Visual imagery and the limits of comprehension

Marc Krellenstein

New School for Social Research

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ABSTRACT

I examined the proposition that there are psychological limits on what scientific problems can be solved, and that these limits may be based on a failure to be able to produce imagable, observation-based models for any possible solution, a position suggested by philosopher Colin McGinn in an argument attempting to prove that the mind-body problem is unsolvable. I examined another likely candidate for an unsolvable problem -- the ultimate origin of the universe (i.e., what might have preceded the Big Bang or any other starting point; why there should be something rather than nothing) -- by exploring the reasoning of physicists about this problem and measuring visual imagery frequency and vividness, with the expectation that those who most believed the problem unsolvable would be more frequent/vivid imagers and therefore more affected by the apparent impossibility of producing an imagable solution. Eight physicists were interviewed and imagery frequency and vividness measurements performed using Cohen & Saslona's IDQ-IHS and Marks's VVIQ, respectively. All subjects considered the problem unsolvable within today's physics and all but one thought the problem still meaningful, though none were optimistic about a solution. The one subject who dismissed the problem had the lowest imagery frequency score, and there was also a significant rank order correlation ($r = 0.83$, $p < .02$) between degree of belief in problem unsolvability (extended to include viewing the problem as meaningful and not already solved) and a composite imagery frequency/vividness score, though the sample was too small to control for some possible confounding factors.

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INTRODUCTION

Cognitive Limits

The question of what if any limits there are to what the human mind can know has long been a subject of philosophical examination. Recently, the problem has been posed more directly as a psychological question: Are there problems that cannot be solved because of inherent limitations in human cognitive processing ? Fodor (1983) argues that the existence of such limitations, which make the mind, to use Fodor's term, "epistemically bounded" (p. 120), are not only supported by his thesis for the modularity of various cognitive functions, but are almost certainly present in any case simply because of the existence at the lowest level of fixed and constrained cognitive structure:

> Any psychology must attribute some endogenous structure to the mind.... And it's hard to see how, in the course of making such attributions of endogenous structure, the theory could fail to imply some constraints on the class of beliefs that the mind can entertain. (p. 125)
>
> A psychology which guarantees our epistemic unboundedness would thus have to guarantee that, whatever sort of subject domain the world turns out to

> be, somewhere in the space of hypotheses that we are capable of entertaining there is the hypothesis that specifies its structure.... I don't see how any remotely plausible cognitive theory could conceivably do so. (pp. 122-123)

Fodor's claim has a priori credibility, but is there good empirical evidence for it ? Fodor offers support from an evolutionary perspective by observing that we accept such limitations without question in the case of other species, and "would presumably not be impressed by a priori arguments intended to prove (e.g.) that the true science must be accessible to spiders" (p. 126).

However, while true, it is also the case that we would not expect a spider to raise or grasp scientific problems, and the interesting claim in the case of humans is not so much that there is, as (presumably) for the spider, knowledge so beyond comprehension that we cannot even grasp the problems that such knowledge would address but rather that there are problems we can grasp but cannot solve. Note also that the psychological question of interest here is only on problems where we suppose that the limitations on being able to solve them are conceptual, or cognitive, in nature. This eliminates problems whose limitations arise from formal aspects of the problem or surrounding theory (e.g., undecidable theorems in mathematics, or quantum uncertainties) or from fairly direct resource constraints (e.g., our inability in a chess game to look ahead sufficiently far to determine the absolute best move).

Unsolvable Problems

The history of science and philosophy suggests at least two problems as possibly being cognitively unsolvable: the problem of explaining the origin of the universe, and the "consciousness" part of the mind-body problem -- providing an explanation for subjective experience. The study methodology will focus only on the problem of the origin of the universe, but some initial examination of the mind-body problem as well from the perspective of unsolvability is useful for better understanding the issues involved and the possible basis for unsolvability proposed below, especially since that proposed basis was suggested by work on the mind-body problem.

There may be other such cognitively unsolvable problems, but, if so, these two are likely the most noteworthy. Also, note again that the focus here is on problems where the limits on solvability are presumed to be psychological and, more specifically, cognitive, rather than, for example, as demonstrated by some external proof (e.g., the halting problem for Turing machines). The interesting question of problems that cannot even be grasped is, again, also ignored; leaving aside the difficulty (impossibility ?) of examining such problems, their solutions are presumably excluded from human understanding as well.

It is also assumed that these problems are in fact substantive and not merely the result of philosophic or linguistic confusion (while the latter has been suggested by some for each problem, the viewpoint of this study is that the problems are real and could, in principle, have scientific answers).

The Origin of the Universe

Historical and modern-day attempts to explain the origin of the universe basically fall into one of three general types:

1. The universe came into existence at some finite point in the past, before which there was "nothing". This sort of explanation can be seen in Biblical and other religious writings and in the modern-day "Big Bang" theory (as described, for example, in Hawking, 1988, or Penrose, 1989), though there is of course considerable variation and contemporary refinement on how this happened (e.g., divine creation vs. a "quantum fluctuation" in the vacuum that preceded the universe, as described by Hawking or Penrose;

this is discussed in more detail below) and what constituted the "nothing" that preceded the universe.

2. The universe has existed forever (or perhaps is born and dies in an endless cycle). This was essentially Aristotle's view (as shown in _On the Heavens_ in McKeon, 1966), and can also be found in the modern-day (though currently not fashionable) "steady-state" theory (see again Hawking, 1988). (I will ignore questions about changes in the universe, e.g., whether it is expanding or contracting, since changes in its form are not relevant to the question of explaining why it should exist at all.)

3. The question of how the universe began is unanswerable, "transcendent," or perhaps meaningless. This is the view of some contemporary philosophers such as Wittgenstein (1921/1961) and Munitz (1986) (though, as Munitz discusses, there are historical antecedents for this view as well), both of whom consider the question not fully answerable but nevertheless legitimate in some sense: "transcendent" for Munitz, and part of the "mystical" for Wittgenstein (though this is the early Wittgenstein of the _Tractatus_), which, though it cannot be talked about, nevertheless exists. Wittgenstein earlier introduces the idea of such limits with regard to ethics and value in general:

> All propositions are of equal value.

> The sense of the world must lie outside the world. In the world everything is as it is ... *in* it, no value exists....
>
> Propositions can express nothing that is higher.
>
> It is clear that ethics cannot be put into words.
>
> Ethics is transcendental.
>
> If the good or bad exercise of the will does alter the world, it can alter only the limits of the world, not the facts -- not what can be expressed by means of language.
>
> In short, the effect must be it becomes an altogether different world. It must, so to speak, wax and wane as a whole. [emphasis in original] (pp. 145-147)

Though real in some way -- "transcendental" -- these things "cannot be put into words," only experienced as "an altogether different world." With regard to the broader problem of why life or the universe should exist at all, Wittgenstein states the following:

> ... is some riddle solved by my surviving for ever ? Is not this eternal life as much of a riddle as our present life ? The solution of the riddle of life in space and time lies *outside* space and time....
>
> The facts all contribute only to setting the problem, not to its solution.

> It is not *how* things are in the world that is mystical but *that* it exists.
>
> To view the world *sub specie aeterni* is to view it as a whole -- a limited whole.
>
> Feeling the world as a limited whole -- it is this that is mystical....
>
> We feel that even when *all possible* scientific questions have been answered, the problems of life remain completely untouched. Of course there are then no questions left, and this itself is the answer.
>
> The solution of the problem of life is seen in the vanishing of the problem.
>
> (Is not this the reason why those who have found after a long period of doubt that the sense of life became clear to them have then been unable to say what constituted that sense ?)
>
> There are, indeed, things that cannot be put into words. They *make themselves manifest*. They are what is mystical. [emphasis in original] (pp. 149-150)

For Wittgenstein, then, the direct experience of the problem -- "feeling the world as a limited whole" -- is real enough. However, all possible facts are only part of the "limited whole"; the solution must exist outside of it, "outside space and time." Although that necessarily yields nothing that can be stated or even talked about, there is the possibility of wordless solutions (or at least experiences) that "make themselves manifest."

Answers that fall under (3) can be viewed as arguing directly (though generally without any particular empirical evidence) for the thesis of cognitive limits I am trying to demonstrate (provided one excludes those explanations that dismiss the problem of the origin of the universe as entirely a pseudo-problem; I take as a given that the problem is substantive, and not to be dissolved entirely by any form of philosophical analysis).

The problem with answers 1 and 2 is that, no matter what explanation is provided, it seems we can turn around and then ask for an explanation of it -- what is it's cause, or what came before it. In the case of a universe that has existed forever, this becomes the question of why or how there should be such a universe at all; and in the case of a universe arising from nothing, this becomes the question of why or how it was transformed from "nothing" to "something."

Simply put, we seem to be stuck with the problem of why there should be anything at all, whether that anything be always existing or coming into existence at some point in time. The underlying problem is captured nicely by Wittgenstein's statement, quoted above, that "the facts all contribute only to setting the problem, not to its solution", and stated more fully by Gasking, as reported in Black's commentary on Wittgenstein (1964):

> What we demand as an answer is something like a well-confirmed hypothesis whose consequent is everything whatsoever -- the world contemplated sub specie aeterni as a limited whole, limited by an antecedent which is something, in spite of everything being in the consequent. (p. 374)

Recently, a possible way out of the above dilemma appears to have been suggested by work in applying quantum mechanics to questions about the origin of the universe -- so-called "quantum cosmology" -- that allows a principled (i.e., within the currently conceived laws of physics) way to talk about "something coming from nothing." The physical basis of this idea is that a quantum fluctuation in the vacuum that preceded the universe led to the Big Bang and the subsequent creation of the universe, as well as the start of time itself. Grunbaum (1989), though primarily interested in rebutting the idea that a quantum cosmology offers support for biblical divine creation, argues that such a cosmology has in fact erased the question of the origin of the universe because (a) the transition from the vacuum to the Big Bang is now explained by physical law, and (b) the period before the Big Bang is also before the start of space/time itself, and it is therefore meaningless to talk about an external cause (or any prior cause at all) for the shift from the vacuum, since there are no periods of time, and hence no meaningful causation, before the Big Bang. He states that Stephen Hawking, the British physicist and cosmologist, "reaches the conclusion that there is no problem of creation, because at that stage, the very distinction between space and time becomes mushy . . . " (p. 393).

But this does not seem to square at all with Hawking's actual conclusions (1988) which, despite his own convincing presentation of the "something from nothing" position are stated as follows:

> How or why were the laws and the initial state of the universe chosen ? (p. 173)
>
> Even if there is only one unified theory, it is just a set of rules and equations. What is it that breathes fire into the equations and makes a universe for them to describe ? The usual approach of science of constructing a mathematical model cannot answer the questions of why there should be a universe for the model to describe. Why does the universe go to all the bother of existing ? (p. 174)

This appears to suggest that the new "quantum cosmology" has (at least for Hawking) only added a layer of new theory that itself needs to be explained. This seems to once again point out that one can always demand a further explanation; that, as Munitz (1986) observes, the boundary of what is intelligible may shift but inevitably leaves an unintelligible residue; that, as Wittgenstein suggested, the facts only contribute to, and cannot solve the problem of why there should be anything at all.

