What Are Intelligence? And Why?

1996 AAAI Presidential Address

Randall Davis

■ This article, derived from the 1996 American Association for Artificial Intelligence Presidential Address, explores the notion of intelligence from a variety of perspectives and finds that it "are" many things. It has, for example, been interpreted in a variety of ways even within our own field, ranging from the logical view (intelligence as part of mathematical logic) to the psychological view (intelligence as an empirical phenomenon of the natural world) to a variety of others. One goal of this article is to go back to basics, reviewing the things that we, individually and collectively, have taken as given, in part because we have taken multiple different and sometimes inconsistent things for granted. I believe it will prove useful to expose the tacit assumptions, models, and metaphors that we carry around as a way of understanding both what we're about and why we sometimes seem to be at odds with one another.

Intelligence are also many things in the sense that it is a product of evolution. Our physical bodies are in many ways overdetermined, unnecessarily complex, and inefficiently designed, that is, the predictable product of the blind search that is evolution. What's manifestly true of our anatomy is also likely true of our cognitive architecture. Natural intelligence is unlikely to be limited by principles of parsimony and is likely to be overdetermined, unnecessarily complex, and inefficiently designed. In this sense, intelligence are many things because it is composed of the many elements that have been thrown together over evolutionary timescales. I suggest that in the face of that, searching for minimalism and elegance may be a diversion, for it simply may not be there. Somewhat more crudely put: The human mind is a 400,000-year-old legacy application…and you expected to find structured programming?

I end with a number of speculations, suggesting that there are some niches in the design space of intelligences that are currently underexplored. One example is the view that thinking is in part visual, and hence it might prove useful to develop representations and reasoning mechanisms that reason with diagrams (not just about them) and that take seriously their visual nature. I speculate as well that thinking may be a form of reliving, that re-acting out what we have experienced is one powerful way to think about and solve problems in the world. In this view, thinking is not simply the decontextualized manipulation of abstract symbols, powerful though that may be. Instead, some significant part of our thinking may be the reuse or simulation of our experiences in the environment. In keeping with this, I suggest that it may prove useful to marry the concreteness of reasoning in a model with the power that arises from reasoning abstractly.

Relax, there's no mistake in the title. I've indulged a bit of British-English that I've always found intriguing: the use of the plural verb with collective nouns (as in "Oxford have won the Thames regatta").

The selection of verb sense is purposeful and captures one of the main themes of the article: I want to consider *intelligence* as a collective noun. I want to see what we in AI have thought of it and review the multiple ways in which we've conceived of it. My intention is to make explicit the assumptions, metaphors, and models that underlie our multiple conceptions.

I intend to go back to basics here, as a way of reminding us of the things that we, individually and collectively, have taken as given, in part because we have taken multiple different, and sometimes inconsistent, things for granted. I believe it will prove useful to expose the tacit assumptions, models, and metaphors that we carry around, as a way of understanding both what we're about and why we sometimes seem to be at odds with one another. That's the first part of the article.

In the second part of the article, I'll ask you to come along on a natural history tour—I'm going to take you away, back to a time around

Mathematical Logic	**Psychology**	**Biology**	**Statistics**	**Economics**
Aristotle				
Descartes				
Boole	James		Laplace	Bentham, Pareto
Frege		Bernoulli	Friedman	
Peano				
	Hebb	Lashley	Bayes	
Goedel	Bruner	Rosenblatt		
Post	Miller	Ashby	Tversky	Von Neumann
Church	Newell	Lettvin	Kahneman	Simon
Turing	Simon	McCulloch, Pitts		Raiffa
Davis		Heubel, Weisel		
Putnam				
Robinson				
LOGIC	SOAR	CONNECTIONISM	Causal networks	Rational agents
PROLOG	Knowledge-based systems	A-life		
	Frames			

Table 1. Views of Intelligent Reasoning and Their Intellectual Origins.

4 million years ago when the first hominids arose and consider how intelligence came to be. We'll take an evolutionary view, consider intelligence as a natural phenomenon, and ask *why* it arose. The vague answer—that it provided enhanced survival—turns out not to be very informative; so, we'll ask, *why* is intelligence, and more important, what does that tell us about how we might proceed in AI?

The third part of the article is concerned with what we might call *inhuman problem solving*; it explores to what degree intelligence is a human monopoly. In this part of the article, AI learns about the birds and the bees: What kinds of animal intelligence are there, and does that, too, inform our search for human intelligence?

I'll end by considering how we might expand our view, expand our exploration of intelligence by exploring aspects of it that have received too little attention. AI has been doing some amount of consolidation over the past few years, so it may well be time to speculate where the next interesting and provocative leaps might be made.

Fundamental Elements

If AI is centrally concerned with intelligence, we ought to start by considering what behaviors lie at its core. Four behaviors are commonly used to distinguish intelligent behavior from instinct and stimulus-response associations: (1) prediction, (2) response to change, (3) intentional action, and (4) reasoning.

One core capability is our ability to predict the future, that is, to imagine how things might turn out rather than have to try them. The essential issue here is *imagining,* that is, the disconnection of thought and action. That disconnection gives us the ability to imagine the consequences of an action before, or instead of, experiencing it, the ability, as Popper and Raimund (1985) put it, to have our hypotheses die in our stead. The second element—response to change—is an essential characteristic that distinguishes intelligent action from inalterable instinct or conditioned reflexes. *Intentional action* refers to having a goal and selecting actions appropriate to achieving the goal. Finally, by *reasoning,* I mean starting with some collection of facts and adding to it by any inference method.

Five Views of Reasoning

AI has of course explored all these in a variety of ways. Yet even if we focus in on just one of them—intelligent reasoning—it soon becomes clear that there have been a multitude of answers explored within AI as to what we mean by that, that is, what we mean when we say intelligent reasoning. Given the relative youth of our field, the answers have often come from work in other fields. Five fields in particular—(1) mathematical logic, (2) psychology, (3) biology, (4) statistics, and (5) economics—have provided the inspiration for five distinguishable notions of what constitutes intelligent reasoning (table 1).[1]

One view, historically derived from mathematical logic, makes the assumption that intelligent reasoning is some variety of formal calculation, typically, deduction; the modern exemplars of this view in AI are the logicists. A second view, rooted in work in psychology, sees reasoning as a characteristic human behavior and has given rise to both the extensive work on human problem solving and the large collection of knowledge-based systems. A third approach, loosely rooted in biology, takes the view that the key to reasoning is the architecture of the machinery that accomplishes it; hence, reasoning is a characteristic stimulus-response behavior that emerges from parallel interconnection of a large collection of very simple processors. Researchers working on several varieties of connectionism are descendants of this line of work; work on artificial life also has roots in the biologically inspired view. A fourth approach, derived from probability theory, adds to logic the notion of uncertainty, yielding a view in which reasoning intelligently means obeying the axioms of probability theory. A fifth view, from economics, adds the further ingredients of values and preferences, leading to a view of intelligent reasoning defined by adherence to the tenets of utility theory.

Briefly exploring the historical development of the first two of these views will illustrate the different conceptions they have of the fundamental nature of intelligent reasoning and will demonstrate the deep-seated differences in mind set that arise—even within our own field—as a consequence.

The Logical View: Reasoning as Formal Calculation Consider first the tradition that uses mathematical logic as a view of intelligent reasoning. This view has its historical origins in Aristotle's efforts to accumulate and catalog the syllogisms, in an attempt to determine what should be taken as a convincing argument. (Note that even at the outset, there is a hint of the idea that the desired form of reasoning might be describable in a set of formal rules.) The line continues with Descartes, whose analytic geometry showed that Euclid's work, apparently concerned with the stuff of pure thought (lines of zero width, perfect circles of the sorts only the gods could make), could in fact be married to algebra, a form of calculation, something mere mortals could do.

By the time of Leibnitz, the agenda is quite specific and telling: He sought nothing less than a *calculus of thought,* one that would permit the resolution of all human disagreement with the simple invocation "let us compute." By this time, there is a clear and concrete belief that as Euclid's once godlike and unreachable geometry could be captured with algebra, so some (or perhaps any) variety of that ephemeral stuff called thought might be captured in calculation, specifically logical deduction.

In the nineteenth century, Boole provided the basis for propositional calculus in his *Laws of Thought*; later work by Frege and Peano provided additional foundation for the modern form of predicate calculus. Work by Davis, Putnam, and Robinson in the twentieth century provided the final steps in mechanizing deduction sufficiently to enable the first automated theorem provers. The modern offspring of this line of intellectual development include the many efforts that use first-order logic as a representation and some variety of deduction as the reasoning engine, as well as the large body of work with the explicit agenda of making logical reasoning computational, exemplified by Prolog.

Note we have here the underlying premise that reasoning intelligently *means* reasoning logically; anything else is a mistake or an aberration. Allied with this is the belief that logically, in turn, means first-order logic, typically sound deduction (although other models have of course been explored). By simple transitivity, these two collapse into one key part of the view of intelligent reasoning underlying logic: Reasoning intelligently *means* reasoning in the fashion defined by first-order logic. A second important part of the view is the allied belief that intelligent reasoning is a process that can be captured in a formal description, particularly a formal description that is both precise and concise.

The Psychological View: Reasoning as Human Behavior But very different views of the nature of intelligent reasoning are also possible. One distinctly different view is embedded in the part of AI influenced by the psychological tradition. That tradition, rooted in the work of Hebb, Bruner, Miller, and Newell and Simon, broke through the stimulus-response view demanded by behaviorism and suggested instead that human problem-solving behavior could usefully be viewed in terms of goals, plans, and other complex mental structures. Modern manifestations include work on SOAR (Rosenbloom, Laird, and Newell 1993) as a general mechanism for producing intelligent reasoning and knowledge-based systems as a means of capturing human expert reasoning.

Where the logicist tradition takes intelligent reasoning to be a form of calculation, typically deduction in first-order logic, the tradition based in psychology takes as the defining characteristic of intelligent reasoning that it is a particular variety of human behavior. In the logicist view, the object of interest is thus a construct definable in formal terms via mathematics, while for those influenced by the psychological tradition, it is an empirical phenomenon from the natural world.

