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# Educating the Evolved Mind

## Conceptual Foundations for an Evolutionary Educational Psychology

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## CHAPTER 7

# EVOLUTION OF SCIENTIFIC THINKING

## Comments on Geary's "Educating the Evolved Mind"

**David Klahr**

When the editors of this volume invited me to write a commentary on David Geary's paper on evolutionary educational psychology, I was surprised, because I do not view evolutionary psychology as an intellectual niche in which my own scientific contributions have any roots. Moreover, one thing that I have gleaned from evolutionary theory is that it is dangerous for an organism to stray very far from its adapted niche. However, upon reading the paper, I discovered that Geary's ideas about the educational implications of human evolutionary history are directly relevant to an area with which I am quite familiar: the development of scientific reasoning skills. Indeed, I believe that some of his ideas can be used to expand and enrich my own perspective on the development and instruction of scientific reasoning processes.

I first offer a summary of the points and principles of evolutionary educational psychology in Geary's Table 1.1, by compressing them into

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my own list of seven "Geary-isms," with an emphasis on the implications for science education:

1. "Mind" is an evolved entity emerging in a biological organism, not an artifact created by humans, and it comprises two quite distinct types of entities: *biologically primary* and *biologically secondary* domains (or knowledge, or systems, or competencies—Geary uses these terms interchangeably).
2. Understanding the consequences of Mind's evolution may provide insights that will enable us to teach more effectively.
3. Doing so requires that we look carefully at the "fit" (or lack of it) between the biologically primary forms of knowledge and motivation, on the one hand, and the structure and content of instructional objectives and the motivations and behaviors necessary to achieve those objectives, on the other.
4. The processes that constitute scientific reasoning are far distant and, in many cases in conflict with, many of the biologically primary forms of cognition and motivation.
5. The survival of human societies requires that some, but not necessarily all, people acquire the cognitive processes and motivations that advance science and technology.
6. Therefore, societies in which a nontrivial proportion of adults are expected to acquire scientific and technical knowledge, skills, and attitudes must provide formal schooling based on carefully crafted instructional design.
7. Instructional designers who do not recognize and adapt to the inherent misalignment—in Geary's words the "ever growing gap" between primary and secondary scientific knowledge—are unlikely to be successful.

My commentary will focus on points 4 and 5 above. To anticipate: I do not agree with point 4, and I would have liked to see more discussion of the implications of point 5.

## SCIENTIFIC REASONING PROCESSES: BIOLOGICALLY PRIMARY OR SECONDARY?

Geary is quite correct in his depiction of the large gap between "everyday reasoning" and scientific reasoning, and the necessity for formal instruction to fill that gap. He notes that:

> Without solid instruction, children do not: (a) learn many basic scientific concepts, .... (b) effectively separate and integrate the hypothesis and experiment spaces; (c) effectively generate experiments that include all manipulations needed to fully test and especially to disconfirm hypotheses; and (d) learn all of the rules of evidence for evaluating experimental results as these relate to hypothesis testing. (Geary, this volume, p. 68)

It is clear that in order to become a practicing scientist, or even a scientifically literate citizen, one must acquire an enormous amount of highly specific conceptual and procedural knowledge—all of it biologically secondary. However—and here is the main point of this commentary—I believe that the most creative scientific advances are highly dependent on the fundamental, biologically primary, broadly applicable, problem-solving heuristics—"search processes," as Newell and Simon (1972) called them, such as generate-and-test, hill-climbing, and means-ends analysis. As Simon and his colleagues put it:

> It is understandable, if ironic, that "normal" science fits pretty well the description of expert problem solving, while "revolutionary" science fits the description of problem solving by novices. It is understandable because scientific activity, particularly at the revolutionary end of the continuum, is concerned with the discovery of new truths, not with the application of truths that are already well known.... It is basically a journey into unmapped terrain. Consequently, it is mainly characterized, as is novice problem solving, by trial-and-error search. The search may be highly selective—the selectivity depending on how much is already known about the domain—but it reaches its goal only after many halts, turning, and backtrackings. (Simon, Langley, & Bradshaw, 1981, p. 5)

This perspective—that the really creative leaps in science utilize some very fundamental (biologically primary) processes—is held not only by cognitive psychologists who study the nature of extraordinary mental accomplishments (Klahr & Simon, 1999), but also by many of the world's greatest nonpsychologist scientists. Their speculations and introspections on the mental processes that led to their own scientific advances imply that the real "action" in scientific discovery rests on the bedrock of biologically primary problem-solving processes.