The Mind-Body Problem

How are we to explain the existence of subjective awareness, of one's sense of self, or of the "raw feels" or qualia that constitute sensations ? Although this study will focus on the problem of the origin of the universe, some review of the mind-body problem is, again, useful for understanding the issues involved and a possible basis for problem unsolvability. Following Churchland (1985) we can quickly summarize the various historical and current solutions to this central aspect of the mind-body problem as falling into one of three camps:

1. Dualist solutions that, in one form or another, posit the existence of an independent subjective realm not reducible to physical or material phenomena.

2. Behavioral/linguistic solutions that effectively dismiss the problem as a pseudo-problem.

3. Various materialist points of view that posit a physical/physiological substrate that in one way or another is responsible for the existence of such subjective

phenomena; these include identity theories (that postulate a direct equivalence between brain states and mental processes), forms of eliminative materialism (that posit a neuroscientific basis for mental states that are, once understood, radically different from our common-sense understanding of those states as given by "folk psychology") and forms of functionalism, the computationally inspired view that equates mental processes or states (e.g., anger) with their place in a causal network that could potentially be instantiated by things other than human beings (e.g., computers or aliens; see Thagard, 1986 for a criticism that such a view is computationally naive, but Krellenstein, 1987, for a rejoinder).

There is today relatively widespread (though certainly not universal) agreement that there must be some materialist and probably functionalist explanation for subjective experience; e.g., Flanagan (1984) states that functionalism is "the currently favored solution to the mind-body problem" (p. 243). However, there would seem to be equally general agreement that there has been no progress in providing any of the presumably physiological details. Worse, there is not even any accepted model or conception of what such an explanation might look like. Wittgenstein (1921/1961) has expressed the difficulty of the problem as follows:

> The feeling of an unbridgeable gulf between consciousness and brain-process. . . . This idea of a difference in kind is accompanied by slight giddiness. . . . (p. 124)

Such success as modern cognitive science has achieved on this issue has not really dealt with the problem of consciousness, which has been almost totally ignored by researchers (one notable exception being philosopher Daniel Dennett, in Dennett, 1978 and 1991, for example). Pylyshyn (1984), for one, has observed that "the theories have set aside questions about what constitutes qualia" (p. 45). Functionalism has done no better with such problems than any other theory, and it is exactly these problems that, in Pylyshyn's words are "the hardest puzzle [in philosophy of mind]" (p. 23).

A Possible Basis for Unsolvability

There is not much in the current literature to suggest an exact explanation for cognitive limitations. Fodor (1983) argues that such limitations may be due to the modularity and isolation of the various components of cognitive architecture, but this view does not easily lend itself to specific predictions about problems it may or may not be possible to solve. A more hopeful line of inquiry, however, has been suggested by McGinn (1989) in the form of a direct argument for the unsolvability of the mind-body problem. McGinn's argument makes the suggestion that any concept which serves to causally explain a property of a physical object (the brain's production of consciousness, in this case) must have its roots, if loosely, in perception; and that this will be impossible in the case of the brain's production of consciousness, since one-half of that relation -- consciousness -- is itself paradigmatically unobservable. McGinn says the following:

> Suppose we try out a relatively clear theory of how theoretical concepts are formed: we get them by a sort of analogical extension of what we observe. Thus, for example, we arrive at the concept of a molecule by taking our perceptual representations of macroscopic objects and conceiving of smaller scale objects of the same general kind. (pp. 358-359)

McGinn points out that such a theory of concept formation does not pertain to all abstract concepts -- our ideas of numbers, for example, do not seem similarly based on some class of physical objects -- but only to those concepts providing causal explanations of physical, material phenomena. (Numbers and numerical relationships can be seen to model real-world phenomena in a process not fully understood, but we do not in any case accord them the kind of direct causation of physical phenomena we accord atoms, or light waves, or forces.)

This "clear theory" of concept formation contains the interesting suggestion that explanatory concepts are always at least loosely based on perceptual, non-abstract phenomena. Looking at this from a slightly different perspective, we might want to say that it must be possible to in some way visualize -- form an image of -- any concepts that can possibly serve to explain physical phenomena. This seems to capture the idea that such concepts must have their roots in perception in that, by virtue of being imagable, they are perceptual, even though the entities involved may of course not be directly observable. (The largely perceptual character of visual imagery is both a common-sense observation and one backed up by a substantial empirical literature; see, for example, Kosslyn, 1980).
Thus, our understanding of liquids (to use an example from McGinn) is plausibly based on a molecular model that, though perhaps not observable, is based on a building-block model we can form an image of, and that can physically (if not observably) connect to the phenomena being explained.

Applied to the problem of the origin of the universe, this suggests that that problem may also be unsolvable because of our inability to imagine (literally, that is, to form an image of) anything outside of the universe -- as would seem to be required of a concept explaining, or causing the universe. The difficulty is that the object to be explained -- the universe -- contains all possible observable phenomena, forcing the explanation to be unobservable in principle. If our explanatory concepts cannot be arbitrarily abstract but, rather, are tied at least by analogy to what we can observe, then we will be unable to form such concepts; there will be no observation-based concepts left to explain everything (the universe) that is potentially observable.

A specific relationship between the unsolvability of "why anything should exist at all" and an inability to form appropriate mental images was suggested around the turn of the century by physicist Ludwig Boltzmann. Boltzmann expressed the view that scientific thinking should begin with images, rather than empirical data. Here are Boltzmann's words as reported by Miller (1984):

> "It is precisely the unclarities in the principles of mechanics that seem to me to derive from not starting at once with hypothetical mental pictures but trying to link up with experience from the outset. . . .
>
> . . . [The] task of theory consists in constructing an image of the external world that exists purely internally and must be our guiding star in thought and experiment. . . ." (pp. 76-77)

Boltzmann went on to try to explicitly limit scientific thinking to problems where such hypothetical mental pictures could in fact be produced, stating that reasoning in the absence of such pictures was to "overshoot the mark" (p. 76), and was a waste of time. Boltzmann in fact gave as one of two explicit examples of such questions the question of "why the world exists at all" (the other example being "why the law of cause and effect itself holds", p. 76).

General Study Objectives and Procedure

The goal of this study will be to explore through interviews how subjects trained in physics but with a range of expertise reason about the origin of the universe, and to see what support their reasoning on this question provides for its being unsolvable, and for the basis of that unsolvability possibly lying in the inability to form a visual image of any possible solution to the problem. The expectation is that a significant number of subjects will claim a belief in the unsolvability of this problem, notwithstanding popular conceptions in the belief (especially among scientists) of the solvability of any problem that can be posed (McGinn, p. 365, states that he expects "that many readers of . . . [his] paper will find its main thesis utterly incredible, even ludicrous").

Commonalities across subjects with varying levels of expertise or background would also offer some support for an explanation grounded in cognitive limitations (vs. problem familiarity or expertise).

As to establishing a possible basis for such unsolvability, McGinn's views suggest a testable hypothesis: that individuals with poor visual imaging abilities (so-called "poor visualizers") will be less sensitive to the inability to imagine conceptual (perceptual) solutions to the problem, and will therefore be more likely to view the problem as abstractly solvable -- or perhaps even as already solved. Such poor visualizers may be more susceptible to a belief in what McGinn refers to as a kind of "magical emergentism" (p. 358): a willingness to believe in or accept the possibility of new concepts (or of the exaggerated explanatory power of existing concepts) that have no basis in what is or can be perceived, and consequently have no hope of really linking to the physical phenomena to be explained. McGinn speculates that there may be other forms of intelligence for whom such concepts are possible; but only a belief in "magic" makes them plausible for humans. (Religious answers to the problem of the origin of the universe may be seen as falling into this category to the extent they do no so much offer additional explanation as categorize and label all of the unknowns into a single equally unexplained entity.)

Put another way, poor visualizers do not as clearly perceive the inherent difficulties in finding physical explanations for unsolvable phenomena (which in fact require unimaginable solutions). Such individuals will be more accustomed to viewing all explanatory concepts as arbitrarily abstract (since the perceptual connectedness of successful explanation will be relatively lost on them), and will therefore be unreasonably optimistic about the arrival of new concepts to solve current problems.

A positive correlation between imagery usage/ability and belief in the unsolvability of these problems may have a different explanation: that these problems are not unsolvable but, rather, do admit to very abstract and indeed non-perception-based solutions; and that individuals with high imagery usage/ability will simply be less inclined to believe in the existence and/or be able to formulate or comprehend such abstract solutions. Strictly speaking, the present study can only hope to show that there is indeed a positive link between imagery usage/ability and belief in problem unsolvability. It will be to future work to better identify the basis for any such observed relationship in the dependence of solvability on imagability rather than in any difficulty good visualizers may have in understanding or apprehending very abstract concepts (or some other factor).

REVIEW OF RELATED WORK

The following literature review addresses the hypothesis that unsolvability may be due to a failure in producing imagable representations, and that a study of the relationship between imagery use/vividness and beliefs in unsolvability can help test this hypothesis. The review does not much address the general question of whether or not there are unsolvable problems. As mentioned above, this has a long philosophic tradition, but, aside from the few works cited above, there is not much directly relevant psychological work.

The review is divided into six sections:

1. Imagery, perception and causation: this section deals with that work most directly related to the hypothesis that causality is a concept constrained by imagable representations.

2. Imagery in scientific reasoning: this section deals with the considerable literature describing the role of imagery among scientists and in scientific discovery. Much of this work is historical and/or anecdotal in nature.

3. Individual differences in imagery: this section deals with the general (remaining) experimental literature concerning measurement of individual differences in imagery

and the relationship of such differences to problem-solving, concept formation, creativity and memory.

4. Differences between novices and experts: this section reviews the literature demonstrating the differences in reasoning between novices and experts in a given domain. Such studies both demonstrate the importance of imagery/perception in the reasoning of novices and experts alike and, to the extent differences are not found in the proposed survey, could provide some support for an explanation of such results that is dependent on cognitive architecture and independent of expertise.

5. Philosophical perspectives: this section discusses some relevant philosophical issues.

6. Summary of relevant work: a summary of the key points in the preceding sections.

Imagery, Perception and Causation

Beyond the ideas of McGinn and Boltzmann, the hypothesis that explanatory adequacy requires perception-based constructs does not seem to have been directly pursued, at least by psychologists. There is, however, substantial work linking perception and causation, as well as work demonstrating the special role of imagery in understanding causal relationships. Zajonc (1976) endorses Goethe's mostly disputed view (presented in Goethe, 1978) that scientific understanding arises not from rational analysis alone but also, and perhaps necessarily, from a perceptual, experiential interaction with the phenomenon being studied; that "to know is to have seen." Zajonc observes that the word "theory" is Greek for "to behold," and argues for an educational program that encourages "perceptual encounters" with the phenomena to be explained.