There are thus two very different assumptions here about the essential nature of the fundamental phenomenon to be captured. One of them makes AI a part of mathematics; the other makes it a part of natural science.

A second contrast arises in considering the character of the answers each seeks. The logicist view has traditionally sought compact and precise characterizations of intelligence, looking for the kind of characterizations encountered in mathematics (and at times in physics). The psychological tradition by contrast suggests that intelligence is not only a natural phenomenon, it is an inherently complex natural phenomenon: as human anatomy and physiology are inherently complex systems resulting from a long process of evolution, so perhaps is intelligence. As such, intelligence may be a large and fundamentally ad hoc collection of mechanisms and phenomena, one for which complete and concise descriptions may not be possible.

The point here is that there are a number of different views of what intelligent reasoning is, even within AI, and it matters which view you take because it shapes almost everything, from research methodology to your notion of success.

The Societal View: Reasoning as Emergent Behavior AI's view of intelligent reasoning has varied in another dimension as well. We started out with the straightforward, introspection-driven view that intelligence resided in, and resulted from, an individual mind. After all, there seems at first glance to be only one mind inside each of us.

But this, too, has evolved over time, as AI has considered how intelligent reasoning can arise from groups of (more or less) intelligent entities, ranging from the simple units that make up connectionist networks, to the more complex units in Minsky's (1986) society of mind, to the intelligent agents involved in collaborative work. Evolutions like this in our concept of intelligence have as corollaries a corresponding evolution in our beliefs about where sources of power are to be found. One of the things I take Minsky to be arguing in his society of mind theory is that power is going to arise not from the individual components and their (individual) capabilities, but from the principles of organization—how you put things (even relatively simple things) together in ways that will cause their interaction to produce intelligence. This leads to the view of intelligence as an emergent phenomenon—something that arises (often in a nonobvious fashion) from the interaction of individual behaviors. If this is so, we face yet another challenge: If intelligence arises in unexpected ways from aggregations, then how will we ever engineer intelligent behavior, that is, purposefully create any particular variety of it?

Consider then the wide variety of views we in AI have taken of intelligent reasoning: logical and psychological, statistical and economic, individual and collaborative. The issue here is not one of selecting one of these over another (although we all may have our individual reasons for doing so). The issue is instead the significance of acknowledging and being aware of the different conceptions that are being explored and the fundamentally different assumptions they make. AI has been and will continue to be all these things; it can embrace all of them simultaneously without fear of contradiction.

AI: Exploring the Design Space of Intelligences. The temptation remains, of course, to try to unify them. I believe this can in fact be done, using a view I first heard articulated by Aaron Sloman (1994), who suggested conceiving of AI as the exploration of the design space of intelligences.

I believe this is a useful view of what we're about for several reasons: First, it's more general than the usual conjunction that defines us as a field interested in both human intelligence and machine intelligence. Second, the plural—intelligences—emphasizes the multiple possibilities of what intelligence is (or are, as my title suggests). Finally, conceiving of it in terms of a design space suggests exploring broadly and deeply, thinking about what kinds of intelligences there are, for there may be many.

This view also helps address the at-times debated issue of the character of our field: Are we science or engineering, analytic or synthetic, empirical or theoretical? The answer of course is, "yes."

Different niches of our field have different characters. Where we are concerned with human intelligence, our work is likely to be more in the spirit of scientific, analytical, and empirical undertakings. Where the concern is more one of machine intelligence, the work will be more engineering, synthetic, and theoretical. But the space is roughly continuous, it is large, and all these have their place.

Why Is Intelligence?

Next I'd like to turn to the question, "Why is intelligence?" That is, can we learn from an explicitly evolutionary view? Is there, or could there be, a paleocognitive science? If so, what would it tell us?

We had best begin by recognizing the difficulty of such an undertaking. It's challenging for several reasons: First, few of the relevant things fossilize. I've checked the ancient bits of amber, and sadly, there are no Jurassic ontologies to be found embedded there; there are no Paleolithic rule-based systems still available for study; and although there is speculation that the cave paintings at Lascaux were the earliest implementation of JAVA, this is, of course, speculation.

The examples may be whimsical, but the point is real—few of the elements of our intellectual life from prehistoric times are preserved and available for study. There are even those who suggest the entire undertaking is doomed from the start. Richard Lewontin (1990), who has written extensively on evolution, suggests that "if it were our purpose in this chapter to say what is actually known about the evolution of human cognition, we would stop at the end of this sentence" (p. 229).

Luckily, he goes on: "That is not to say that a good deal has not been written on the subject. Indeed whole books have been devoted to discussions of the evolution of human cognition and its social manifestations, but these works are nothing more than a mixture of pure speculation and inventive stories. Some of these stories might even be true, but we do not know, nor is it clear…how we would go about finding out" (p. 229). Hence, we had better be modest in our expectations and claims.

A second difficulty lies in the data that are available. Most attempts to date phenomena are good only to something like a factor of two or four. The taming of fire, for example, probably occurred around 100,000 years ago, but it might have been 200,000 or even 400,000. Then there is the profusion of theories about why intelligence arose (more on those in a moment). Luckily for our purposes, we don't actually have to know which, if any, of these many theories are correct. I suggest you attend not to the details of each but to the overall character of each and what it may tell us about how the mind might have arisen.

Presumably the mind evolved and should as a consequence have some of the hallmarks of anything produced by that process. Let's set the stage then by asking what's known about the nature of evolution, the process that was presumably in charge of, and at the root of, all this.

The Nature of Evolution

The first thing to remember about evolution is that it is engaging in a pastime that's quite familiar to us: *blind search.* This is sometimes forgotten when we see the remarkable results—apparently elegant and complex systems—that come from a few million years' worth of search. The issue is put well in the title of one article—"The Good Enough Calculi of Evolving Control Systems: Evolution Is Not Engineering" (Partridge 1982). The article goes on to contrast evolution and engineering problem solving: In engineering, we have a defined problem in the form of design requirements and a library of design elements available for the solution. But "biology provides no definition of a problem until it has been revealed by the advantage of a solution. Without a predefined problem, there is no prerequisite domain, range, form for a solution, or coordinates for its evaluation, except that it provides a statistically improved survival function. This filter selects 'good enough' new solutions and thereby identifies solved problems" (p. R173).

… can we learn from an explicitly evolutionary view? Is there, or could there be, a paleocognitive science? If so, what would it tell us?

Consider in particular the claim that "biology provides no definition of a problem until it has been revealed by the advantage of a solution." The warning here is to be wary of interpreting the results of evolution as nature's cleverness in solving a problem. It had no problem to solve; it was just trying out variations.

The consequences of blind search are familiar to us; so, in some ways what follows seems obvious, but the consequences are nevertheless worth attending to.[2]

One consequence of random search is that evolution wanders about, populating niches wherever it finds them in the design space and the environment. Evolution is not a process of ascent or descent; it's a branching search space being explored in parallel.

A second consequence is that nature is sometimes a lousy engineer. There are, for example, futile metabolic cycles in our cells—apparently circular chemical reactions that go back and forth producing and unproducing the same molecules and depleting energy stores for no apparent purpose (Katz 1985).

Third, despite the size of the design space, blind search sometimes doubles back on itself, and evolution rediscovers the same mechanisms. One widely cited example is the eye of the mammal and the eye of the octopus. They are quite similar but for one quite striking fact: The human eye is backward compared with the octopus (Katz 1985). In the mammalian eye, the photoreceptors are in the retinal layer nearest the rear of the eye; as a consequence, light has to go through the retinal "back plane" before it encounters the photoreceptors.

A second striking example arises in the evolution of lungs in mammals and birds. Both appear to have arisen from the swim bladders that fish use to control buoyancy, but birds' lungs are unidirectionally ventilated, unlike the tidal, bidirectional flow in other vertebrates. (As a consequence, avian lungs are much more efficient than ours: Himalayan geese have been observed not only to fly over human climbers struggling with their oxygen tanks to reach the top of Mt. Everest but to honk as they do so (Encyclopedia Brittannica 1994–1997); presumably this is nature's way of reminding us of our place in the scheme of things.)

The differences in end results suggest the different paths that were taken to these results, yet the remaining similarities in eyes and lungs show that evolution can rediscover the same basic mechanisms despite its random search.

Fourth, there are numerous examples of how nature is a satisficer, not an optimizer. For instance, one of the reasons cuckoos can get away with dropping off their eggs in the nests of other birds is that birds have only a very crude algorithm for recognizing their eggs and their chicks (Calvin 1991). The algorithm is good enough, most of the time, but the cuckoo takes advantage of its only adequate (manifestly nonoptimal) performance.

The control of human respiration provides another example. Respiration is, for the most part, controlled by the level of CO_2 in the blood. There appear to be a variety of reasons for this (for example, controlling CO_2 is one way to control pH levels in the blood), but it's still only an adequate system. Its limits are well known to mountain climbers and divers. Mountain climbers know that they have to be conscious of the need to breathe at altitude because the thin air leaves CO_2 levels in the blood low, eliminating the normal physiological cues to breathe, even through blood-oxygen levels are also low.

Divers need to understand that hyperventilation is dangerous: It can drive the CO_2 level in the blood near zero, but it cannot increase blood-oxygen saturation past the blood's normal limits. As a result, the CO_2 level can stay abnormally low past the time that oxygen levels have significantly decreased, and the diver will feel no need to breathe even though blood-oxygen levels are low enough to lead to blackout.

Fifth, evolution sometimes proceeds by functional conversion, that is, the adoption of an organ or system serving one purpose to serve another. The premier example here is bird wings: The structures were originally developed for thermal regulation (as they are still used in insects) and, at some point, were coopted for use in flight.

Finally, evolution is conservative: It adds new layers of solutions to old ones rather than redesigning. This in part accounts for and produces vestigal organs and systems, and the result is not necessarily pretty from an engineering viewpoint. As one author put it, "The human brain is wall-to-wall add-ons, a maze of dinguses and gizmos patched into the original pattern of a primitive fish brain. No wonder it isn't easy to understand how it works" (Bickerton 1995, p. 36).