> The whole of science is nothing more than a refinement of every day thinking. It is for this reason that the critical thinking of the physicist cannot possibly be restricted to the examination of concepts of his own specific field. He cannot proceed without considering critically a much more difficult problem, the problem of analyzing the nature of everyday thinking. (Einstein, 1936, p. 59)

> The scientific way of forming concepts differs from that which we use in our daily life, not basically, but merely in the more precise definition of concepts and conclusions; more painstaking and systematic choice of experimental material, and greater logical economy. ("The Common Language of Science," 1941, reprinted in Einstein, 1950, p. 98)

> I think what needs to be emphasized about the discovery of the double helix is that the path to it was, scientifically speaking, fairly commonplace. What was important was *not the way it was discovered*, but the object discovered—the structure of DNA itself. (Crick, 1988, p. 67; emphasis added)

The weak methods involved in problem solving—of all kinds—are available to children quite early. While there are many studies demonstrating that very young children can execute a variety of problem solving methods (e.g., Chen & Siegler, 2000; Sodian, Zaitchik, & Carey, 1991; Welsh, 1991; Willatts, 1990), I will illustrate the point with just an anecdote from my own experience. Several (many, actually) years ago, I had the following exchange with my daughter, who was 5 or 6 years old at the time.

> Scene: Child & father in back yard. Child's playmate appears riding a bike.
>
> Child: *Daddy, would you unlock basement door?*
> Father: Why?
> Child: *I want to ride my bike.*
> Father: Your bike is in the garage.
> Child: *But my socks are in the dryer.*

At the time, it was quite clear to me what my daughter wanted, and why she wanted it, and thus I found the conversation quite unremarkable. But later that week, as I was preparing a lecture on problem solving, I realized that a tremendous amount of thinking had occurred in the few seconds that led her to formulate the request. My armchair analysis is illustrated in Table 7.1. As is evident from the amount of subgoaling, retrieval, and inferencing, this little episode required a substantial amount of problem solving, and yet it is hard to imagine that any formal instruction was necessary to get a child of this age to accomplish this kind of thinking. More formal studies have demonstrated quite convincingly that by the time they enter preschool, children are quite capable of generating two or three subgoals in their problem-solving behavior, even in contexts that are quite unfamiliar and arbitrary (Klahr, 1978; Klahr & Robinson, 1981), and even infants have been shown to demonstrate simple means-ends analysis.

**Table 7.1. Hypothetical Sequence of Problem-Solving Steps**

**Goal: Ride bike (with friend)**
  Memory retrieval: family rule—must have shoes on for biking
  Fact: feet are bare
  **Subgoal 1:** Get shoes
    Observation: Shoes in yard
    Memory retrieval: Shoes hurt on bare feet
    **Subgoal 2:** Protect feet (get socks)
      Memory retrieval: Sock drawer empty this morning
      Inference: socks still in dryer
      **Subgoal 3:** Get to dryer
        Memory retrieval: dryer in basement
        **Subgoal 4:** Enter basement
          Memory retrieval: short route through yard door to basement
          Memory retrieval: yard door always locked
          **Subgoal 5:** Unlock yard door to basement
            Memory retrieval: Dad has keys
            **Subgoal 6:** Ask Dad to unlock door