Some empirical support comes from work on the reasoning of novices and experts (reviewed more fully below), especially on the commonalities in the reasoning of novices and experts with regard to the use of imagery and image-based concepts. diSessa (1983) looked at how novices and experts approach problems in physics. While rejecting Goethe's idea that "phenomenology must be manifest in explicit science" (p. 16) -- an idea not itself required by the hypothesis that explanatory concepts are at least analogs of perceived objects -- diSessa presents evidence for the importance of direct experience in developing and applying abstract scientific concepts. Both the novices and experts in diSessa's study approach the solution of problems by recognizing phenomenal "primitives" such as springiness and rigidity. diSessa is principally concerned in showing that such immediate, black-box recognition, which she posits may have underlying neurophysiological support in the manner suggested by Carey and Diamond (1980) for facial recognition, is important for both novices and experts and evolves with the acquisition of expertise. But her novice and expert protocols also show the important links between such recognition and primitives that are themselves phenomenally based and cued rather than arbitrarily abstract. While diSessa never directly suggests that her subjects' (particularly the experts') explanations are intrinsically tied to a phenomenal model, these protocols clearly support such a view (such support possibly being due to other factors):

> The general point . . . is, again, that one should expect expert understanding to be organized around phenomenology as much as simply around the abstract structure of the domain. This is true for reasons of continuity with naive ideas and insofar as control of reasoning (e.g. cueing) is an integral part of expert knowledge. (p. 28)
>
> One might think experts would drop such [phenomenal] interpretations, except for pedagogical purposes. On the contrary, at least in some circumstances they invent more of them! (p. 25)

Larkin (1983, and Larkin and Simon, 1987) has done similar work on scientific problem representation. Larkin showed that such representation differs significantly between experts and novices: novice representations consist of real-world objects and processes simulated in real time, while experts, though continuing to make use of naive representations, additionally have a repertoire of "fictitious" technical entities which they use. Despite these differences, however, Larkin points out the perceptual, concrete basis for most (if not all) of even the experts' concepts:

> The naive representation [of the novice] is a direct simulation of events involving real (imagable) objects. It is less clear that the physical representation must always be imagable, but it is worthy of comment that most physical representations seem to have this feature. Even very abstract physical phenomena (e.g., energy states of an atom, conservation of quantum properties in the interaction of elementary particles) have corresponding imagable representations (energy levels, Feynman diagrams) used in solving related problems. (p. 79)

Similarly, Yates, Bessman, Dunne, Jertson, Sly, & Wendelboe (1988) found from interviews that novice subjects attempting to solve motion problems did so through an imagined enactment of the problem situation, drawing on fairly specific and often inconsistent prototypes representing aspects of the motion involved; and drawing on incomplete formal theories only when personal experience was inadequate for such imagined enactments. deKleer and Brown (1988) discuss more generally the class of mental models of physical systems (whether held by novices or experts) built around such imagined enactments. In their terms, such enactments are called "envisionments," and are defined as "running a qualitative simulation in the mind's eye" (p. 286). deKleer and Brown go on to say the following:

> One of the most important properties of envisionment is its ability to manifest a system's causality, which not only makes it extremely useful for constructing causal models of how and why the system functions, but also makes the envisionment sufficiently self-evident that it, also, can be "run" efficiently in the mind's eye; that is, envisionments have the property that each new state change is directly caused by a prior event. (p. 286)

(More generally, the use of imagery in solving problems related to some sort of dynamic processing is today well established; see, for example, Kosslyn, 1980. Larkin and Simon, 1987, discuss the power of pictorial representations for inferencing in general.)

From a developmental perspective, the existence of an early fundamental relationship between imagery/perception and causality has been addressed by Leslie and Keeble (1987), who demonstrated that 27-week old infants showed sensitivity to causal events (as suggested by recovery of attention following habituation after exposure to reversal of a causal vs. a non-causal event, controlling for other event similarities). Leslie and Keeble suggest that such perception of causality may be a hard-wired, "cognitively impenetrable" capability, as also suggested by the persistence of "causal illusions" in adults (e.g., the perception of causation in certain successive movements even when the underlying mechanism is known); or as suggested by the Gestalt "common cause" dynamic (Rock, 1983).

The idea that cause and effect may be more a fundamental capability than learned concept is also supported by its centrality in reasoning; as Leslie and Keeble observe, "the idea of cause and effect lies at the heart of both commonsense and scientific thought" (p. 265). Similarly, Shoham (1990) states that ". . . there is a feeling that "nothing happens without a cause"; this is the so-called "principle of causality." (p. 217)

Some recent research concerns the supposed developmental shift from perceptual to conceptual reasoning. Some of the work here (e.g., Keil, 1989, and Wellman and Gelman, 1988) offers evidence that contradicts this supposed shift, arguing not that the later reasoning is perceptual but rather that even young children's reasoning is often theory-based and built around causal concepts that are abstractions from directly perceived features. At first glance this appears to argue against the idea that perception-based reasoning is important at all stages. However, the early theories of children discussed by Keil and others are only abstract in the sense that they deal with non-observables, as opposed to being abstract in the sense of being non-perception-based (the latter being the sense of "abstract" most used in this paper). As such, this work demonstrates only that the ability to embrace non-visible and analogical concepts is already present in young children, and not that non-perception-based concepts (e.g., numbers or other abstract models) are importantly found in the causal reasoning of children (or adults).

In fact, this developmental work often demonstrates the continuity between perceptual evidence and the earliest abstract (i.e., based on non-observables) reasoning, and, again, the special importance of causation. Medin and Ross (1989), for example, offer a variety of evidence not only pointing to the importance of specific examples (vs. some sort of abstractions) in reasoning but also for the position that "abstraction arises as a by-product of the use of examples," rather than as "the product of some autonomous process" (p. 206).

Imagery in Scientific Reasoning

Imagery has been studied at least since Aristotle. James (1890) observes that imagery has figured importantly in the work of Hume, Berkeley, Locke and others, but goes on to point out that it was only with the work of Fechner in 1860 that the philosophic assumption that there was a typical human mind with a constant set of abilities was first challenged with regard to mental images. Fechner studied his own images and those of "several other individuals," and "the result was to show a great personal diversity" (pp. 50-51).

However, it was Galton's survey of the imaging ability of 100 men (reported in Galton, 1883) that really marked the first wide-scale psychological study of imagery. (Indeed, Heidbreder, 1933, reports that Galton's questionnaire is "said to be the first employed for a large-scale investigation in psychology" (p. 109), and James, p. 51, describes Galton's publication of his results "to have made an era in descriptive Psychology.")

Galton's work not only began the serious scientific study of imagery but also began a tradition of studying the place of imagery in scientific reasoning. Galton states that "at least half [of the 100 men surveyed] . . . are distinguished in science or in other fields of intellectual work" (p. 89). Galton asked these men questions about their background and subjective experience of visual images, many based on their response to imagining a now well-known "breakfast-table," the basic form of which is to be found in several modern measurements of imagery (e.g., the Vividness of Visual Imagery Questionnaire, or VVIQ for short, as described by Marks, 1973):

> "Before addressing yourself to any of the Questions on the opposite page, think of some definite object -- suppose it is your breakfast-table as you sat down to it this morning -- and consider carefully the picture that rises before your mind's eye.
>
> 1. Illumination.--Is the image dim or fairly clear? Is its brightness comparable to that of the actual scene?
>
> 2. Definition.--Are all the objects pretty well defined at the same time, or is the place of sharpest definition at any one moment more contracted than it is in a real scene?
>
> 3. Colouring.--Are the colours of the china, of the toast, bread-crust, mustard, meat, parsley, or whatever may have been on the table, quite distinct and natural?" [quotations in original] (p. 84)

The results of Galton's survey are not presented with much statistical detail, and are freely mixed with even less formal and anecdotal material. They nevertheless present some striking results and observations (more or less based on those results) that are echoed by much, though not all, subsequent research. One of these is the significant variability in imagery that Galton found, including its reported absence in about 10% of his sample, especially among a significant number of scientists (which surprised Galton, given the self-reported visual character of his own thinking):

> To my astonishment, I found that the great majority of the men of science to whom I first applied protested that mental imagery was unknown to them. . . . They had no more notion of its true nature than a colour-blind man . . . has of the nature of colour. (p. 85)

Galton contrasts these responses with those of non-scientists:

> On the other hand, when I spoke to persons whom I met in general society, I found an entirely different disposition to prevail. Many men and a yet larger number of women, and many boys and girls, declared they habitually saw mental imagery, and that it was perfectly distinct to them and full of colour. The more I pressed and cross-questioned them, professing myself to be incredulous, the more obvious was the truth of their first assertions. They described their imagery in minute detail. . . . (pp. 85-86).

Of the people who had at least some understanding of imagery, Galton goes on to describe in detail a wide range of reported vividness that, he says, testifies "to the variety of experiences to be met with in a moderately large circle" (p. 89). This includes the above descriptions of very vivid images ("brilliant, distinct, never blotchy") through "fairly clear" and finally to "dim and indistinct" (pp. 89-91).

Galton concludes from the relative lack of imagery among scientists that vivid imagery is, in general, antagonistic to the abstract thought of such scientists (though he says elsewhere that the evidence, though perhaps suggesting an hereditary factor, does not let us conclude whether lack of imagery is a cause or effect of such abstract thought):

> My own conclusion is, that an over-ready perception of sharp mental pictures is antagonistic to the acquirement of habits of highly generalised and abstract thought, especially when the steps of reasoning are carried on by words as symbols, and that if the faculty of seeing the pictures was ever possessed by men who think hard, it is very apt to be lost by disuse. (p. 88)

This point has been made informally by many others. Pear (1927), discussing the general utility of imagery in thinking, says that "Napoleon's famous dictum has impressed many, that 'those who . . . [ellipses in original] form a picture (*tableau*) of everything . . . are unfit to command'" (p. 6).

Galton elaborates further on this point by pointing out that relatively clearer imagery is found among the less abstract vocations -- he mentions mechanics, engineers, architects and physicists (presumably experimental physicists, assuming the idea of a purely theoretical physicist was not as familiar at the time Galton worked as it is today) -- and less prominent among those "men who deal much with abstract ideas" (p. 110), and Galton says he has found exactly that to be the case among philosophers. (An interesting point of anecdotal support for this position and for the current proposal that imagery vividness is related to a belief in the unsolvability of the problems under consideration is the fact that philosopher Daniel Dennett -- one of the most ardent and optimistic workers at developing theoretical explanations of consciousness -- claims (according to D. Reisberg, personal communication, 1987) to have no visual mental images at all.)