Evolution then is doing random search, and the process is manifest in the *product*. As one author put it,

> In the natural realm, organisms are not built by engineers who, with an overall plan in mind, use only the most appropriate materials, the most effective design, and the most reliable construction techniques. Instead, organisms are patchworks containing appendixes, uvulas, earlobes, dewclaws, adenoids, warts, eyebrows, underarm hair, wisdom teeth, and toenails. They are a meld of ancestral parts integrated step by step during their development through a set of tried and true ontogenetic mechanisms. These mechanisms ensure matching between disparate elements such as nerves and muscles, but they have no overall vision. Natural ontogenies and natural phylogenies are not limited by principles of parsimony, and they have no teleology. Possible organisms can be overdetermined, unnecessarily complex, or inefficiently designed (Katz 1985, p. 28).

The important point here for our purposes is that what's manifestly true of our anatomy may also be true of our cognitive architecture. Natural intelligence is unlikely to have an overall vision and unlikely to be limited by principles of parsimony; like our bodies, it is likely to be overdetermined, unnecessar-

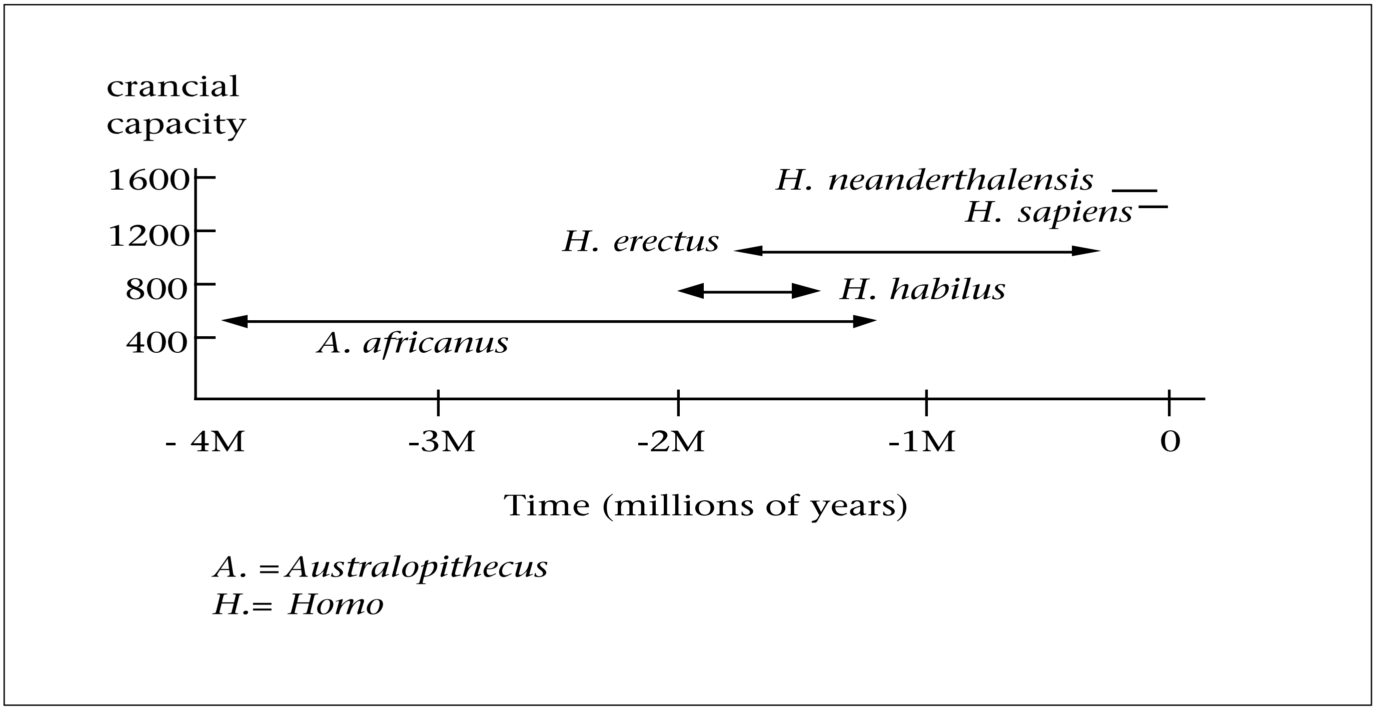

Figure 1. The Fossil Record (derived from data in Donald [1991], Eccles [1989], Mithen [1996], and Hyland [1993]).

Note: The averages shown in this chart do not make evident the apparent discontinuities in the size increases. As Mitherton (1996) discusses, there were apparently two bursts of brain enlargement, one about two million years ago, at the transition from *A. africanus* to *H. habilis,* and another about 500,000 years ago, with the transition from *H. erectus*. And yes, the brains of *H. neanderthalensis* were on average larger than those of modern man, though so, too, was its body. Finally, note that the data in this field change more rapidly than one might expect: This chart was accurate when drawn in August 1996, but by December 1996 new evidence (Swisher et al. 1996) was reported suggesting that *H. erectus* did not in fact die off 250,000 years ago and may have lived contemporaneously with *H. sapiens* and the Neanderthals.

ily complex, and inefficiently designed.

In the face of that, searching for the minimalism and elegance beloved by engineers may be a diversion, for it simply may not be there. Somewhat more crudely put: The human mind is a 400,000-year-old legacy application…and you expected to find structured programming?

All that in turn gives us all the more reason to explore deeply into the design space of intelligence, for the human solution, and its sources of power, may be extraordinarily quirky.

The Available Evidence

If we can't rely on the fossil record for preserved bits of cognition, can it supply other useful information? One observation from the record of particular relevance is the striking increase in what's called the *encephalization quotient*—the ratio of brain size to body size. Fossil records give clear evidence that the encephalization quotient of human ancestors increased by a factor of three to four over about four million years (Donald 1991). In evolutionary terms, this is an enormous change over a short period of time. Simply put, our brains got very big very fast.

This is interesting in part because brains are metabolically very expensive. In the adult, about 20 percent of our metabolism goes into maintaining our brains; in children, the brain consumes about 50 percent of metabolic output (Bickerton 1995). This makes the question all the more pressing: Considering how expensive large brains are, why do we have them? Why is intelligence? What benefit arose from it?

A second clear piece of evidence, this time from current studies of the brain, is lateralization: The standard examples are language (found in the left hemisphere in approximately 93 percent of us) and the rapid sequencing of voluntary muscles for things such as throwing (found on the left in 89 percent) (Calvin 1983). This is striking in part because the human brain has very few anatomical asymmetries; the observed asymmetries are almost entirely functional (Eccles 1989). It is also striking because the asymmetry arose with the hominids (*Homo* and our ancestors) and appears unique to them; the brains of our closest living relatives—apes and monkeys—are

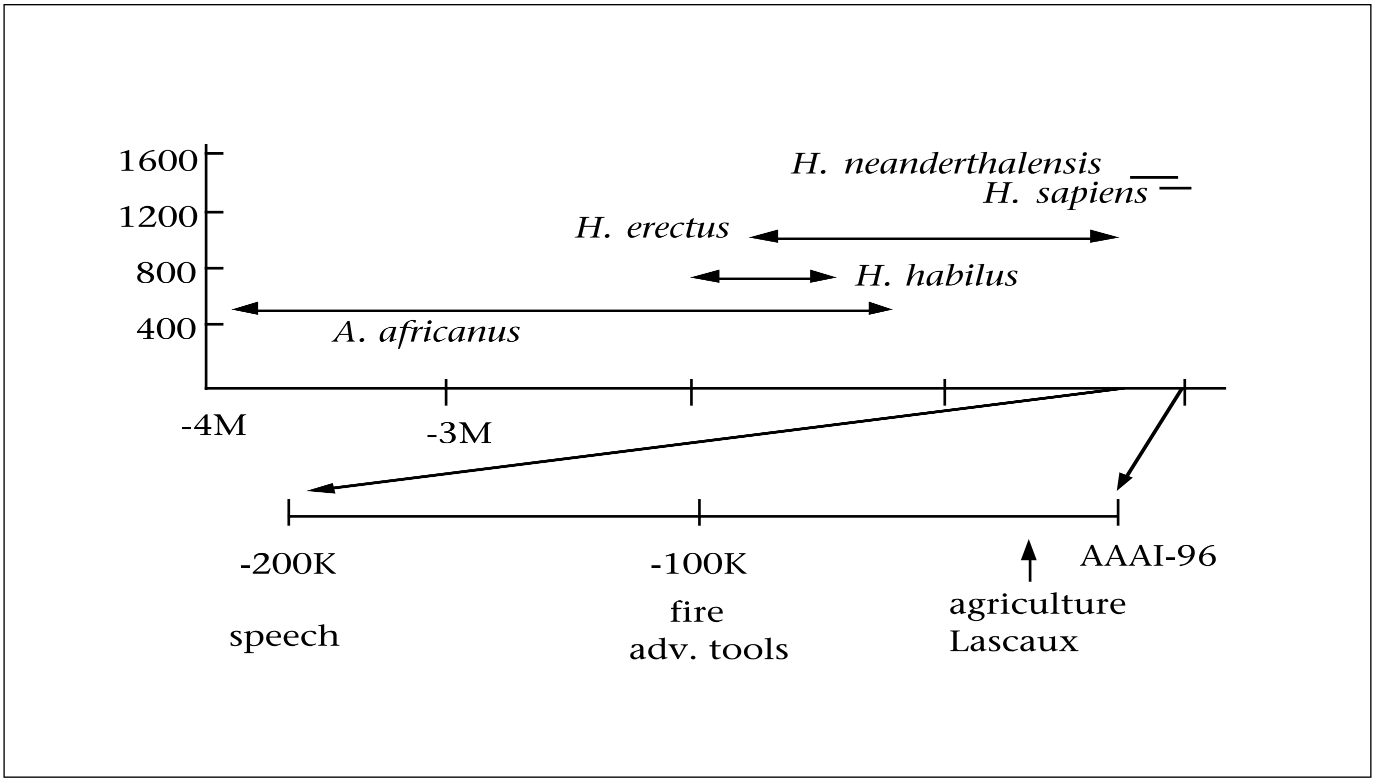

Figure 2. A More Detailed Look at the Fossil Record.

symmetrical both anatomically and functionally (Eccles 1989).

