some of the rudimentary operations of theoretical thought are available in very limited forms and contexts before 5 to 6 years. Even treating available evidence liberally, it is difficult to see the rudiments of evidence evaluation and theory testing before age 4 in normally-developing children. Note that conceptual change still results, presumably from implicit, unconscious, protracted, incremental inductive processes and from direct instruction.

In contrast, there is evidence that by the beginning of elementary-school children are occasionally sensitive to links between theory and evidence. In other words, this is when children cross the boundary from atheoretical thought, as depicted in the top part of Figure 2, to at least sporadic theoretical thought, as in the bottom of Figure 2. For example, Sodian, Zaitchik, and Carey (1991) demonstrated that as many as half of 1st and 2nd graders can choose a test that conclusively answers a simple question. Similarly, there is a body of research showing that effective changes in the design of learning environments and instructional sequences can engage school-aged children in complex scientific reasoning. Metz, in a review of research (1995) makes a strong case for the need to abandon deficit models about children's reasoning. Her research (Metz 1991; 1993) and that of others (Duschl & Gitomer 1997; Penner, Giles, Lehrer & Schauble 1997; Schauble 1990; Schauble, Glaser, Duschl, Schulz & John 1995) suggests that we have underestimated the ability of children to construct and evaluate models, explanations, and experiments. This supports Carey and Spelke's (1996) claim that older children engage in conscious theory revision. But this research also makes very clear our earlier point that this requires the right environment. Getting children to engage in boundary adjustments and boundary crossings requires an enormous effort to coordinate curriculum, instruction, and assessment such that the discourse, activities and tasks facilitate, model, and honor the public display and discussion of private knowledge.

CONCLUSIONS

We have argued that an evolutionary account for an innate genetic disposition to build and revise theories is at best half the story. An accurate application of evolutionary theory to cognitive development must account for the equally important role environmental factors play in trait selection. Thus, the expression of a trait like curiosity drive derives an adaptive advantage when the individual or population possessing the trait live and function in an environment that selects for that trait. Classrooms and the conditions of informal learning are environments that can be designed to nurture theory building and theory revision.

We have raised fundamental questions about what allows humans to build and revise various kinds of theories. Building *any* explanation within a domain would meet the criteria set out by Schwitzgebel. The growth of knowledge in science, though, is characterized by domain shifts of such consequence that over time valid observations have moved away from sense precepts to theory driven inferential data. Recognizing that social and technological context will always affect theory building and theory choice, the learner or members of a population can choose whether to engage in uptake of theory-driven knowledge building processes. We have referred to the transition of explanations in a domain from grounding in sense perception observations to grounding in theory driven observations as a boundary crossing. Boundary crossing demands a different kind of curiosity, which must include critical and evaluative consideration of the parts of theories – e.g., what evidence, what patterns, which models, and what explanations 'count'.

The metacognitive processes of theory building owe as much to the environmental conditions of inquiry as to an innate drive. Social conditions that support taking private knowledge public are essential. Epistemological issues are hammered out in the public arena; science is after all a consensual way of seeking knowing. The goal of science learning should not be to acquire or 'have' theories, it should be learning to revise or 'hone' theories. It is the case that theories of the sort held by scientists only become accessible around the time children begin school. Learners (or communities) can then hone theories by recognizing, evaluating and handling anomalous data. What comes to count as anomalous, though, is bound up in collective knowledge and standards.

Innate individual curiosity aside, an expanded application of evolutionary theory to the theory theory would focus on environmental conditions that have selected for curiosity, metacognitive reasoning, and the cultural evolution of social forums that exploit our human potential for reasoning as scientific inquiry. To explain humans' *capacity* of to learn strategies for theory building, we must study learning environments in which children develop more or less powerful theories, and in which they learn procedures to make their theories more powerful. Thus, critical tests will occur in social and technological contexts that facilitate or impede boundary crossing. Getting children to engage in boundary adjustments and boundary crossings, however, will require an enormous effort to coordinate curriculum, instruction, and assessment. These efforts will tell us how children's learning activities can be shaped to facilitate adherence to public display and discourse of private knowledge and knowledge change.

REFERENCES

Ackermann, R. J.: 1985, *Data, Instruments, and Theory; A Dialectical Approach to Understanding Science*, Princeton, NJ: Princeton University Press.