However, far from dismissing the importance of imagery for scientific thought, Galton goes on to suggest that this often-found absence of imagery is a hindrance to the best scientific thinking:

> The highest minds are probably those in which it [the faculty of seeing the pictures] is not lost, but subordinated, and is ready for use on suitable occasions. (p. 88)

Galton recounts many of the familiar stories of the impressive ways images are sometimes used (e.g., in blindfolded chess play, or in the ability to take in a large amount of information at a glance, as it were). He goes on to observe the following:

> There can, however, be no doubt as to the utility of the visualising faculty when it is duly subordinated to the higher intellectual operations. A visual image is the most perfect form of mental representation wherever the shape, position and relations of objects in space are concerned. . . . Strategists, artists of all denominations, physicists who contrive new experiments, and in short all who do not follow routine, have need of it. (p. 113)

In summary, Galton makes several points we will see repeated by others:

1. There is considerable variability in visual imagery ability.
2. Imagery can be antagonistic to abstract thinking.
3. Imagery can nevertheless be useful, if not necessary, for the very best or most creative thinking.

These points all offer some support for the current proposal in that they suggest that:

1. Imagery may play a central or necessary role for certain thinking.

2. Despite (and perhaps because of) this role, imagery or the lack thereof (a lack which may come not only from poor visualizing ability but from problem characteristics) may be a limiting factor for certain problems.

3. Individual differences in imagery may be profitably examined.

James (1890) cites Galton's findings approvingly, and, by way of both summary and support for Galton's finding of significant imagery variability, makes the often cited observation (exemplified by James's report of one of his students) that "some people undoubtedly have no visual images at all worthy of the name" (p. 57).

This idea has received support from a number of other early writers on the subject. Griffitts (1927), in a survey of various types of imagery, reports that "it was very interesting to find some subjects in doubt as to just what a visual image is" (p. 70). Aveling (1927), arguing for the position that imagery may be useful but hardly, as the ancients thought, necessary for thinking, reasons from the basis of his own lack of visual images while thinking.

Aveling's self-report is rendered more believable by being placed in a context that shows Aveling at least understands the concept:

> I do not normally enjoy visual imagery in thinking; nor can I call it up at will. . . . Yet . . . I know what it is to experience visual imagery, since the dreams I remember are often sufficiently vivid to be confused with actual visual perception; and, moreover, of imagery of other kinds I possess a fair abundance. (p. 15)

(More recently, McKellar, as reported in Kosslyn, 1980, studied members of Mensa, an organization for high IQ individuals, and found that 97% of those surveyed reported having visual images. Though the 3% without such images is a smaller number that Galton's 10%, it is of perhaps greater interest that, again, a significant if small number of individuals report having no such imagery at all.)

The mathematician Hadamard (1945) has also looked at the role of imagery in scientific (especially mathematical) thought, as well as speculating about the reasons for this role. The key point for Hadamard is the ability of imagery to present to the mind a complete creative effort -- be it a mathematical proof, a chess position or a symphony -- as a single entity. Hadamard compares the process to that of recognizing a person (cf. the work of diSessa described above; diSessa makes exactly the same comparison to facial recognition):

> The true process of thought in building up a mathematical argument is certainly . . . to be compared with . . . the act of recognizing a person. An intermediate case which illustrates the analogy . . . is afforded by psychological studies on chess players, some of whom, as is well known, can play ten or twelve games simultaneously without seeing the chess boards. Inquires were started, especially by Alfred Binet, in order to understand how this was possible: their results may be summed up by saying that for many of these players, each game has, so to say, a kind of physiognomy, which allows him to think of it as a unique thing, however complicated it may be, just as we see the face of a man.
>
> Now, such a phenomenon necessarily occurs in invention of any kind. . . .
>
> Similarly, any mathematical argument, however complicated, must appear to me as a unique thing. I do not feel I have understood it as long as I do not succeed in grasping it in one global idea. (p. 65)

Hadamard presents a similar statement by Mozart describing his process of composition:

> "The work grows; I keep expanding it, conceiving it more and more clearly until I have the entire

> composition finished in my head though it may be long. Then my mind seizes it as a glance of my eye a beautiful picture or a handsome youth. It does not come to me successively, with its various parts worked out in detail, as they will be later on, but it is in its entirety that my imagination lets me hear it." (p. 16)

Hadamard also cites the mathematical work of Poincare. Poincare (1908) has written about the particular importance of this global view at the moment of creative problem solution -- of the "appearances of sudden illumination" (p. 55) that, in a glance, reveals the long-sought solutions of various mathematical problems. (Wallis, 1926, subsequently postulated four stages of creative thought: preparation, incubation, illumination and verification.)

Hadamard also presents an excerpt from a letter by Einstein stressing his use of images, particularly with regard to their role in presenting combinations of elements:

> "The words or the language, as they are written or spoken, do not seem to play any role in my mechanism of thought. The psychical entities which seem to serve as elements in thought are certain signs and more or less clear images which can be voluntarily reproduced and combined.

> There is, of course, a certain connection between those elements and relevant logical concepts. It is also clear that the desire to arrive finally at logically connected concepts is the emotional basis of this rather vague play with the above mentioned elements. But taken from a psychological viewpoint, this combinatory play seems to be the essential feature in productive thought. . . ." (p. 142)

Similarly, Hadamard reports Poincare's point that imagery seems necessary not only for problem recognition but also, in the last (or "verification") stage of creative work, to maintain the combination of elements in a particular problem solution while the details are worked out or verified, "in order that the useful hookings, once obtained, may not get lost" (p. 77).

Despite the importance of images for Hadamard himself and for the work of several others he describes, his general review of work in this area convinces him of the variability of the exact nature and role of imagery in scientific thinking; he states that "the nature of .. concrete representations may vary considerably from one mind to the other" (p. 99). Hadamard also recognizes the point made by Galton and others that imagery may not always play a facilitating role, and mentions a statement by Binet that "there exists a kind of antagonism between image and reflection" (p. 73).

Some data describing such differences on a vocational basis -- data that is more recent and carefully presented than the vocational data of Galton -- is available from Roe (1951), who has studied the personalities of research scientists in a variety of professions with some emphasis on the place of imagery in their work. Roe concludes the following:

> The biologists are concentrated in the visual imagery group. So are the experimental physicists, while the theoretical physicists more characteristically employ verbal or other symbolizations. The psychologists and anthropologists are heavily concentrated in the verbal group (this includes all of the cultural anthropologists). (p. 463)

Roe, as Galton did before her, observes that the direction of causality of such differences is unknown:

> My data offer no information on why subjects have come to rely on some modes of thinking rather than others. Whether there is a hereditary factor, as Galton suggested, or whether it is largely training or experience, and if so how early and by what means the mode is set and how changeable it is are unsolved but fascinating problems. (p. 469)

Arthur Miller's Imagery in Scientific Thought (1984) discusses the central role of imagery in the formation of new concepts in 20th century physics, reviewing in particular the work and beliefs of Bohr and Boltzmann (discussed above), as well as Einstein and Poincare. Of Einstein's work, Miller says "the matrix of science, philosophy, and technology in which Einstein was educated and worked placed a high premium on visual thinking, a mode of thought that he preferred for creative scientific thinking" (p. 48).

Miller also discusses the tensions during the early development of quantum mechanics between the very abstract and mathematical, particle-based approach of Heisenberg (with any visualization of a particle explicitly rejected) and the generally preferred, more concrete and visualizable wave mechanics of Schrodinger (the equivalence of the different solutions and the wave-particle duality of matter were subsequently demonstrated). Miller quotes Schrodinger himself: "I knew of . . . [Heisenberg's] theory, of course, but felt discouraged not to say repelled, by the methods of transcendental algebra, which appeared very difficult to me and by the lack of visualizability. . . ." (p. 143)

Similarly, it was with relief that the physics community eventually greeted Feynman's now widely accepted diagrammatic approach to quantum theory. Miller attests not only to the preference for such a model but to its supposed superiority: "It is possible that just as in many cases of productive thinking, the problem situation attains a higher plateau of clarification once the proper diagram is drawn" (p. 257).

Miller's view of the basis of the importance of imagery in scientific thinking is similar to what is herein proposed: that psychological structure constrains concept formation, and this structure is itself constrained by the world of sensations and perceptions. Miller presents a statement by Poincare on this point:

> "Mr. Russell will tell me no doubt that it is not a question of psychology, but of logic and epistemology; and I shall be led to answer that there is no logic and epistemology independent of psychology." (p. 1)

More specifically, Miller points to the world of sensations and perceptions as providing and limiting the material from which concepts, at least in physics, can be formed:

> There was general agreement [among physicists] on the sorts of models available for representing a theory adequately. . . . These pictures were abstracted from previous visualizations of objects in the world of perceptions. (p. 128)

Lightman (1989) makes much the same points:

> Ultimately, we are forced to understand all scientific discoveries in terms of the items from daily life -- spinning balls, waves in water, pendulums, weights on springs. We have no other choice. We cannot avoid forming mental pictures when we try to grasp the meaning of our equations, and how can we picture what we have not seen ? As Einstein said in The Meaning of Relativity, "The universe of ideas is just as little independent of the nature of our experiences as clothes are of the form of the human body." (p. 99)

Miller's discussion of Heisenberg's emphasis on abstraction during the early development of quantum mechanics and Heisenberg's explicit abandonment at that time of a visualizable model, though a minority position, requires some further attention. Heisenberg's early successes came in the context of the then prevalent and historically captivating Bohr model of the atom, which pictures a planetary-like structure of electrons orbiting a nucleus. Heisenberg correctly saw that this model did not meet the experimental data, and that, in fact, no simple picture of a concrete electron would do owing (according to Miller's description of Heisenberg's thinking at the time) to the quantum uncertainties in the electron's position and very individuality as a particle. Miller paraphrases and cites Heisenberg's own words:

> In the past we attributed to electrons "the same sort of reality as the objects of our daily world; we represented to ourselves these basic building blocks as extraordinarily small particles of known charge and mass but unknown internal structure, which move precisely according to fathomable laws in space and time and certainly complying with our intuition of the familiar continuity of the space-time world." Yet, Heisenberg went on, "in the course of time this representation has proved to be false." For the "electron and the atom possess not any degree of direct physical reality as the objects of daily experience. . . . The program of quantum mechanics has above all to free itself from these intuitive pictures. . . . The earlier theory had the benefit of direct visualizability . . . ; the new theory ought above all to give up totally on visualizability," thereby avoiding any internal contradictions. (p. 148)

According to Miller, "Heisenberg thrived on this mode of thinking" (p. 155), and produced several important results, including the famous uncertainty relations.