The interesting question here of course is why, in a world of symmetry, is the human brain lateralized, even in part?

One useful way to set the stage for the various suggested answers is to consider the sequence of events that lead to *Homo (H.) sapiens*. Figure 1 gives an overview of the last four million years, indicating the evolutionary span of several of our immediate ancestors and their average cranial capacity.

If we zoom in on the last 200,000 years, we see a few additional events of note (figure 2). Speech arrives quite recently, around 200,000 to 400,000 years ago; fire doesn't get tamed until around 100,000 years ago, which is when more advanced tools also begin to appear. The conversion from hunter-gatherers to a settled society dependent on the use of agriculture happens roughly 10,000 to 15,000 years ago, about the same time as the cave paintings at Lascaux.

One question to ask about all this is, What changed between four million years ago and now? Four million years ago, there was (presumably) nothing we would recognize as human-level intelligence; now there is. What changed in between?

Theories of the Origin of Intelligence

A variety of theories have been suggested.

Early Man, the Primal Tool Maker One theory is wrapped up in the notion that man is a tool maker. The construction of increasingly elaborate tools both gave early man a survival advantage and produced evolutionary pressure for yet more elaborate tools and the brains to build them. Unfortunately, another look at our time scale provides some disquieting data. The earliest tools show up around 2.5 million years ago and stay largely unchanged until about 300,000 years ago (Calvin 1991). Yet during all that time our brains are growing quickly. The tool theory thus seems unlikely.

Early Man and the Killer Frisbee A second theory (Calvin 1991, 1983) is centered on hunting methods and involves passing a device that is sometimes whimsically referred to as the *killer frisbee* (figure 3). It's one of the earliest tools and is more properly called a hand ax because it was believed to be a handheld ax. The curious thing about it is that if you look closely, you'll see that all its edges are sharp—not a very good idea for something designed to be held in the hand.

One researcher built replicas of these and discovered that if thrown like a discus, it flies

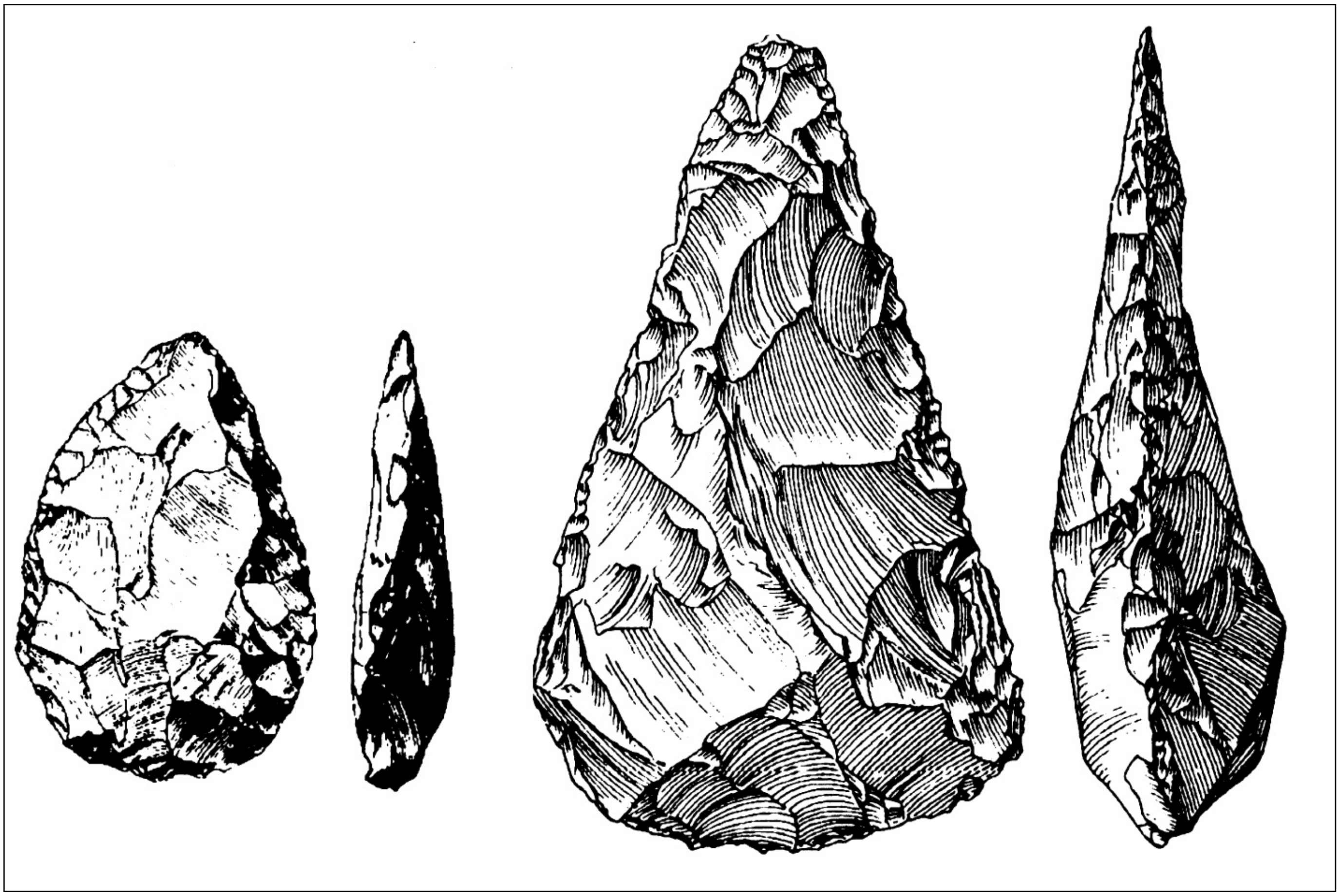

Figure 3. An Early Tool: Top and Side Views.

Reproduced with permission from Calvin (1991).

like a frisbee at first but soon turns on edge and lands with its sharp edge embedded in the earth. Now add to this the fact that many of these artifacts have been found in the mud near ancient waterholes. This led to the theory that the artifacts were thrown by our ancestors at herds of animals gathered at waterholes, with the intent of wounding one of them or knocking it down.

But why should throwing things be interesting—because throwing accurately requires precise time control of motor neurons. For example, if you want to throw accurately at a target the size of a rabbit that's 30 feet away (figure 4), the motor-control problem is substantial: the time window for release of the projectile is less than 1 microsecond. But individual neurons are not in general that accurate temporally. How do we manage?

One way to get the needed accuracy is to recruit populations of neurons and synchronize them: Enright (1980) shows how precise timing can be produced from mutual coupling of heterogeneous, inaccurate oscillators (that is, those with differing intrinsic average frequencies and that are individually unreliable on a cycle-to-cycle basis). With this arrangement, the standard deviation of cycle length between successive firings is proportional to

$$\sqrt[1]{N}$$

so quadrupling the number of elements cuts the standard deviation in half. This might account for the ability of our brains to control muscle action to within fractions of a millisecond, when individual neurons are an order of magnitude less precise.

The theory then is that our brains grew larger because more neurons produced an increase in throwing accuracy (or an increase in projectile speed with no reduction in accuracy), and that in turn offered a major selective advantage: the ability to take advantage of a food source—small mammals—that was previously untapped by hominids. A new food source in turn means a new ecological niche ripe for inhabiting. The advantage resulting from even a limited ability to make use of a new source of food also provides a stronger and more imme-

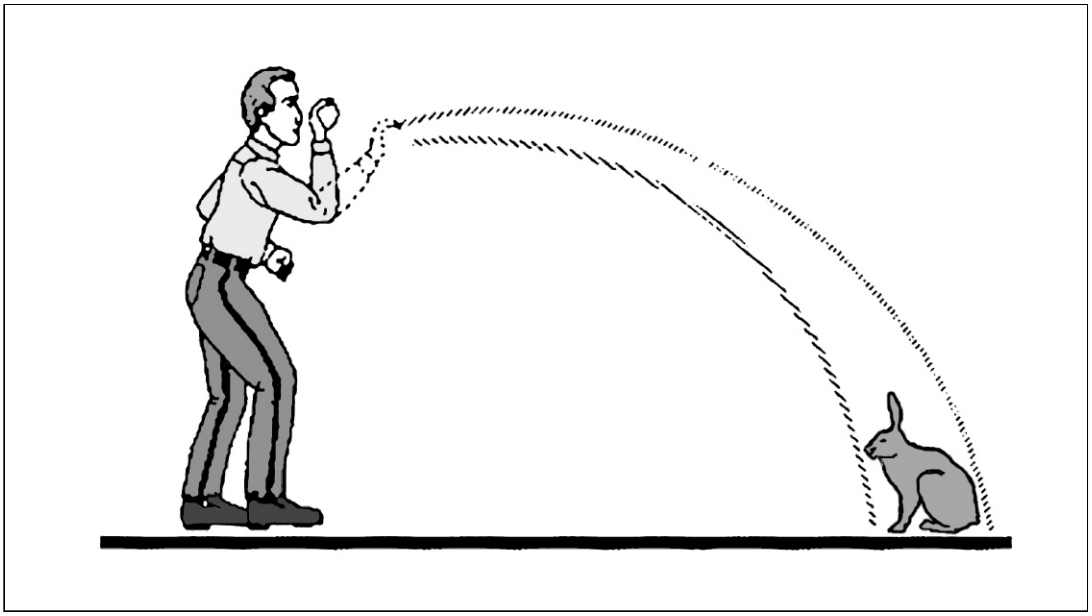

Figure 4. Throwing Stones.

A. At 4 meters, the launch window is 11 microseconds; at 8 meters, it narrows to 1.4 microseconds. Reproduced with permission from Calvin (1991).

diate selective pressure than is likely to have arisen from other advantages of a slightly enlarged brain (for example, some limited protolanguage ability).