Many years later I found myself reflecting on another piece of effortless problem solving in another mundane circumstance. The problem I faced was getting from my office at Carnegie Mellon to a conference room in Colorado. The "difference" between my initial state and my goal state was one of distance, and among the set of distance-reduction operators were: flying, walking, biking, and so forth. Flying was the operator of choice, but I could not fly directly from my office to Breckenridge, Colorado. This presented the subproblem of creating conditions for flying (e.g., getting to an airport, getting on a plane, etc.). Getting to the airport could best be done via taxi, but there was no taxi at Carnegie Mellon. The sub-subproblem involved making a phone call to the cab company. But all the university phones were out of order for the day during a transition to a new system; only the pay phones worked. An even deeper subproblem: how to make a call on a pay phone (remember them?) when I had no change?. However, a Coke machine was handy, and it accepted dollar bills and gave change. So I bought a Coke in order to get on the solution path to transport myself to Colorado.

My claims here are that the processes I used in this example are the same as those used by my 6-year-old daughter, that these general problem solving methods are biologically primary, that they change very little over the life span, and that they need no formal instruction. Of course, all of these weak methods, these problem-solving heuristics, these processes that guide search in the space of hypotheses and the space of experiments (Klahr, 2000), must be augmented by the specific knowledge and methods that are relevant to each scientific domain, and this domain-specific knowledge is unlikely to be acquired without formal instruction. In contrast, biologically primary weak methods remain, at their core, pretty much the same throughout the life span. There is scant evidence that any of the techniques aimed at improving these fundamental problem solving processes are effective (Sweller, 1990).

This is not to say that the so called "scientist in the crib" (Gopnik, Meltzoff, & Kuhl, 1999) is prepared to make the discoveries of a Crick, or a Darwin, or an Einstein. Clearly, formal education, and quite a lot of it, is necessary to provide the context and the massive knowledge accumulation that characterizes expertise in any area. In fact, I wish that Geary had been even more specific about exactly the type of instruction that he deems necessary to help students acquire all of this knowledge. In an earlier paper (Geary, 1995), he is quite direct in this regard in discussing the implications of his evolutionary perspective for instruction in mathematics, but the argument is equally valid for the biologically secondary aspects of scientific reasoning.

> "many constructivist researchers reject outright the use of drill-and-practice for acquiring mathematical skills. Indeed, formal drill-and-practice does not appear to be necessary for the acquisition and maintenance of many biologically primary cognitive abilities.... The evolved natural activities of humans, however, do not include embedded practice of the abilities that are associated with biologically secondary domains.... The acquisition and maintenance of biologically secondary abilities over the long-term almost certainly require some amount of sustained practice.... Cultural values that support student involvement in this practice are essential ... because evolution has not provided children with a natural enjoyment of the activities, such as drill-and-practice, that appear to be needed in order to master the abilities that are associated with complex secondary domains.... Although drill-and-practice is the bane of many contemporary educational researchers, it is probably the only way to ensure the long-term retention of basic, biologically secondary procedures. (pp. 32-33)

## ADVANCING THEORY IN THE CRUCIBLE OF PRACTICE: PASTEUR'S QUADRANT IN SCIENCE EDUCATION

At the outset, Geary warns that his theory "is not a perspective that is ready for direct translation into school curricula." I agree, and I believe that one important way to advance that theory is to move from the "science" of analyzing different aspects of scientific thinking, to the "engineering" of specific instructional objectives. We can view this effort as occurring in Pasteur's Quadrant (Stokes, 1997), where the attempt to solve applied problems leads to advances in basic theory.