Early on, Heisenberg was troubled by the non-intuitive (as opposed to non-visualizable) aspects of his work, including the changes in viewpoint in traditional mechanistic causality brought about by probabilistic quantum mechanics and the difficulties the data presented for conceiving of anything like a traditional particle located in a particular space and time. However, Heisenberg's work on the uncertainty relations eventually led him to a re-cast point of view that allowed him to claim an intuitive grasp of these abstractions. Miller says: "But what sort of 'intuitive meaning' could Heisenberg have meant when previously he had been emphatic on rejecting visualizability in the modes of pictures or images?" (p. 150)

The answer appears to have been as follows:

> In the atomic domain a revision of our usual kinematical and mechanical concepts "appears to follow directly from the fundamental equations of the quantum mechanics. . . ." Since the uncertainty relations placed limits on the accuracy to which initial conditions could be determined, Heisenberg rejected the causal law from classical mechanics that required visualization. . . . Thus, concluded Heisenberg, if we bear in mind the uncertainty principles, we "should no longer regard the quantum mechanics as unintuitive and abstract." (p. 150)

Put another way, Heisenberg seems to have adjusted to a view of reality dictated by the quantum theory that was not based on traditional causality and, as a result, on any easily imagable model, and that he came to see this view as both explanatory and intuitive.

This appears to count as some evidence against the broadest proposal under consideration -- that imagability is necessary for a good explanatory model. However, the damage is not as great as it would seem. For one thing, it is not clear that Heisenberg clearly embraced a non-imagable paradigm (though it was apparently perceived that way at the time, and Miller presents it that way). The quantum view of a particle (and certainly that of a wave), while having many strange attributes, would still seem to derive by extension from perceived attributes of real particles, and it might be more accurate to say that Heisenberg moved from a dominant image -- the Bohr atom -- and certain relatively common-sense views on particles and causality to admittedly more foreign and less intuitive -- but still imagable -- concepts such as the uncertainty of a particle's exact location/momentum, or the fact that the smallest units of matter sometimes behave as a wave and sometimes as a particle (but not in fact both in the same experiment, which would indeed be hard to produce an image of).

It is also the case that Heisenberg's eventual self-acclaimed intuitive grasp of a physical reality described by quantum mechanics does not automatically confirm it as a valid explanatory model, any more than any other individual who claims to now fully understand the origin of the universe or the solution of the mind-body problem in any particular abstraction. Of course, this is slippery ground, in that, in the absence of some objective measure for what constitutes a full and satisfactory explanation, it is the subjective reports of subjects that count as primary evidence. Still, it should be remembered that individual disconfirming (or confirming) instances are not conclusive. It is worth mentioning in this regard that Heisenberg's view of the intuitive reality of quantum mechanics is sometimes today challenged; Bernstein (1991, September 26) states that "more and more physicists are becoming dissatisfied with the conventional formulation of quantum mechanics," and Shimony (1991) claims that "the abandonment of a realistic interpretation of quantum mechanics of physical systems" -- i.e., that "there is no quantum world . . . only an abstract quantum physical description" -- is an increasingly familiar point of view (p. 523).

It would have been interesting to test Heisenberg's level of imagery vividness and use of imagery. Even if his theorizing is viewed as disconfirming the stronger proposal that an imagable model is necessary for explanation, it would very possibly have served as another point of confirmation of the general individual difference hypothesis that low imagery use/vividness is correlated with belief in the possibility (and, for Heisenberg, the actuality, to some extent) of abstract explanations of physical phenomena.

Many contemporary physicists have written about the importance of imagery in their work (e.g., Penrose, 1989). (This is of course of limited statistical value; there do not seem to be too many first-hand accounts by physicists who expressly do not make use of images, and one would not expect the negative position to be considered as interesting to report.) A slightly broader accounting of the current use of imagery among physicists can be found in the Cosmology Interview Project conducted by Lightman and Brawer (1987-1989, by permission of the Niels Bohr Library, Center for History of Physics, American Institute of Physics; and 1990). This consisted of in-depth interviews with 27 leading cosmologists over the period 1987 to 1989. The goal of the study to date has been to extract data (the one published work, Lightman and Brawer, 1990, is largely unanalyzed extracts from the transcribed interviews) that would shed light on "the ways in which personal, philosophical, and psychological factors enter the scientific progress" (1987-1989, p. 2).

Lightman and Brawer asked a fairly standard set of questions about early childhood experiences, motivations and approaches in studying cosmology and views on specific cosmological questions. One set of questions that was asked of most of the subjects concerned their use of imagery: whether they used visual images in thinking about cosmological problems, whether they ever tried to visualize the Big Bang, etc. As the work by Galton, Roe and others discussed above would lead us to believe (though contrary to Galton's finding that "most" scientists were unfamiliar with imagery), there was considerable variability in the responses, with 13 indicating they did use visual images to varying degrees, and 6 responding that they basically did not use them. Here is a sampling (from the original interviews, 1987-1989; page numbers are the number within each individual interview) of the responses of several of the cosmologists about the use of imagery (sometimes together with the interviewer's question), as well as some of the responses about the problem of the origin of the universe (the latter was not standardly pursued but came up at various times in the interviews; the responses were not numerous enough to correlate with the reports of the use of imagery):

> Dicke: There's still one point in cosmology that I find very disagreeable, and that's the idea of time and space having no meaning up to a certain point and then suddenly appearing. A universe which is suddenly switched on I find highly disagreeable. (p. 13)

Geller: I don't have a vivid image of the Big Bang itself. . . . The things I understand very well, I probably have some level of visual image. And the Big Bang, I mean I have some images, but they're not images that are particularly vivid. (p. 14)

Lightman: . . . do you find that you use visual images much in your work ?

Gunn: Oh, quite a lot. That also is something that happens more and more as you get older . . . -- you rely on mental pictures. But I always have, to a very large extent. . . . Unless I can make an image for something, I don't really feel that I understand it. There are dangers in that because you can often make images that are not right. (p. 16)

Guth: . . . I think it's very possible that the universe is a quantum fluctuation starting from absolutely nothing. . . .

Lightman: . . . If the universe began as a quantum fluctuation, what was there before the fluctuation ? How do you think about that ?

Guth: OK, I can tell you the image I use for that, although I'm not sure it will hold up in time. What I think now is that . . . there will be a space of all the possible states of the universe . . . and among all of those states . . . I assume that one of the possibilities is a . . . universe with its radius equal to zero or something like that. . . .

Lightman: Then what meaning do you give to the words "the universe came into being?" Does that just mean that a particular universe changed from having . . . zero radius to having a finite radius ?

Guth: Actually, it probably has no precise meaning. . . . I think that once you get down toward the beginning of the universe . . . you really should not talk about the universe beginning at a time. (p. 10-11)

Hawking: I really have to be able to visualize a problem. (p. 3)

Lightman: Are visual images important to you in your actual research . . . ?

Hoyle: No. I was never a very good geometer. I had to do all my geometry algebraically. I'm not very good at visual imagery. (p. 19)

Lightman: I know there have been certain physicists in the past who have used images and visualization and pictures more than other physicists. I think Einstein used a lot of visual images. . . . One question that I've been very interested in, and some psychologists are interested in too, is how physicists use mental pictures. Maybe not exactly pictures but, for example, the way we say in quantum mechanics that sometimes things act as particles and sometimes as waves. I guess we're attempting to make a connection to our daily experience with the world. How do you use images in your work? Do you find images useful or harmful?

Linde: Typically, I just use them. (pp. 3-4) [Note Lightman's point -- similar to the point made above that the renouncement of visualization for quantum mechanics is not really complete -- that the underlying model(s) of quantum mechanics draw on common-sense (imagable) constructs]

Lightman: . . . do you use visual images much in your own work ?

Peebles: Yes I do. . . . I don't know -- how else do you think, besides in images? (p. 18)

Lightman: . . . do you use visual images a lot ?

Ostriker: Yes. . . . There was a volume in honor of Stan Ulam. . . . He commented . . . that physicists always think in just pictures first. . . . [Not apparently true]

Lightman: You think that helps you work on problems?

> Ostriker: I wouldn't even make it as weak as that. It's essential. (p. 21)

A final interesting point: when Lightman was questioned about why he did not ask all the interviewees about their use of imagery (as determined by a reading of the complete transcripts), Lightman responded that he stopped asking these questions part way through the interviews because "many scientists don't use visual images and those that do seem to have trouble articulating the experience" (Lightman, personal correspondence, August 8, 1991). This again attests to the variability in imagery usage but also to the difficulty collecting reliable and useful data about such usage.

Individual Differences in Imagery

Relevant work on individual differences in imagery has been mostly focused on demonstrating a functional role for imagery in problem solving and concept formation and on the link between imagery and creativity, as well as some more general studies on the nature and extent of individual differences with regard to memory. Imagery ability has most often been defined as imagery vividness, and is typically measured either by Betts's (1909) Questionnaire upon Mental Imagery (QMI) or by Marks's (1973) Vividness of Visual

Imagery Questionnaire (VVIQ). Some work has also focused on the role of imagery frequency. Such studies have also tried to demonstrate what factors limit or enhance the role of imagery, including stimulus attributes and familiarity and instructions/priming to use imagery. Finally, while the emphasis has been on the facilitative role of imagery, several studies have shown that imagery can sometimes retard performance.

The following review will focus on the central works in each of the above areas. General recent surveys of the imagery literature (though not touching all of the areas of interest here) can be found in Ernest (1977) and Reisberg, Culver, Heuer & Fischman (1986). Forisha (1978) has surveyed work on imagery and creativity.

Imagery in Problem Solving and Concept Formation

In a study typical of those demonstrating a functional role for imagery, Ashton, McFarland, Walsh and White (1978) repeated the well known study of Cooper and Shepard (1975) on hand recognition but examined the role of imagery vividness, which Cooper and Shepard did not consider. Level of imagery vividness of subjects was measured using Betts's QMI, and groups of high, medium and low imagers were constructed, each with two right and two left handers. Line drawings of a hand were then tachistoscopically presented to subjects, with the hand presented being either the right hand or left hand, front or back view and in any of six orientations (upright, 60 degrees from upright, 120 degrees from upright, upside down, etc.). The stimulus was preceded either by a 2 sec. blank field or by 2 sec. of a thumbless outline of a hand in the same orientation as the stimulus hand. Subjects were in addition sometimes "instructed to imagine one of the four versions of the human hand (left/right, front/back) as being superimposed" (p. 256) over the thumbless outline. Reaction time was measured from presentation to correct identification of the stimulus as either a right or left hand.

Results showed that high imagers had shorter reaction times than medium imagers, who had shorter reaction times than low imagers. In addition, reaction times were shorter in the imagery instruction (vs. the no instruction) trials. Interestingly, in a second experiment in which no imagery instructions were presented at any time, there was no significant difference based on imagery vividness. Ashton et al. conclude that imagery ability is important but only when use of imagery is suggested; it appears that high imagery ability does not by itself automatically lead to its usage in a problem-solving situation.

Ashton et al. also found that the effects of imagery differences were most pronounced for unusual hand orientations, and least observed at the 0 and 360 degree positions. This led them to suggest that the functional demonstration of individual differences imagery depends not only on instructions to use imagery but also on task unfamiliarity, with familiar tasks presumably capable of being performed regardless of imagery ability.