The theory has a number of appealing corollaries. It suggests one source of lateralization because throwing is fundamentally asymmetric: One-armed throwing is far more accurate and effective than two armed for any reasonable-sized projectile (imagine baseball pitchers or outfielders propelling the ball overhead with both arms). As a result, only the neurons on one side of the brain need be specialized for the operation (for why this turns out, in nearly 90 percent of us, to be the left side of the brain, see Calvin [1983]).[3] That lateralization, which more generally involves precise sequential muscle control, may in turn have been a key predecessor to language, which also requires fast and accurate control of musculature.

Thus, the brain may have gotten larger to allow us to hunt better. The interesting punchline for our purposes is that thinking may be an extra use of all those neurons that evolved for another purpose.

Early Man and the Killer Climate A third theory suggests that climate plays a central role (Calvin 1991). The last few hundred thousand years of our history have been marked by a series of ice ages. A being used to surviving in a temperate climate would face a considerable collection of challenges as the weather worsened and winters arrived. In order to survive the winter, it would have had to be good enough at hunting to accumulate extra food beyond the day-to-day needs (hence the related utility of being able to throw accurately), and then it would have had to develop both the foresight to put aside some of that for the winter and the "technology" for doing so. There is, of course, a stiff Darwinian penalty for failure to be that smart.

Early Man, the Primal Frugivore A fourth theory suggests that the crucial element was the evolution of early man into a *frugivore,* or fruit eater. Why should this matter—because you need to be smart to be a frugivore. Fruit comes in relatively small pieces, so you need to collect a lot of it, and it must be collected within a relatively narrow time window. As a consequence, frugivores need good spatial maps of their environments (so they know where the sources of fruit are) and good temporal maps (so they know when to show up). Perhaps this need for good spatial and temporal maps was a force for the evolution of larger brains.

Early Man, the Primal Psychologist Yet another theory suggests that our primary use of intelligence is not for making tools, hunting, or surviving the winter; it's to get along with one another (Humphrey 1976; also see Byrne and Whiten [1988]). This theory is sometimes called *Machiavellian intelligence.* In this view, the primary function of intelligence is the maintenance of social relationships.

The evidence for this comes from several sources, among them the behavior of monkey troops that have been studied extensively. They are seen to spend a good proportion of their time servicing and maintaining their relationships within their groups, tending to issues of rank and hierarchy and what appear to be allegiances.

A second source of evidence comes from a study (Dunbar 1992) that plotted group size against neocortex ratio (ratio of neocortex size to the size of the rest of the brain) for a variety of animals: a nearly linear relationship emerged. Perhaps this held true for early man as well: As early group size grew, along with the advantages of larger groups came increasing demands to be able to understand, predict, and perhaps even control the behavior of others. We saw earlier that prediction was a key component of intelligent behavior; what more complex, fascinating, and useful thing could there be to predict than the behavior of then other humans?

Early Man, the Primal Linguist Finally, Bickerton (1995) has suggested that language was the crucial driving force behind the evolution of our brains. He starts with the interesting observation that if we look back at the historical time line, we notice that although brain size grows roughly steadily for about three million years, progress in the development of modern culture was not nearly so gradual. In fact, "instead of a steady ascent . . . we find, for 95% of that period, a monotonous, almost flat line" (Bickerton 1995, p. 47). Almost nothing happens. It is well after the appearance of *H. sapiens*, and well after the leveling off of brain size, that we see the appearance of language and all the other elements of what we have come to call civilization.

Bickerton calls these the two most shocking facts of human evolution: (1) our ancestors stagnated so long despite their ever-growing brains and (2) human culture grew exponentially only after the brain had ceased to grow. It appears that we showed our most obvious evidence of intelligence only after our brains stopped growing.

What was it that happened to produce that evidence? He suggests that the crucial event was some sort of reorganization within the brain, a reorganization that happened well after size stopped increasing. That reorganization made possible two essential things: first, a *generative syntax,* that is, a true language, and second, *thought,* that is, the ability to think about something (like a leopard) without having to experience the thing perceptually, and equally important, without having to react to it in the way one would on meeting one.

This leads to what appears to be a crucial distinction between animal intelligence and human intelligence. Animal intelligence has a here and now character: With animal calls, for example, there is an immediate link from the perception to the mind state to the action. If a monkey sees a leopard, a certain mind state ensues, and a certain behavior (giving the appropriate call) immediately follows.[4]

Human thought, by contrast, has an unlimited spatiotemporal reference, by virtue of several important disconnections. Human thought involves the ability to imagine, the ability to think about something in the absence of perceptual input, and the ability to imagine without reacting.

In human thought we have the ability, the luxury, of "re-presentation." The pun is intentional and probably educational: Representations allow us to re-present things to ourselves in the absence of the thing, so that we can think about it, not just react to it.

Enormous things change when we have both thought and language. Thought and its useful disconnection from immediate stimuli and immediate action is clearly a great boon—it's the origin of our ability to have our hypotheses die in our stead. But what about language? For our purposes, the interesting thing about language is that it makes knowledge immortal and makes society, not the individual, the accumulator and repository of knowledge. No longer is an individual's knowledge limited to what can be experienced and learned in a lifetime. Language not only allows us to think, it allows us to share and accumulate the fruits of that thought.

But what then caused our brains to grow over the three million or so years during which neither language nor thought (as we know them) was present? What was the evolutionary pressure? The theory suggests that the life of a successful hunter-gatherer is fact rich and practice rich. In order to survive as a hunter-gatherer, you need to know a lot of facts about your world and need to know a fair number of skills. This then is the hypothesized source of pressure: the increasing accumulation of survival-relevant information communicated through a form of protolanguage. Early man needed to store "the vast amount of lore . . . in the collective memories of traditional societies: the uses of herbs, the habits of animals, aphorisms about human behavior, detailed knowledge of the spatial environment, anecdotes, old wives' tales, legends and myths" (Bickerton 1995, p. 63).[5]

Where does this collection of theories (figure 5) leave us? One obvious caution is that they are unlikely to be either independent or

… another theory suggests that our primary use of intelligence is not for making tools, hunting, or surviving the winter; it's to get along with one another.

Early man, the primal tool maker
Early man and the killer frisbee
Early man and the killer climate
Early man, the primal frugivore
Early man, the primal psychologist
Early man, the protolinguist

Figure 5. Theories of the Evolution of Intelligence.

mutually exclusive. They may be mutually supportive and all true to some extent, with each of them contributing some amount of the evolutionary pressure toward larger brains and intelligence.

A second point to note is that human intelligence is a natural phenomenon, born of evolution, and as suggested earlier, the end product likely shows evidence of the process that created it. Intelligence is likely to be a layered, multifaceted, and probably messy collection of phenomena, much like the other products of evolution.

It also may be rather indirect. Here's Lewontin (1990) again: "There may have been no direct natural selection for cognitive ability at all. Human cognition may have developed as the purely epiphenomenal consequence of the major increase in brain size, which, in turn, may have been selected for quite other reasons" (p. 244), for example, any of the reasons in figure 5.

This, too, suggests a certain amount of caution in our approach to understanding intelligence, at least of the human variety: The human mind is not only a 400,000-year-old legacy application, it may have been written for another purpose and adopted for current usage only after the fact. In light of that, we should not be too surprised if we fail to find elegance and simplicity in the workings of intelligence.

Inhuman Problem Solving

As we explore the design space of intelligences, it's interesting to consider some of the other varieties of intelligence that are out there, particularly the animal sort. With that, let me turn to the third part of my article, in which it's time for AI to learn about the birds and the bees. What do animals know, and (how) do they think?

Clever Hans and Clever Hands

Before we get too far into this, it would we wise to consider a couple of cautionary tales to ensure the appropriate degree of skepticism about this difficult subject. The classic cautionary tale concerns a horse named Clever Hans, raised in Germany around 1900, that gave every appearance of being able to do arithmetic, tapping out his answers with his feet (Boakes 1984) (figure 6). He was able to give the correct answers even without his trainer in the room and became a focus of a considerable amount of attention and something of a celebrity.

In the end, it turned out that Hans was not mathematically gifted; his gift was perceptual. The key clue came when he was asked questions to which no one in the room knew the answer; in that case, neither did he. Hans had been attending carefully to his audience and reacting to the slight changes in posture that occurred when he had given the correct number of taps.[6]

The clever hands belong to a chimpanzee named Washoe who had been trained in American Sign Language (Gardner et al. 1989). One day Washoe, seeing a swan in a pond, gave the sign for *water* and then *bird*. This seemed quite remarkable, as Washoe seemed to be forming compound nouns—water bird—that he had not previously known (Mithen 1996). But perhaps he had seen the pond and given the sign for water, then noticed the swan and given the sign for bird. Had he done so in the opposite order—bird water—little excitement would have followed.

The standard caution from both of these tales is always to consider the simpler explanation—trainer effects, wishful interpretation of data, and so on—before being willing to consider that animals are indeed capable of thought.