Bretherton, I., McNew, S., & Beeghly-Smith, M.: 1981, 'Early Person Knowledge as Expressed in Gestural and Verbal Communication: When Do Infants Acquire a Theory of Mind?', in M. Lamb & L. Sherrod (eds.), *Infant Social Cognition: Empirical and Theoretical Considerations*, Erlbaum, Hillsdale, NJ.

Byrnes, J. P. & Overton, W. F.: 1986, 'Reasoning about Certainty and Uncertainty in Concrete and Propositional Contexts', *Developmental Psychology* **22**, 793–799.

Callanan, M. A. & Oakes, L. M.: 1992, 'Preschoolers' Questions and Parents' Explanations: Causal Thinking in Everyday Activity', *Cognitive Development* **7**, 213–233.

Carey, S.: 1985, *Conceptual Change in Childhood*, Bradford/MIT Press, Cambridge, MA.

Carey, S. & Gelman, R. (eds.): 1991, *The Epigenesis of Mind*, Erlbaum, Hillsdale, NJ.

Carey, S. & Spelke, E. S.: 1996, 'Science and Core Knowledge', *Philosophy of Science* **63**(4), 515–533.

Chi, M. T. H.: 1992, 'Conceptual Change Within and Across Ontological Categories: Examples from Learning and Discovery in Science', in R. Giere (ed.), *Cognitive Models of Science: Minnesota Studies in the Philosophy of Science*, University of Minnesota Press, Minneapolis, MN, 129–186.

DiSessa, A. A.: 1993, 'Toward an Epistemology of Physics', *Cognition and Instruction* **10**(2&3), 105–225.

Duschl, R. A.: 1988, 'Abandoning the Scientistic Legacy of Science Education', *Science Education* **72**(1), 51–62.

Duschl, R. A. & Gitomer, D. H.: 1997, 'Strategies and Challenges to Changing the Focus of Assessment and Instruction in Science Classrooms', *Educational Assessment* **4**(1), 37–73.

Duschl, R. A. Hamilton, R. J. & Grandy, R. E.: 1990, 'Psychology and Epistemology:

Match or Mismatch When Applied to Science Education?', *International Journal of Science Education* **12**(3), 220–243.
Duschl, R. A., & Hamilton, R. J.: 1998, 'Conceptual Change in Science and the Learning of Science', in B. Fraser & K. Tobin, (eds.), *International Handbook of Science Education*, Kluwer Academic Publishers, Dordrecht.
Fischer, K. W. & Bidell, T.: 1991, 'Constraining Nativist Inferences about Cognitive Capacities', in S. Carey & R. Gelman (eds.), *The Epigenesis of Mind*, Erlbaum, Hillsdale, NJ, 199–235.
Giere, R. N.: 1996, 'The Scientist as Adult', *Philosophy of Science* **63**(4), 538–541.
Gopnik, A.: 1988, 'Conceptual Change and Semantic Development as Theory Change: The Case of Object Premanance', *Mind & Language* **3**(3), 197–216.
Gopnik, A.: 1996a, 'The Post-Piaget Era', *Psychological Science* **7**(4), 221–225.
Gopnik, A.: 1996b, 'The Scientist as Child', *Philosophy of Science* **63**(4), 485–514.
Gopnik, A. & Meltzoff, A. N.: 1997, *Words, Thoughts, and Theories*, MIT Press, Cambridge, MA.
Gottlieb, G.: 1991, 'Experiential Canalization of Behavioral Development: Theory', *Developmental Psychology* **27**(1), 4–13.
Greenough, W. T.: 1991, 'Evolution as a Component of Normal Development: Evolutionary Considerations', *Developmental Psychology* **27**(1), 14–17.
Hanson, N. R.: 1958, *Patterns of Discovery*, Cambridge University Press, London.
Hull, D.: 1988, *Science as a Process*, University of Chicago Press, Chicago.
Inhelder, B. & Piaget, J.: 1958, *The Growth of Logical Thinking from Childhood to Adolescence*, Basic Books, New York.
Karmiloff-Smith, A.: 1988, 'The Child is a Theoretician, Not an Inductivist', *Mind & Language* **3**(3), 183–195.
Kitcher, P.: 1993, *The Advancement of Science; Science without Legend, Objectivity without Illusions*, Oxford Press, New York.
Klahr, D., Fay, A. L. & Dunbar, K.: 1993, 'Heuristics for Scientific Experimentation: A Developmental Study', *Cognitive Psychology* **25**, 111–146.
Kuhn, D.: 1989, 'Children and Adults as Intuitive Scientists', *Psychological Review* **96**, 674–689.
Kuhn, D., Amsel, E., & O'Laughlin, M.: 1988, *The Development of Scientific Thinking Skills*,Academic Press, New York.
Leslie, A. M. & Keeble, S.: 1987, 'Do Six-Month-Old Infants Perceive Causality?' *Cognition* **X**, 265–288.
Lickliter, R. & Berry, T. D.: 1990, 'The Phylogeny Fallacy: Developmental Psychology's Misapplication of Evolutional Theory', *Developmental Review* **10**, 348–364.
Longino, H.: 1990, *Science as Social Knowledge*, Princeton University Press, New Jersey.
Mayr, E.: 1982, *The Growth of Biological Thought*, Harvard, Cambridge, MA.
McClosky, M.: 1983, 'Intuitive Physics', *Scientific American* **248**(4), 114–122.
Metz, K. E.: 1991, 'Development of Explanation: Incremental and Fundmental Change in Children's Physics Knowledge', *Journal of Research in Science Teaching* **28**, 785–798.
Metz, K. E.: 1993, 'Preschoolers' Developing Knowledge of the Pan Balance: From New Representation to Transformed Problem Solving', *Cognition and Instruction* **11**(1) 31–93.
Metz, K. E.: 1995, 'Reassessment of Developmental Constraints on Children's Science Instruction', *Review of Educational Research* **65**(2), 93–127.
Nagel, E.: 1961, *The Structure of Science: Problems in the Logic of Scientific Explanation*, Harcourt, Brace, & World, New York.
Penner, D. E., Giles, N. D., Lehrer, R. & Schauble, L.: 1997, 'Building Functional Models: Designing an Elbow', *Journal of Research in Science Teaching* **34**(2), 125–143.
Piaget, J.: 1952, *The Origins of Intelligence in Children*, International Universities Press, New York.
Piéraut-Le Bonniec, G.: 1980, *The Development of Modal Reasoning: Genesis of Necessity and Possibility Notions*, Academic Press, New York.
Pinker, S.: 1997, *How the Mind Works*, Norton, New York.