DeSoto, London & Handel (1965) also demonstrated a functional role for imagery, reporting that when subjects solve 3-term problems -- e.g., given that Tom is taller than Sam and John is shorter than Sam, who is the tallest ? -- subjects reported creating images of spatial arrays of the items, arranging them in the order given by the premises and then inspecting the array to provide the problem solution. Huttenlocher (1968) further showed that the latencies and number of errors recorded for such problems are "parallel [to] their mental operations in determining the place of a real item in a spatial array from a verbal description" (p. 555).

Also working with 3-term problems, Shaver, Pierson and Lang (1974) reported that a significant majority of their subjects claimed to use a spatial approach to solving the problems. In addition, Shaver et al. showed that:

1. Subjects with better scores on spatial-reasoning tests (from Thurstone's Chicago Tests of Primary Mental Abilities) made fewer errors (at least for men, while the

findings for women were not statistically significant; we shall continue to see occasional though hard to explain gender differences in such studies)

2. Problems in which the relation among the terms was spatial (e.g., above/below vs. lighter/darker) were easier to solve.

3. Instructions to use imagery were again significant, with fewer errors reported when users were explicitly instructed to use imagery.

Despite the numerous reports in the psychological and anecdotal literature on the use of imagery in problem-solving, Kosslyn, Seger, Pani & Hillger (1990), reviewing the results of a set of diaries kept by subjects describing images as they occurred throughout the day, found that "relatively few images were reported to be used in the service of what we took to be the primary purposes of imagery, that is, recall and mental simulation" (p. 150). Of course, as Kosslyn et al. observe, much of any given day is spent in fairly mundane activities, so it is perhaps not surprising that when all of the imagery that transpires is chronicled, only a small part is seen as purposeful. Kosslyn et al. did find that vivid imagers (the top half of the group as measured by the VVIQ) had a statistically significant greater number of images per day (16) than those with less vivid imagery (12).

Katz (1983) cites work showing that desensitization therapy involving imagery is more effective among those scoring higher on subjective (unspecified) measures of imagery. However, when the mode of the therapy was based on verbal self-instructions, high imagers did worse, again showing the importance of instructions and suggesting an interfering effect of imagery.

Interference by imagery in certain kinds of concept learning was also demonstrated by Hollenberg (1970). Hollenberg reasoned that children with good imagery ability would learn the names of objects more quickly than weak imagers since the ability to mentally reconstruct a picture of an object would allow "silent rehearsal and solidification of the object-label tie" (p. 1004). However, Hollenberg hypothesized that weaker imagers would grasp "concepts underlying the application of verbal labels more quickly than children who have strong imagery" since "visual imagery, by preserving so vividly the perceptual aspects of experience, might act to focus attention and recall on perceptual similarities among objects and thereby impede the acquisition of the meaning categories underlying language" (p. 1005)".

Hollenberg presented 64 children from grades 1 through 4 with a battery of tests aimed to measure how much the children relied on visual imagery in problem-solving. In order to test the hypothesis that high imagers would learn names more quickly, the children were then presented nonsense names for pictures of 4 objects, and then asked to identify the pictures in different orderings, with incorrect results being corrected; the names were considered learned when there were 3 consecutive sets of error-free identifications. For the hypothesis that low imagers would have superior concept attainment, Hollenberg then showed the subjects a series of additional pictures of objects each of which had some conceptual group identification with one of the original pictures, and asked subjects to guess which of the learned nonsense names applied to them. The subjects' responses were corrected, and the trials repeated with new pictures until once again a certain level of error-free response was reached.

Hollenberg's results basically confirmed her hypotheses. High-imagery children required fewer trials to learn the nonsense names than did low-imagery children at most grade levels, and in general showed less difference between grade levels than did the low-imagery children, who could be seen to more significantly improve with increasing grade-level. The results for concept learning were more pronounced, with low-imagery children clearly requiring fewer trials up to the 4th grade, at which point the differences between low- and high-imagery groups seemed to disappear; Hollenberg suggests that by this time the high-imagery children had learned alternative compensating strategies for concept attainment.

There is a significant body of work by Paivio and others showing that stimulus imagability itself (vs. imagery ability of the individual) facilitates learning and recall; indeed, Paivio has said that stimulus imagability is "the best single predictor of associate learning involving meaningful material that we have been able to identify" (Paivio, 1970, p. 389). The proposed explanation for this is as follows:

> High-imagery, or concrete, stimulus terms such as "house" function as efficient stimulus "pegs" from which associates can be hung and retrieved by means of mediating images. To use Kohler's example, when a pair such as "sugar-lake" is presented, it evokes a compound spatial image. When the stimulus word "sugar" is presented on the test trial, it evokes the compound image of the sugar in the lake, which in turn mediates the overt response "lake". . . . This hypothesis generated the prediction that concreteness or image-evoking value would have a greater effect when varied on the stimulus side than on the response side of pairs in paired-associate learning, for it is the stimulus term that must reinstitute the mediating image on the recall trial. This prediction has been repeatedly confirmed in a series of experiments. . . .

[quotation marks replace italics in the original] (pp. 387-388)

Imagery and Creativity

Schmeidler (1965), working from a psychodynamic perspective that equates visual imagery with the primary process thinking of the unconscious, investigated the hypothesis that creative individuals are more likely to admit such primary process material into their consciousness, as measured by the greater vividness of their visual imagery. Schmeidler tested 307 college students for imagery vividness and creativity, using a modified version of Galton's breakfast-table questionnaire to test imagery vividness and using the Barron Independence of Judgment Scale, produced by interviews and tests of creative and non-creative workers in the same field, to test creativity. The results showed a significant correlation ($r = .21$, $p = .008$) between imagery vividness and creativity. Interestingly, "no Ss with very high imagery scores had very low creativity scores" (p. 78), though there were very creative individuals with low imagery scores.

Shaw and DeMers (1986) tested both academically gifted and normal fifth and sixth grade students for imagery vividness (using the VVIQ and additional tests for visual memory and visual imagery control) and creativity (using the battery of tests developed by Torrance). Results showed a positive relationship between imagery control and originality and flexibility (two of the more qualitative sub-scores of the creativity tests), especially among high-IQ subjects and especially between the VVIQ and originality. No gender differences were found.

Forisha (1981) administered imagery and creativity tests to 320 college students (both undergraduate and graduate). The imagery tests consisted of an adaptation of the QMI plus an imagery control questionnaire, and the creativity tests consisted of Torrance's Unusual Uses Subtest and four Thematic Apperception Test cards, scored by Stewart's Psychological Adaptation to the Environment Scale. Results showed a significant correlation in total imagery and creativity scores for the entire sample, as well as for several subsets of the sample; correlations were strongest in psychology and business majors for males (vs. engineering and education) and in education for females. Regression equations showed a significant contribution to creativity by imagery. However, as has often been the case, there was the suggestion of a negative imagery effect as well: a factor analysis turned up two factors on which imagery and creativity were highly loaded, and on one of these factors they were loaded in opposite directions.

Forisha (1978) also reports on some earlier work of hers that shows mixed or inconsistent results. In one study, there were clear negative correlations for men between imagery vividness and a number of creativity sub-scores, while women showed non-significant positive correlations. A second study showed no significant correlations for men and numerous significant correlations for women. Forisha also compares such inconsistencies (and some reported elsewhere) with the numerous anecdotal and subjective reports (e.g., Poincare, Einstein, Nietzsche, Arthur Koeslter and others) attesting to the role of visual and auditory imagery in forming ideas, though here too, as we have seen, there is often the suggestion (or more) of a possible negative role for imagery. Forisha speculates that a possible basis for such inconsistencies is an interaction between specific imagery abilities (vividness, flexibility, etc.) and stage of personality development, as described in works such as those by Witkin and Maslow:

> Consistent findings for women of a low, positive relationship between creativity and imagery are in accord with the hypothesis that women are more aware of their imagery and that imagery may play a more integrated role in their cognitive processes. This agrees with the theory that women, even creative women, are more autocentric in their thinking, more inner-oriented, and more receptive to unconscious processes. The contradictory findings for men indicate

> that this is not so in a male sample and that other moderating variables are at work. Such variables as field dependence and independence, imagery rigidity and flexibility, autonomy and control, as well as the men's conscious direction of attention . . . are all suggested variables. Speculating further, in a sample of moderately creative individuals one would expect to find more "differentiated" male personalities in which imagery is neither a continuous nor very welcome counterpoint to verbal and rational objectivity. Hence, such imagery might become an obstruction to both abstract and creative thinking.
>
> On the other hand, in a sample of either highly creative men or the ones particularly selected because of humanistic interest, one might expect to encounter more of an awareness and utilization of imagery. The results described above indicate that this might be so. In men who are integrated rather than differentiated, or who are more open to humanistic concerns, one is more likely to find an awareness and utilization of imagery in furthering creative thought. (p. 231-232)

This evokes Galton's comment (presented above) that, despite the lack of imagery among large numbers of talented people, imagery is still likely a component of the "highest minds":

> The highest minds are probably those in which it [the faculty of seeing the pictures] is not lost, but subordinated, and is ready for use on suitable occasions. (Galton, 1883, p. 88)

Similarly, there is Bartlett's remark that "the image method remains the method of brilliant discovery" (1932, p. 226).

Imagery and Memory

The literature studying the relationship between imagery and memory contains many significant findings but also a number of inconsistencies. Marks (1973), in the work that introduced the VVIQ, found that good imagers were better in recalling incidental details (e.g., the number on a golf ball) of color photographs. Gur and Hilgard (1975) found that subjects with more vivid imagery as measured by the VVIQ had shorter reaction times in identifying differences between two versions of a picture, with pairs of pictures presented both simultaneously and successively.

Slee (1980) found that vividness (as measured by the Visual Elaboration Scale, or V.E.S., an instrument designed by Slee) correlated with recall in a number of appearance-related tasks, including recall of a line drawing differing in only small structural details from another. On the other hand, Slee found no relationship between vividness and a number of recognition tasks, nor between vividness and certain kinds of reconstruction of ambiguous figures in which there was a clear conceptual interpretation. Slee interprets the lack of an imagery/recognition (vs. imagery/recall) relationship as supporting the view that imagery is related only to the "temporary retrieval and conscious representation [of information] and not to its storage" (p. 112). Slee sees the lack of a relationship in the presence of a conceptual representation as indicating the following:

> Visual imagery has no special role with respect to information corresponding with a prior conceptual interpretation of a configuration, but . . . it has a more or less unique role with respect to information corresponding with detailed features of visual structure. (p. 111)

There are many studies that have found no relationship between vividness and recall, and some that have found inverse relationships. Berger & Gaunitz (1977) performed experiments similar to those of Marks and of Gur and Hilgard. Imagery vividness was measured with the VVIQ, and subjects had to determine whether two successively presented pictures were either identical or only very similar. In addition, Berger & Gaunitz attempted to control for a number of demand characteristics and other possible confounding variables not explicitly controlled for in the earlier works, including experimenter and subject knowledge of the VVIQ score and when the VVIQ was administered (half were tested before the trials, half afterwards). The results indicated no significant relationship between vividness and accuracy of difference judgments.