Narrow Intelligence: Birds and Bees

Given that, we can proceed to explore some of the varieties of animal intelligence that do exist. Several types of rather narrowly defined intelligence are supported by strong evidence. Among the birds and the bees, for example, bees are well known to "dance" for their hive mates to indicate the direction of food sources they have found. Some birds have a remarkable ability to construct a spatial map. The Clark's nutcracker, as one example, stores away on the order of 30,000 seeds in 6,000 sites over

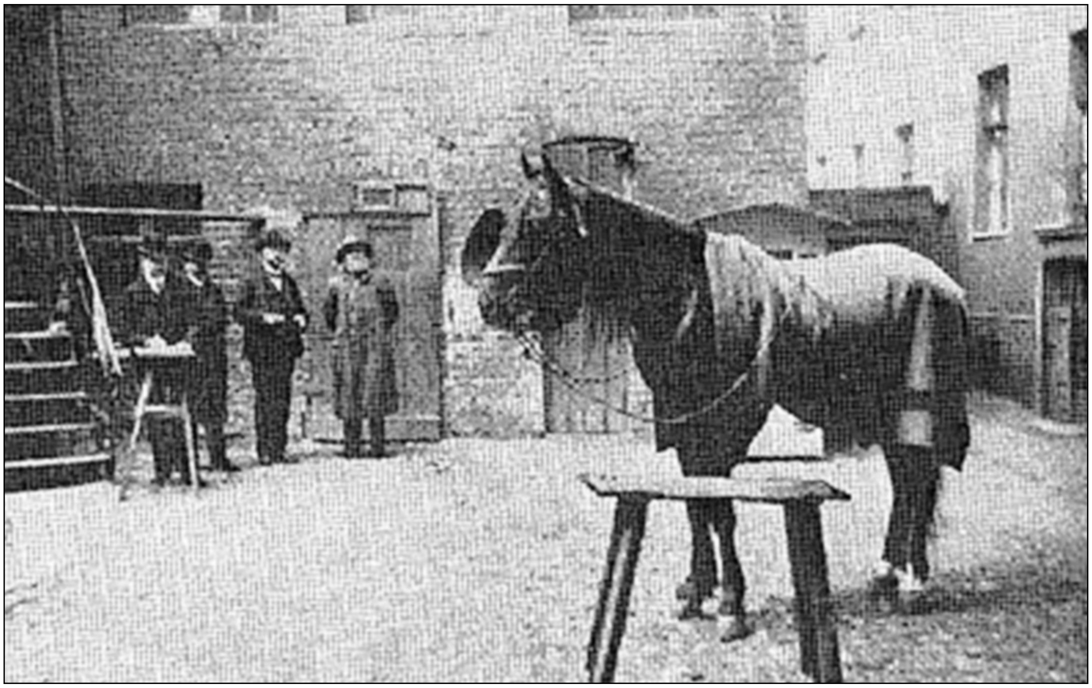

Figure 6. Clever Hans, the Mathematical Horse.

His owner and trainer is rightmost of the group at the rear. Reproduced with permission from Boakes (1984).

the course of the spring and summer and is able to find about half of those during the winter (Balda and Kamil 1992). This is a narrowly restricted kind of intelligence but, at 6000 locations, nonetheless impressive.

Broader Intelligence: Primates

Broader forms of intelligence are displayed by some primates. One particular variety—the vervet monkey—has been studied widely in the wild and has displayed a range of intelligent-seeming behaviors (Cheney and Seyfarth 1990). One of the important elements in the life of a monkey group is *status*—your place in the dominance hierarchy. Vervet monkeys give every sign of understanding and being able to reason using relations such as higher-status-than and lower-status-than. They can, for example, do simple transitive inference to establish the place of others in the hierarchy: If A can beat up B, and B can beat up C, there's no need for A and C to fight; the result can be inferred (allowing our hypotheses to get battered in our stead).

The monkeys also appear capable of classifying relationships as *same* or *different,* understanding, for example, that mother-of is a different relation from sibling-of. This can matter because if you fight with Junior, you had better avoid mother-of(Junior) (who might be tempted to retaliate), but sibling-of(Junior) presents no such threat.

They also seem to have a vocabulary with semantic content—different calls that correspond to the notion of *leopard, eagle,* and *python,* the three main monkey predators. That the calls are truly referential is suggested by the facts that they are given only when appropriate, they are learned by trial and error by the young monkeys, and the troop takes appropriate action on hearing one of the calls. Hearing the eagle call, for instance, all the troop members will look up, searching for the eagle, then take cover in the bushes. Note that we have referred to this as a vocabulary, not a language, because it appears that there is no syntax permitting the construction of phrases.

Lies—Do Monkeys Cry Leopard?

There is also some anecdotal evidence that the monkeys lie to one another. They have been observed to lie by omission when it concerns food: When happening on a modest-sized store of food, a monkey may fail to give the standard call ordinarily given when finding food. Instead, the lone monkey may simply consume it.

A more intriguing form of misrepresentation has been observed to occur when two neighboring monkey troops get into battles over territory. Some of these battles have ended when one of the monkeys gives the *leopard* call—all the combatants scatter, climbing into trees to escape the predator, but there is in fact no leopard to be found. The monkeys may be lying to one another as a way of breaking up the fight (Cheney and Seyfarth 1991).[7]

Psittacine Intelligence: Bird Brains No Longer

One final example of animal intelligence concerns an African Grey Parrot named Alex, who has been trained for quite a few years by Dr. Irene Pepperberg of the University of Arizona. Alex seems capable of grasping abstract concepts such as same, different, color, shape, and numbers (Pepperberg 1991).

A videotape of Alex in action (WNET 1995) is particularly compelling; even a transcript of the conversation will give you a sense of what's been accomplished. Pay particular attention to Alex's ability to deal with, and reason about, abstract concepts and relations.

> *Narrator:* For 17 years, Alex and Dr. Irene Pepperberg have been working on the mental powers of parrots. Their efforts at the University of Arizona have produced some remarkable results.
>
> *Dr. Pepperberg:* What shape (holding up a red square)?
>
> *Alex:* Corners.
>
> *Dr. Pepperberg:* Yeah, how many corners? Say the whole thing.
>
> *Alex:* Four…corners.
>
> *Dr. Pepperberg:* That's right, four corners. Good birdie.
>
> *Alex:* Wanna nut.
>
> *Dr. Pepperberg:* You can't have another nut.
>
> OK, what shape? (holding up a green triangle).
>
> *Alex:* Three…corners.
>
> *Dr. Pepperberg:* That's right, three corners; that's a good boy.
>
> Now tell me, what color (holding the same green triangle)?
>
> *Alex:* Green.
>
> *Dr. Pepperberg:* Green, ok; here's a nut.
>
> OK, and what toy (holding up a toy truck)?
>
> *Alex:* Truck.
>
> *Dr. Pepperberg:* Truck; you're a good boy.
>
> OK, let's see if we can do something more difficult
>
> (holding two keys, one green plastic, one red metal; the green is slightly larger).
>
> Tell, me, how many?
>
> *Alex:* Two.
>
> *Dr. Pepperberg:* You're right, good parrot.
>
> *Alex:* Wanna nut.
>
> *Dr. Pepperberg:* Yes, you can have a nut.
>
> Alright, now look, tell me, what's different (same keys)?
>
> *Alex:* Color.
>
> *Dr. Pepperberg:* Good parrot. You're right, different color.
>
> Alright, now look, tell me, what color bigger? What color bigger (same keys)?
>
> *Alex:* Green.
>
> *Dr. Pepperberg:* Green; good boy. Green bigger. Good parrot.
>
> Oh you're a good boy today. Yes, three different questions on the same objects.
>
> Good parrot.
>
> *Dr. Pepperberg:* What we've found out is that a bird with a brain that is so different from mammals and primates can perform at the same level as chimpanzees and dolphins on all the tests that we've used and performs about at the level of a young, say, kindergarten-age child.

This is an interesting bit of animal intelligence, in part because of the careful training and testing that's been done, suggesting that, unlike Hans, Alex really does understand certain concepts. This is all the more remarkable given the significant differences between bird and mammalian brains: Parrot brains are quite primitive by comparison, with a far smaller cerebral cortex.

Consequences

These varieties of animal intelligence illustrate two important points: First, they illuminate for us a number of other distinguishable points in the design space of intelligences. The narrow intelligences of birds and bees, clearly more limited than our own, still offer impressive evidence of understanding and reasoning about space. Primate intelligence provides evidence of symbolic reasoning that, although primitive, has some of the character of what seems central to our own intelligence. Clearly distinguishable from our own variety of intelligence, yet impressive on their own terms, these phenomena begin to suggest the depth and breadth of the natural intelligences that have evolved.

Second, the fact that even some part of that intelligence appears similar to our own suggests the continuity of the design space. Human intelligence may be distinct, but it does not sit alone and unapproachable in the space. There is a large continuum of possibilities in that space; understanding some of our nearest neighbors may help us understand our own intelligence. Even admitting that there can be near neighbors offers a useful perspective.

Primate Celebrities

I can't leave the topic of animal intelligence without paying homage to one of the true unsung heroes of early AI research. Everyone in AI knows the monkey and bananas problem of course. But what's shocking, truly shocking, is that so many of us (myself included) don't know the real origins of this problem.

Thus, for the generations of AI students (and faculty) who have struggled with the monkey and bananas problem without knowing its origins, I give you, the monkey (figure 7):[8]

This one is named Rana; he and several other chimps were the subjects in an experiment done by gestalt psychologist Wolfgang Kohler (1925) in 1918. Kohler was studying the intelligence of animals, with particular attention to the phenomenon of insight, and gave his subjects a number of problems to solve. Here's Grande, another of the chimps, hard at work on the most famous of them (figure 8).

Thus, there really was a monkey and a stalk of bananas, and it all happened back in 1918. Just to give you a feeling of how long ago that was, in 1918, Herb Simon had not yet won the Nobel Prize.

Searching Design Space

In this last segment of the article, I'd like to consider what parts of the design space of intelligence we might usefully explore more thoroughly. None of these are unpopulated; people are doing some forms of the work I'll propose. My suggestion is that there's plenty of room for others to join them and good reason to want to.

Thinking Is Reliving

One exploration is inspired by looking at alternatives to the usual view that thinking is a form of internal verbalization. We also seem to be able to visualize internally and do some of our thinking visually; we seem to "see" things internally.

As one common example, if I were to ask whether an adult elephant could fit through your bedroom door, you would most likely attempt to answer it by reference to some mental image of the doorway and an elephant.