There is a venerable history of this type of bi-directional boundary crossing between basic research in the psychology laboratory and applied research on instructional development, richly described in Lagemann's (2000) account of how—during any particular period—the dominant theories in psychology have tended to frame efforts at "instructional engineering." Thus, for a period during the last century, they were heavily influenced by the behaviorist tradition. The Sixties produced several new efforts based on the excitement and promise of the "cognitive revolution" (e.g., Atkinson, 1968; Gagne, 1968; Glaser & Resnick, 1972; Suppes & Groen, 1967). More recent efforts, based on emerging perspectives on cognition and cognitive development, are exemplified by the work of Case (1992), who pioneered research that sought both basic understanding of child development and effective instruction for children. Brown and colleagues (Brown, 1992; Brown & Campione, 1994; Palincsar & Brown, 1984) led a successful research program that took "reciprocal teaching" from the laboratory to the classroom across many school topics. Rittle-Johnson, Siegler, and Alibali (2001) showed how an examination of good learners could guide improved instruction in decimal fractions. My colleagues and I have followed this path in our work on the acquisition of experimental design skills in middle school children (Klahr & Li, 2005). Anderson and colleagues (Anderson, Corbett, Koedinger, & Pelletier, 1995) developed an effective intelligent tutoring system for learning algebra—now used in thousands of schools nationwide—from a basic research program in computational modeling of cognition. These educational engineering efforts have led to important advances in fundamental theoretical issues such as the effects of feedback, practice, and metacognition on learning (Mathan & Koedinger, 2005).

The point of all this, with respect to Geary's evolutionary educational psychology, is that the theory probably can't be advanced much beyond where it now stands until educators begin to attempt to fashion science instruction that is sensitive to the many distinctions that Geary delineates between different forms of biologically primary scientific knowledge, and the secondary forms of scientific knowledge that are required in different domains. One important outcome of such efforts will be the discovery of just what can and cannot be taught and how much is already there, ready to be harnessed as children first enter the science classroom.

## VARIATION AND SELECTION IN EDUCATING SCIENTISTS

At the outset of this commentary, I acknowledged the dangers of venturing beyond my own areas of scientific expertise. However, I can't resist the temptation—speaking more as a citizen speculating on the values of a society than as a scientist—to respond to another fundamental theme in Geary's paper: the fact that evolution produces distributions of important attributes in a population. Intelligence and motivation are two such distributed attributes, and Geary suggests that this evolved variability has clear implications for society's educational goals and practices. More specifically, Geary argues that the evolution of mind has produced substantial variation in children's starting points for learning science. " ... *most children will not be sufficiently motivated nor cognitively able to learn all of secondary knowledge needed for functioning in modern societies without well organized, explicit and direct teacher instruction* (p. 43, emphasis in original). This implies that it is folly to construct a one-size-fits-all approach to science education, with respect to both starting points and desired end states. As Geary puts it: "attempts to achieve within-culture 'equity' may come at a long-term cost in terms of the ability to compete with other cultures" (p. 75). This position has important political implications, and I wish that Geary had been clearer in elucidating the policy recommendations that he thinks might flow from his position.

In contemporary society, in the United States at least, the idea of an educational system that acknowledges and adapts to the existence of intellectual elites is pretty unpopular—often among those very elites. Nevertheless, Geary appears to argue for the inevitability, indeed the necessity, for educational planners to recognize this variability as a biological fact, no different from the much more widely accepted idea of elites in sports or the arts. I was frustrated by his reluctance to state this more boldly, and to address the kind of likely response it would generate once readers figured out the implications of his account of intelligence. But perhaps that must await Geary's next thoughtful and provocative paper.

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## CHAPTER 8

# EVOLUTIONARY BIOLOGY AND EDUCATIONAL PSYCHOLOGY

**John Sweller**

In his ambitious monograph "Educating the Evolved Mind: Conceptual Foundations for an Evolutionary Educational Psychology," David Geary successfully provides educational psychology with a new intellectual base. The work is encyclopaedic, novel, and timely.

Whether or not educational psychologists explicitly use evolution by natural selection in their theories, most are likely to agree that human cognition must have evolved according to the same Darwinian principles as all other biological structures and functions. If human cognition evolved according to Darwinian principles, that evolutionary process has implications for both the nature of human cognition and the manner in which we should present information to learners. Geary's work, concerned with those implications, demonstrates that by explicitly using biological evolution as a base for educational psychology, the discipline can take on an entirely different character with regard to many long-standing controversies. In this commentary, I will attempt to analyze further the use of evolutionary principles in educational psychology by

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