Reisberg, Culver, Heuer & Fischman (1986) found a clear inverse relationship between imagery vividness and both long-term incidental and short-term intentional memory for colors, with vivid imagers doing significantly worse. Reisberg et al. argue that this is because vivid imagers can more easily imagine any color as the correct answer, and therefore are more readily lured into mistakenly identifying some color as the correct one. They further argue that much of the inconsistency in the literature can be attributed to a failure to distinguish between visual tasks (such as theirs), which many studies show are related to vividness (though few modern empirical studies demonstrate the inverse relationship they have found) and spatial tasks, which tend not to show a relationship to vividness. However, even within their own review of the literature there are findings unexplained by such a hypothesis.

Cohen & Saslona (1990) found a positive correlation between subjects' reported frequency of visual imagery and recall of incidentally viewed colors, but no correlation between vividness (using the VVIQ) and frequency or between vividness and color recall, and vividness was inversely correlated with recall of location information. Imagery frequency was measured using items from Paivio's Individual Differences Questionnaire, or IDQ (1971), that Paivio later found loaded highly on a frequency of imagery factor (Paivio, 1983). Work by Heueur, Fischman and Reisberg (1986), using essentially the same instruments, also demonstrated no relationship between frequency and vividness. There is also, as Cohen and Saslona report, some support in the early survey by Griffitts (1927) of individual differences in imagery for the independence (at least as factors) of imagery frequency and vividness, in that Griffitts found some individuals for whom visual imagery was dominant (vs. auditory or other types of imagery) but very unclear. (Cohen and Saslona fail to mention that Griffitts nevertheless found a strong positive correlation between dominance of a particular type of imagery and the clarity of that imagery.)

From this Cohen and Saslona argue for the utility of imagery frequency (vs. vividness) as a facilitator of certain tasks, and for the confusion of frequency and vividness as a partial explanation (to the extent the two are confounded in some tests, such as Paivio's original IDQ) for the inconsistent results in the individual differences literature. Cohen and Saslona suggest (but leave unresolved) two possible mechanisms for the effects of imagery frequency: "It is not clear . . . whether [frequent] visualizers encode visual information more 'automatically,' pay more attention to visual aspects . . . or have a greater facility for recalling visual information once encoded" (p. 111).

The demonstrated importance of imagery frequency strikes a resonant note with the literature on imagery in scientific reasoning, where it is often imagery usage (vs. or at least not clearly distinguished from vividness) that is mentioned, though the lack of a relationship between frequency and vividness is a little surprising on a priori grounds if we assume the validity of the vividness measures (which Cohen & Saslona don't especially; see just below).

Furthermore, picking up on a rejected speculation by Reisberg et al., Cohen & Saslona speculate that their finding of an inverse relationship between vividness and location recall is due to subject over-confidence. Reisberg et al. mention the limitations of introspective self-report, especially as that might be adequate to explain only small correlations, but basically accept the validity of such a measure. Cohen and Saslona, however, point out that those scoring the highest vividness scores on the VVIQ have fairly frequently chosen (both in their study and others) the option labeled "perfectly clear and as vivid as normal vision" (p. 110) for describing some of their images, a description which seems (to Cohen & Saslona, at least) fairly unlikely to be true as often as it is reported (if indeed it is ever true, in their opinion) by such vivid imagers. This suggests that such subjects may be more indicating their confidence in their imagery (or themselves) rather than its vividness, and doing this despite any errors in their imagery.

Such over-confidence, Cohen & Saslona reason, would be inappropriate for their fairly difficult spatial location discrimination, resulting in poorer performance for such subjects. Similarly, the argument continues, in those cases where (over-) confidence is less relevant or perhaps even a useful motivator, such vivid imagers might be expected to do the same or better, respectively, than less vivid imagers. (A few studies are mentioned as possibly supporting this point of view but it is basically left as a speculation requiring further research.)

Differences between Novices and Experts

Differences in Encoding and Recall

Much of the early and most familiar work in this area describes the differences between novices and experts in their ability to encode and recall information from a given problem space. deGroot (1965) presented chess positions to experts and novices for a few seconds and then removed the pieces, and found that experts could correctly replace a much larger number of pieces than novices. When the pieces were arranged randomly, there was no novice/expert difference, suggesting a chunking by the experts of individual pieces in the actual games' positions into larger meaningful units.

Similarly, Chase and Simon (1973) found that expert chess players attempting to reconstruct a game position tended to do so in chunks of chess-meaningful units, and concluded from this and other studies that "the ability to perceive familiar patterns quickly . . . [is] the basic ability underlying chess skill" (p. 267).

These findings have been replicated in a number of domains, including computer programming (e.g., McKeithen, Reitman, Rueter and Hirtle, 1981) and bridge (Charness, 1979).

Differences in Categorization and Representation

Work on psychological diagnosis by Murphy and Wright (1984) found that expert categories were richer and more complex than those of novices, if sometimes fuzzier. In physics, Chi, Feltovich and Glaser (1981) found that expert problem representation was often based on more abstract and functional relationships than on the superficial attributes used by novices.

As discussed fully above, Larkin (1983) showed that problem representation differed significantly between experts and novices, with novice representations consisting of real-world objects and expert representations consisting of both these and "fictitious" technical entities, though such technical entities nevertheless tended to be based on imagable constructs.

Differences in Reasoning

Larkin, McDermott, Simon and Simon (1980) showed that, while solving problems in physics, experts tended to reason forwards from the data at hand, using appropriate physics principles, while novices tended to work backwards from a stated goal or unknown value in an equation, sometimes in more or less trial-and-error fashion. Similarly, Patel and Groen (1986) found that cardiologists making a correct diagnosis from a written description of a case used bottom-up (i.e., from the data given) forward reasoning, while those with inaccurate diagnoses (also experts) used a mixture of backward and forward reasoning. (In more design-oriented tasks, such as computer programming, such forward reasoning may not be possible, and even experts will need to work backwards from a goal; see Koedinger & Anderson, 1990, for a brief discussion.)

Naive Theories

There has been considerable research aimed at showing that novice performance can be explained by appeal to consistent naive theories that result from innate cognitive structure and/or everyday experience. In a series of studies, McCloskey and others (McCloskey, Caramazza and Green, 1980; Caramazza, McCloskey and Green, 1981; McCloskey, 1983) have provided evidence that people develop through everyday interaction a naive and consistent theory of motion that is, however, inconsistent with the laws of physics, and in fact resembles a pre-Newtonian physical theory ("impetus theory") developed several hundred years ago. These studies have shown that this theory is strongly held and not easily changed, as demonstrated by its persistence even among college physics majors.

Additional evidence for the existence of such naive theories is provided for Aristotelian dynamics by diSessa (1982) and White (1983); for wheel dynamics by Proffitt, Kaiser and Whelan (1990); and for naive statics by Roncato and Rumiati (1986). In addition, several researchers (e.g., Wellman and Gelman, 1988, and Keil, 1989) have made the related case for the existence of consistent (if scientifically inaccurate) theories in the reasoning of young children.

Kaiser, Jonides and Alexander (1986), examining McCloskey's initial findings, present evidence that naive subjects were more successful with similar motion problems when the problems evoked familiar motion events and were less artificial (though formally equivalent) to those in McCloskey's work. Kaiser et al. also found that such success failed to generalize to the more abstract problems.

This leads Kaiser et al. to propose a two-stage approach to solving such problems: first, subjects search for a solution based on past experiences; and then, only if that fails do they go on to draw on often faulty formal theoretical notions. Given such a model, the ability to solve familiar problems does not benefit later attempts to solve more abstract and artificial ones because the familiar ones, solved on a very concrete level, do not provide for the sort of similarity mapping to the formal (non-concrete) analysis of the abstract problems that analogy-based transference would require (as laid out, for example, in the discussion of reasoning through analogy by Gentner, 1982).

Similarly, Roncato and Rumiati (1986) speculate that naive concepts are "procedurally encoded" (to use the distinction between procedural and declarative knowledge discussed by Winograd, 1975, and others), making them both efficient and resistant to change, and are used whenever a problem situation either resembles the context of acquisition of the naive concepts or when the taught, formal (and putatively "declarative") knowledge of the situation is incomplete (as would be for McCloskey's novice subjects).

When Experts Don't Do Better than Novices

Expertise does not always result in better performance. Frensch and Sternberg (1988), studying the effect of variant bridge rules on novice and expert players, found that experts adapted more poorly to a deep structural change in the game than did novices, causing them to conclude that the increased proceduralization and automatization characteristic of expertise (as demonstrated, for example, in Anderson, 1983) can in certain cases result in less flexibility for experts in the domain of expertise.

Adelson (1984) showed that novice computer programmers can outperform experts when the task is oriented around the surface structure of a program rather than the deeper, more abstract structure that other studies have shown to characterize and perhaps explain some of the success of experts.

Finally, Lewis (1981) found little difference in the performance of novices and experts in the solution of algebraic equations, observing that the numerous mistakes of experts may be due to the lack of incentive to excel at the relatively mundane task of solving equations.

Despite showing poorer or unimproved performance by experts, none of these studies actually contradict any earlier work but, in effect, demonstrate situations in which the characteristics of experts believed instrumental to their success are either irrelevant or tend to work against them.

Other Explanations of Novice/Expert Differences

One possible explanation for some of the demonstrated differences between novices and experts is a difference between such groups in individual attributes other than expertise, particularly differences in aptitude. However, Schoenfeld and Hermann (1982) studied students before and after a course in mathematical problem-solving (together with students in a control group that were enrolled in a different course), and demonstrated that the perceptual changes characteristic of expertise were produced as a result of the students' acquisition of expertise. Ceci and Liker (1986) also showed that aptitude (specifically, IQ) was unrelated to the complex expertise demonstrated by expert horse race handicappers.

Philosophical Perspectives

A question to be considered is what sort of causation or kind of explanation is being appealed to in the claim that explanatory constructs must be perception-based. There is today no clear philosophical consensus on the concepts of causation and explanation. Following Boyd (1991), we can sketch out three broad approaches in recent philosophy of science on the general nature of scientific knowledge and explanation: (a) logical empiricism (sometimes known as logical positivism), (b) scientific realism and (c) constructivism.

Logical empiricism arose early in the 20th century as a descendant of an empirical tradition going back at least as far as Hume. A central tenet of logical empiricism is verificationism, which grounds the meaning of a theory or explanation "with the set of procedures by which it can be tested and thus verified or disconfirmed" (Boyd, p. 5). References to unobservables or metaphysical entities are considered meaningless; the content of scientific theories is to be found strictly in the predictions of observable phenomena. Any unobservables that are used in the theories are simply models assisting in such predictions; no existential weight is given to the unobservable objects (e.g., atoms) of these models. A closely related point of view, operationalism, attempts to formally define theoretical terms by the laboratory procedures or operations that measure them and that, it is viewed, give them their only meaning.