There is more than anecdotal evidence to support the proposition that mental imaging is closely related to perception; a variety of experimental and clinical data also support the notion. As one example, patients who had suffered a loss of their left visual field as a consequence of a stroke showed an interesting form of mental imagery loss (Bisiach and Luzzatti 1978). These patients were asked to imagine themselves standing at the northern end of a town square that they knew well and asked to report the buildings that they could "see" in

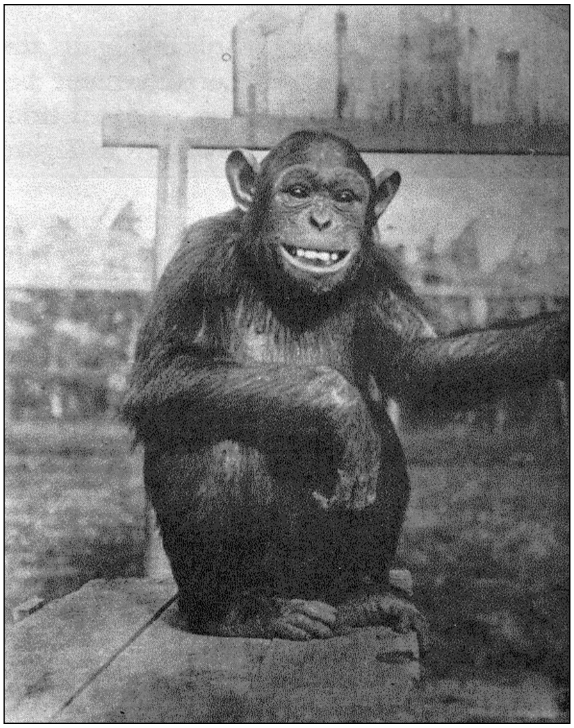

Figure 7. Rana, Star of an Early AI Problem.

Reproduced with permission from Kohler (1969).

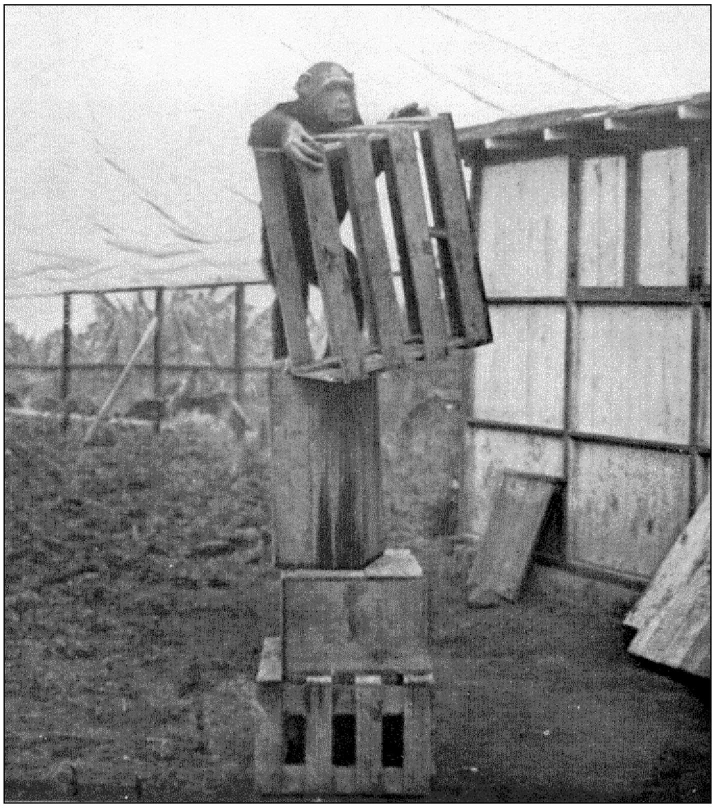

Figure 8. Grande Going for the Gold(en) Bananas.

Reproduced with permission from Kohler (1925).

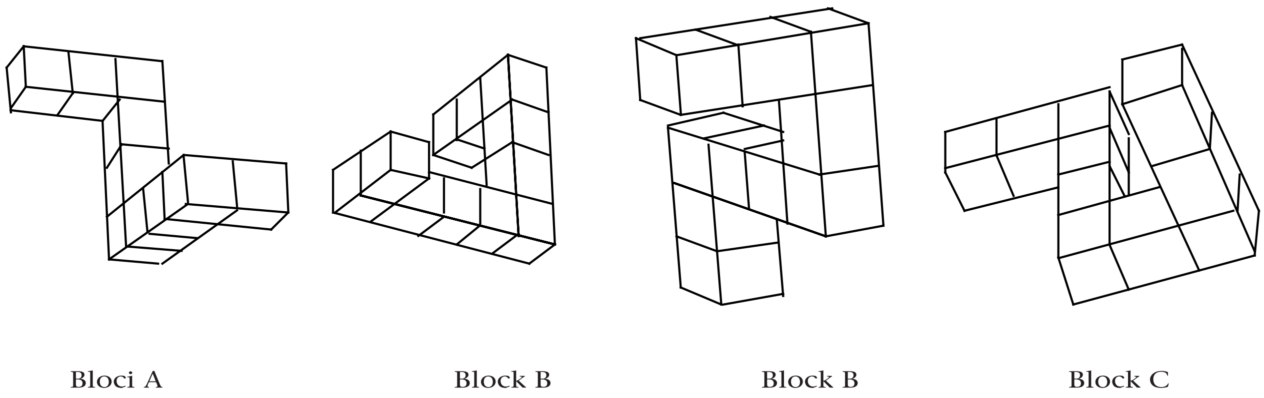

Figure 9. Are A and B the Same Object; Are B and C?

Reprinted with permission from Shepard, R. N., and Metzler, J., Mental Rotation of Three-Dimensional Objects, *Science* 171:701–703, copyright 1971, American Association for the Advancement of Science.

their mental image when looking south. Interestingly, they report what they would in fact be able to see out of the right half of their visual field; that is, they report buildings to the south and west but none to the east.

Even more remarkably, if they are then asked to imagine themselves on the south end of the square looking north and asked to report on what they “see” in their mental image, they describe the buildings in what is now the right half of their visual field (that is, buildings to the north and east) and fail completely to report those on the west side of the square, even though they had mentioned them only moments earlier.

The process going on in using the mind’s eye to “see” is thus remarkably similar in some ways to what happens in using the anatomical eye to see.

A second source of support for this view comes from the observation of like-modality interference. If I ask you to hold a visual image in your mind while you try to detect either a visual or an auditory stimulus, the ability to detect the visual stimulus is degraded, but detection of the auditory stimulus remains the same (Segal and Fusella 1970).

A third source of evidence comes from experiments done in the 1970s that explored the nature of visual thinking. One well-known experiment involved showing subjects images that looked like figure 9 and then asking whether the two images were two views of the same structure, albeit rotated (Shepard and Metzler 1971).

One interesting result of this work was that people seem to do a form of mental rotation on these images. The primary evidence for this is that response time is directly proportional to the amount of rotation necessary to get the figures in alignment.

A second experiment in the same vein involved mental folding (Shepard and Feng 1972). The task here is to decide whether the two arrows will meet when each of the pieces of paper shown in figure 10 is folded into a cube.

If you introspect as you do this task, I think you’ll find that you are recreating in your mind the sequence of actions you would take were you to pick up the paper and fold it by hand.

What are we to make of these experiments? I suggest two things: First, it may be time to take seriously (once again) the notion of *visual reasoning,* that is, reasoning with diagrams as things that we look at, whose visual nature is a central part of the representation.

Second is the suggestion that thinking is a form of reliving. The usual interpretation of the data from the rotation and folding experiments is that we think visually. But consider some additional questions about the experiments: Why does it take time to do the rotation, and why does the paper get mentally folded one piece at a time? In the rotation experiment, why don’t our eyes simply look at each block, compute a transform, then do the transformation in one step? I speculate that the reason is because our thought processes mimic real life: In solving the problem mentally, we’re re-acting out what we would experi-

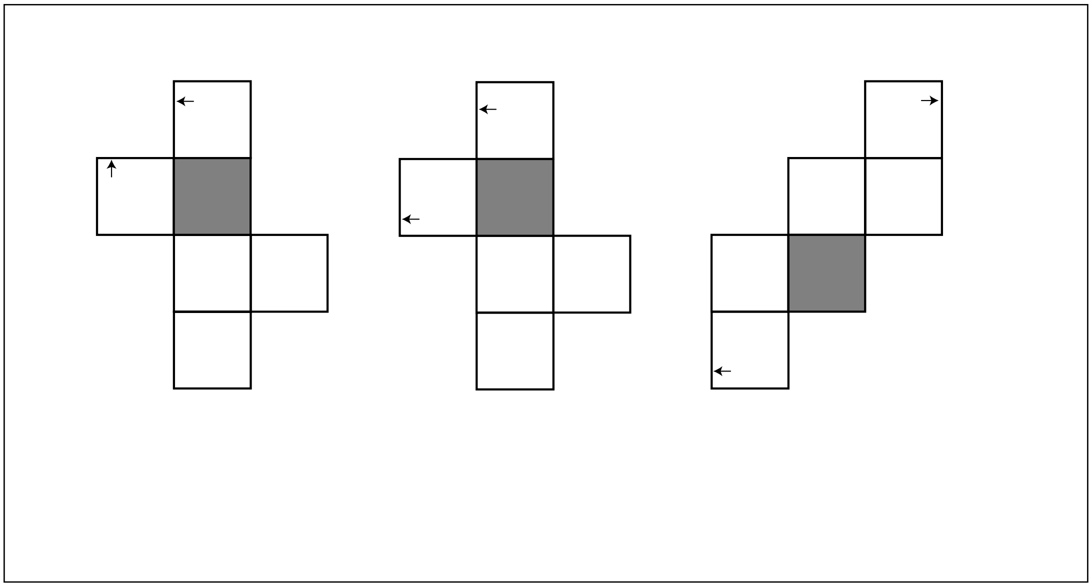

Figure 10. Do the Arrows Meet When the Paper Is Folded into a Cube?

Reprinted with permission from Shepard, R. N., and Feng, C., A Chronometric Study of Mental Paper Folding, *Cognitive Psychology* 3:228–243, copyright 1972, American Association for the Advancement of Science.

ence in the physical world.

That's my second suggestion: Take seriously the notion of thinking as a form of reliving our perceptual and motor experiences. That is, thinking is not simply the decontextualized manipulation of abstract symbols (powerful though that may be). Some significant part of our thinking may be the reuse, or simulation, of our experiences in the environment. In this sense, vision and language are not simply input-output channels into a mind where the thinking gets done; they are instead a significant part of the thought process itself. The same may be true for our proprioreceptive and motor systems: In mentally folding the paper, we simulate the experience as it would be were we to have the paper in hand.