Pfundt, H. & Duit, R.: 1994, *Bibliography; Students' Alternative Frameworks and Science Education* (4th ed.), Institute for Science Education, Kiel Germany.

Posner, G., Strike, K. Hewson, P. & Gertzog, W.: 1982, 'Accomodation of a Scientific Conception: Toward a Theory of Conceptual Change', *Science Education* **66**, 211–227.

Rogoff, B.: 1982, 'Integrating Context and Cognitive Development', in M. Lamb & A. Brown (eds.), *Advances in Developmental Psychology* (Vol. 2), Erlbaum, Hillsdale, NJ.

Samarapungavan, A. & Wiers, R.: 1994, 'Do Children Have Epistemic Constructs about Explanatory Frameworks: Examples from Naive Ideas About the Origin of Species', in A. Ram & K. Eiselt (eds.), *Proceedings of the Sixteenth Annual Meeting of the Cognitive Science Society*, Erlbaum, Mahwah, NJ, 778–783.

Schauble, L.: 1990, 'Belief Revision in Children: The Role of Prior Knowledge and Strategies for Generating Evidence', *Journal of Experimental Child Psychology* **49**, 31–57.

Schauble, L., Glaser, R., Duschl, R., Schultz, S. & John, J.: 1995, 'Students' Understanding of the Objectives and Procedures of Experimentation in the Science Classroom', *The Journal of the Learning Sciences* **4**(2) 131–166.

Shapere, D.: 1982, 'The Concept of Observation in Science and Philosophy', *Philosophy of Science* **49**, 485–525.

Smith, C., Carey, S. & Wiser, M.: 1985, 'On Differentiation: A Case Study of the Development of the Concepts of Size, Weight, and Density', *Cognition* **21**(3), 177–237.

Smith, C. A. & Lazarus, R. S.: 1990, 'Emotion and Adaptation', in L. Pervin (ed.), *Handbook of Personality: Theory and Research*, Guilford, New York.

Sodian, B., Zaitchik, D. & Carey, S.: 1991, 'Young Children's Differentiation of Hypothetical Beliefs from Evidence', *Child Development* **62**, 753–766.

Taylor, M., Esbensen, B. M. & Bennett, R. T.: 1994, 'Children's Understanding of Knowledge Acquisition: The Tendency for Children to Report that They Have Always Known What They Have Just Heard', *Child Development* **65**, 1581–1604.

Vygotsky, L. S.: 1978, *Mind in Society*, Harvard, Cambridge, MA.