There is, by the way, a plausible evolutionary rationale for this speculation that thinking is a form of reliving. It's another instance of functional conversion: Machinery developed for perception turns out to be useful for thinking. Put differently, visual thinking is the offline use of our ability to see. We're making use of machinery that happened to be there for another purpose, as has happened many times before in evolution.[9]

One further, ambitious speculation concerns the neural machinery that might support such reliving: Ullman (1996) describes *counter-streams,* a pair of complementary, interconnected pathways traveling in opposite directions between the high-level and low-level visual areas. Roughly speaking, the pathway from the low-level area does data-driven processing, but the opposite pathway does model-driven processing. One possible mechanism for thinking as reliving is the dominant use of the model-driven pathway to recreate the sorts of excitation patterns that would result from the actual experience.

One last speculation I'd like to make concerns the power of visual reasoning and diagrams. The suggestion here is that diagrams are powerful because they are, among other things, a form of what Johnson-Laird (1983) called *reasoning in the model*. Roughly speaking, that's the idea that some of the reasoning we do is not carried out in the formal abstract terms of predicate calculus but is instead done by creating for ourselves a concrete miniworld where we carry out mental actions and then examine the results.

One familiar example is the use of diagrams when proving theorems in geometry. The intent is to get a proof of a perfectly general statement, yet it's much easier to do with a concrete, specific model, one that we can manipulate and then examine to read off the answers.

Consider, for example, the hypothesis that any triangle can be shown to be the union of two right triangles.

We might start by drawing a triangle (figure

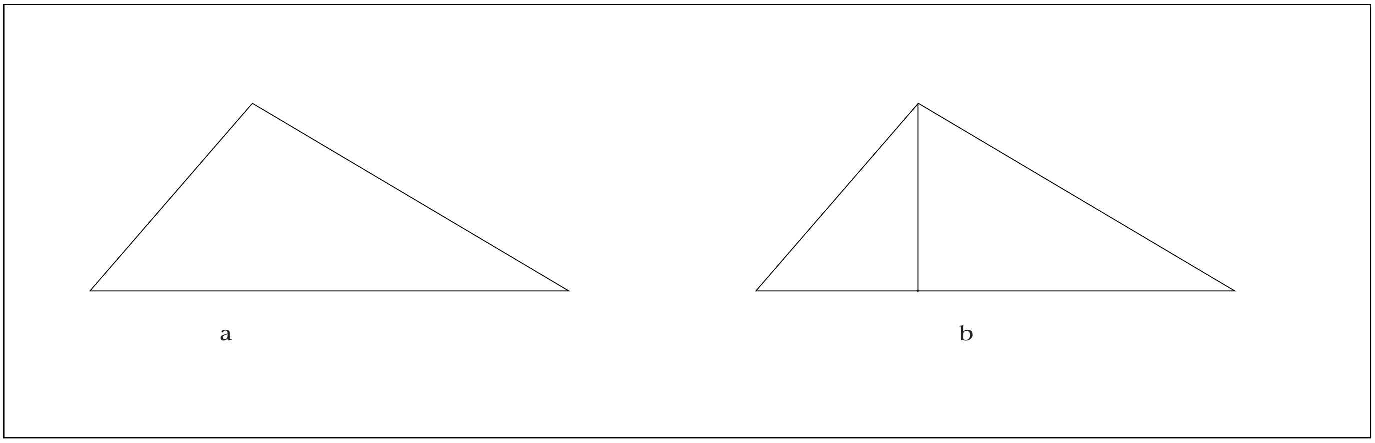

Figure 11. Triangles.

A. A random triangle. B. A random triangle with a perpendicular.

11a). The proof of course calls for any triangle, but we find it much easier with a concrete one in front of us.

We might then play with it a bit and eventually hit on the idea of dropping a perpendicular (figure 11b).

Wary of a proof from a single concrete example, we might try a number of other triangles and eventually come up with a formal abstract proof. But it's often a lot easier to have a concrete example to work with, manipulate, and then examine the results of our manipulations.

What works for something as plainly visual as geometric theorems also seems to work for things that are not nearly so visual, such as syllogisms. Consider these sentences describing a group of people (Johnson-Laird 1983, p. 5):

Some of the children have balloons.

Everyone with a balloon has a party hat.

There's evidence that when asked to determine the logical consequences of these statements, people imagine a concrete instance of a room and some finite collection of people, then examine it to determine the answer.

The good news about any concrete example is its concreteness; the bad news is its concreteness, that is, its lack of generality—as many a high school geometry student has discovered when he/she drew an insufficiently general diagram. For diagrams in particular, the problem is compelling: There's no such thing as an approximate diagram. Every line drawn has a precise length, every angle a precise measure. The good news is that diagrams make everything explicit; the bad news is that they can't possibly avoid it.

Yet there are times when we'd like to marry the virtues of reasoning in a concrete diagram with the generality that would allow us to draw a line that was about three inches long or long enough to reach this other line.

That's my last speculation: There may be ways to marry the concreteness of reasoning in the model with the power and generality of abstraction. One early step in this direction is discussed in Stahov, Davis, and Shrobe (1996), who discuss how a specific diagram can automatically be annotated with constraints that capture the appropriate general relationships among its parts, but there is plainly much more to be done.

Summary

With that, let me summarize. I want to suggest that intelligence are many things, and this is true in several senses. Even within AI, and even with the subfield of inference, intelligence has been conceived of in a variety of ways, including the logical perspective, which considers it a part of mathematical logic, and the psychological perspective, which considers it an empirical phenomenon from the natural world.

One way to get a synthesis of these numerous views is to conceive of AI as the study of the design space of intelligences. I find this an inspiring way to conceive of our field, in part because of its inherent plurality of views and in part because it encourages us to explore broadly and deeply about all the full range of that space.

We have also explored how human intelligence is a natural artifact, the result of the process of evolution and its parallel, opportunistic exploration of niches in the design space. As a result, it is likely to bear all the hallmarks of any product of that process—it is likely to be layered, multifaceted, burdened with vestigal components, and rather messy. This is a second sense in which intelligence are many things—it is composed of the many elements that have been thrown together over evolutionary timescales.

Because of the origins of intelligence and its resulting character, AI as a discipline is likely to have more in common with biology and anatomy than it does with mathematics or physics. We may be a long time collecting a wide variety of mechanisms rather than coming upon a few minimalist principles.

In exploring inhuman problem solving, we saw that animal intelligence seems to fit in some narrowly constrained niches, particularly for the birds and bees, but for primates (and perhaps parrots), there are some broader varieties of animal intelligence. These other varieties of intelligence illustrate a number of other distinguishable points in the design space of intelligences, suggesting the depth and breadth of the natural intelligences that have evolved and indicating the continuity of that design space.

Finally, I tried to suggest that there are some niches in the design space of intelligences that are currently underexplored. There is, for example, the speculation that thinking is in part visual, and if so, it might prove very useful to develop representations and reasoning mechanisms that reason with diagrams (not just about them) and that take seriously their visual nature.

I speculated that thinking may be a form of reliving, that re-acting out what we have experienced is one powerful way to think about, and solve problems in, the world. And finally, I suggested that it may prove useful to marry the concreteness of reasoning in a model with the power that arises from reasoning abstractly and generally.

Notes

1. Table 1 and some of the text following is from Davis, Shrobe, and Szolovits (1993).

2. For a detailed exploration of the consequences and their potentially disquieting implications, see Dennett (1995).

3. In brief, he suggests that it arises from the near-universal habit of women carrying babies in their left arms, probably because the maternal heartbeat is easier for the baby to hear on that side. This kept their right arms free for throwing. Hence the first major league hunter-pitcher may have been what he calls the *throwing madonna* (not incidentally, the title of his book).

4. That's why the possibility of monkeys "lying" to one another (see later discussion) is so intriguing—precisely because it's a break in the perception-action link.

5. Humphrey (1976) also touches on this idea.

6. Oskar Phungst, who determined the real nature of Hans's skill, was able to mimic it so successfully that he could pretend to be a mentalist, "reading the mind" of someone thinking of a number: Pfungst simply tapped until he saw the subtle changes in posture that were unconscious to the subject (Rosenthal 1966).

7. For a countervailing view on the question of animal lying, see the chapter by Nicholas Mackintosh in Khalfa (1994).

8. A true-life anecdote concerning life in Cambridge: When I went to a photographer to have this photo turned into a slide, the man behind the counter (probably an underpaid psychology graduate student) looked at the old book with some interest, then laughed at the photo I wanted reproduced. I pretended to chide him, pointing out that the photo was of a famous contributor to psychological theory. "A famous contributor to psychology?" he said. "Then I know who it is." "Who?" I asked. "Why that's Noam Chimpsky, of course," he replied. Yes, it really happened, just that way.

9. There has been significant controversy concerning the exact nature and status of mental images; see, for example, Farah (1988), who reviews some of the alternative theories as well as neuropsychological evidence for the reality of mental images. One of the alternative theories suggests that subjects in experiments of the mental-rotation sort are mentally simulating their experience of seeing rather than actually using their visual pathways. For our purposes, that's almost as good: Although literal reuse of the visual hardware would be a compelling example of functional conversion, there is also something intriguing in the notion that one part of the brain can realistically simulate the behavior of other parts.

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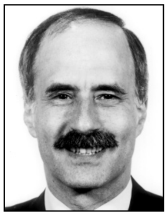

Randall Davis is a professor of computer science at the Massachusetts Institute of Technology, where he works on model-based reasoning systems for engineering design, problem solving, and troubleshooting. He has also been active in the area of intellectual property and software, serving on a number of government studies and as an adviser to the court in legal cases. He received his undergraduate degree from Dartmouth College and his Ph.D. from Stanford University. He serves on several editorial boards, including those for *Artificial Intelligence* and *AI in Engineering*. In 1990, he was named a founding fellow of the American Association for Artificial Intelligence and served as president of the association from 1995–1997. His e-mail address is davis@ai.mit.edu.