The verificationist (and, more broadly, empirical) view of explanation is often referred to as the "covering-law model of explanation" (sometimes known as the deductive-nomological model), which, as described by Gasper (1991) states the following:

> An event of a certain kind is explained by citing a general law (or laws) that relates events of that kind to events or conditions of some other kind and showing that events or conditions of the latter kind took place or were in effect. (p. 291)

Thus, events are explained by appeal to certain general laws and to background, observable conditions. This is an intuitive approach that reaches back to Hume's assertion that causation is a matter of "constant conjunction," or the idea that "one event is the cause of another . . . [if] events like the first one are always (or usually, or typically) followed by events like the second" (Gasper, p. 290; this is also similar to the common-sense, though, viewed philosophically, inadequate approach to causation based on necessary and sufficient conditions). Within such a model, an explanation has the same structure as a prediction:

> If we have an adequate explanation of some occurrence, then, in principle, we could have predicted it before it actually took place. . . . A theory that provides us with good explanations is confirmed in exactly the same was as one that yields true predictions. (pp. 291-292)

But as Gasper points out, there are several problems with this model, problems now "widely (though by no means universally) regarded by contemporary philosophers of science as decisive" (p. 292). One problem is whether it is really possible to come up with the general laws needed without making mention of unobservable entities or "causal factors" ruled out by the basic verificationist assumptions. A second problem relates to "asymmetries of explanation":

> Many mathematical laws link events in such a way that, given information about either one, information about the other can be derived. Thus, given the laws of optics, the position of the sun and the height of a certain flagpole, we can calculate the length of the shadow that the flagpole will cast. Here, the covering-law model conforms with out intuition that the height of the flagpole explains the length of the shadow. But, given the length of the shadow and the other information, we can equally calculate the height of the flagpole. In terms of the covering-law model,

> the two cases are parallel, yet it seems that we would not want to say that the length of the shadow explains the height of the flagpole. (Gasper, p. 292)

Of interest in this criticism of the covering-law model is the recognition of what could be considered a psychological sense of causation/explanation -- over and above the formalism of the explanation -- that is violated, and hence unexplained by the formal model. In addition, the covering-law model of explanation, with its rejection of unobservables, provides at least indirect support for the importance of imagability, in that one could argue that, to the extent unobservables might be at all admitted, they must be, as it were, observable (imagable) in principle, and unobservable in practice only contingently (e.g., by being too small for the resolution of human eyes).

Today, verificationism and its related forms are far less influential (though the covering-law model continues to have influence even among those who do not subscribe to a verificationist position). The complete elimination of the real existence of all unobservable objects -- the "elimination of metaphysics" -- is considered by many as unacceptable, and attempts to explain and limit scientific practice to specific unchanging procedures is regarded as inconsistent with actual scientific practice, in which scientists are always changing their procedures to improve measurement of "the sorts of theoretical entities or properties reference to which operationalism is supposed to eliminate" (Boyd, p. 9).

One reaction to logical empiricism, and an influential view among philosophers today, is scientific realism, which posits the existence of a reality, including potentially unobservable objects, independent of any particular theory or measurement. A good theory or measurement describes this reality relatively well, while a poor one does not.

From a realist perspective, the sources of explanation are to be determined by the scientific process itself, and may well include reference to unobservable entities (to the extent a good theory is dependent on them) that are considered to be "real," among other naturally occurring objects. Harre (1988) goes further, and points out that, eventually, explanations must terminate (on pain of infinite regress) with objects that have intrinsic "causal powers":

> At the end of every explanatory regress we must perforce shift from causal mechanisms to causal powers. So far as we know there is no further level of "mechanism" which will explain the behaviour of quarks. If they exist then their properties are indeed basic dispositions, unanalysable causal powers. Gravity may also be a referent of last resort,

> explanatorily. To explain the behavior of falling bodies by reference to gravitational potential may be to cite a basic causal power. (p. 142)

The view that explanation is perception-based is especially consonant with a realist perspective that confers an independent physical existence to objects on both sides of an explanatory relationship. Harre makes the point explicitly, observing that real causes, if unobservable, must be imagined (though the example is from the scientific explanation of evolution, a very different kind of phenomenon, a similar point could presumably be pressed about a more immediate physical phenomenon);

> What was the mechanism of evolution ? It was no good making any more observations or collecting any more specimens. If the process occurred at all, it was both too minute in its workings and too diffuse in its temporal span to appear before the eyes of any man. The mechanism, that is the explanation of the change of species, had to be imagined. But it had to be imagined within some conceptual framework, or (if one pays attention to the predominantly iconic modes of scientific thinking . . .), within a system of images which would endow it with existential plausibility. . . . (p. 140)

A second important alternative to verificationism is constructivism, a position most closely associated with T. S. Kuhn (1962). Constructivists argue that scientific observation is itself dependent on scientific theories, and that there is no reality independent of that viewed through a set of socially imposed, theoretical constructions. Such a reality, together with unobservables, is "real" to any individual conceiving it, but it is a reality that is not independent of those constructions, and given, for example, two sufficiently conflicting constructions -- said to be "incommensurable" -- there may in fact be no mutually accepted way of resolving which is correct. According to Kuhn, it just such a conflict between incommensurable constructions or "paradigms" that characterize key revolutions in basic scientific world-views.

Similarly, Kuhn (1977, pp. 24 - 28) has argued that what counts as explanatory is rooted in prevalent scientific theories and, like those theories, has changed over time. In particular, he cites four phases (so far) in causal explanation: (a) the Aristotelian approach based on material, efficient, formal and final causes, an approach which gave way around the scientific renaissance of the 17th century and came to be viewed as so much "word-play"; (b) a mechanical approach that arose with the success of celestial mechanics, in which all causation was eventually traced to some sort of "physical impact"; (c) a mathematical approach which paralleled the increased mathematicization of physics, in which an equation from which effects could be derived substituted for mechanical causation and even eliminated, to an extent, the explicit use of the term "cause"; and (d) a 20th century notion of causation tempered by the probabilities and uncertainties of quantum mechanics, in which, in some cases, the very idea of a cause of an event is completely eschewed.

To what extent each of these causal modes counted as satisfactory explanation also evolved over time, though was ultimately dependent on the associated theory:

> The pragmatic success of a scientific theory seems to guarantee the ultimate success of its associated explanatory mode. Explanatory force may, however, be a long time coming. The experience of many contemporaries with quantum mechanics and relativity suggests that one may believe a new theory with deep conviction and still lack the retraining and habituation to receive it as explanatory. That comes only with time, but to date it has always come (p. 29)

A constructivist viewpoint can also be viewed as supportive of the idea of a psychological basis for a satisfactory explanation in perception/imagability in that reality itself is perceived only through the psychological constraints imposed by theoretical constructions. However, the arbitrary and open-ended nature of these constructions, and the evolving nature of "explanatory force" are at odds with any attempt to fix a limit on what can be satisfactorily explained, and it appears that the possibility of as now unimaginable solutions to problems such as the origin of the universe is perhaps most explicitly embraced by a constructivist viewpoint. Of course, past evolution of what counts as explanatory is no guarantee of its unlimited future success. Further, any constructions would, as Fodor has suggested, still face certain limiting conditions imposed by the existence of some (any) cognitive architecture. Nevertheless, granting the social-conventional and changing nature of what counts as satisfactory explanation in the constructivist point of view would reduce one's faith in the ability to discern those limits.

Moving to less formally philosophic and more psychological work, one finds that the idea of subjective or direct understanding shows up in Gestalt psychology (e.g., Kohler, 1947) and in work in perception and theories of meaning (cf. Lakoff's concept of "experiential understanding in Lakoff, 1987). In addition, there is the specific view that mental images are not pictures subject to interpretation but, rather, directly represent (our understanding of) certain ideas. On this view, images are "embodiments of thoughts" (Reisberg and Chambers, 1986, p. 209), structured if pictorial representations of concepts that by definition cannot be ambiguous or interpreted in multiple ways. Under such an interpretation, the link between imaging and conceptualizing is almost tautologous: the failure to produce an image is equivalent to rather than responsible for the failure to produce a corresponding concept; and claiming the origin of the universe cannot be conceived because no suitable image can be formed only begs the question, being equivalent to claiming no concept of it is possible.

While such an interpretation of images, if true, would weaken the explanatory power of the hypothesis under consideration, it still leaves the impossibility of such images as evidence for the impossibility of the corresponding concepts (though there could be other reasons, presumably, for the absence of images). Such an interpretation also leaves intact the expectation that vivid imagers would view the absence of such images as evidence for the impossibility of the corresponding concepts, and so be more pessimistic than poor visualizers.

Summary of related work

The following is a summary of some of the important points demonstrated or suggested in the work just reviewed:

1. Imagery is frequently used in problem solving, and facilitates learning and recall in many situations. Problem representation and solution of both novices and experts often seems to embrace a perception-based, recognition component.

2. Causality may be a hard-wired basic construct that is directly perceived. Imagery is often used to simulate processes or otherwise demonstrate causal relationships.

3. There is considerable variability in reported imagery vividness, with the likelihood that at least some people do not have visual images at all. Individual differences appear to vary systematically to at least some extent by vocation, though all levels of imagery usage and vividness can likely be found in any occupation and at any level of expertise.

4. Vivid visual imagery can interfere with performance, including verbal or abstract thinking, concept attainment and recall of certain information.

5. The effects of imagery are related not only to vividness but to instructions/readiness to use imagery, to imagery frequency and possibly to unfamiliarity.

6. Imagery appears to play some role in creativity, at least for many, especially in its ability to simultaneously represent many aspects of a situation.

7. Experts are more likely to use forward-based reasoning than novices, to have fuzzier, more complex encodings and to have developed abstractions not available

to novices; however, experts continue to also use simple concepts and examples, and even expert abstractions tend to be image-based.

8. Contemporary philosophy offers no consensus view of causation that would either support or contradict the thesis under consideration, but the scientific realism dominant among professional philosophers is consistent with the view that causal relationships require imagable entities.

9. Psychological structure may in fact limit concept attainment, and such limitations may be defined by the limits set by what is imagable/intuitive. Imagery may be necessary for widespread understanding of a phenomenon from a realistic perspective.

METHOD

Subjects

Eight physicists/astronomers were recruited from Boston-area universities through advertisements placed on department bulletin boards. Subjects were chosen so as to represent a range of expertise, and included one 1st-year graduate student in astronomy, two 4th-year physics graduate students (both with M.S. degrees and additional study in physics), a working astronomer (with an M.S. in astronomy), one ABD physicist, two recent Ph.D's in astrophysics and an astrophysicist who received his Ph.D. in 1985. Several of the subjects specialized in cosmology. There were 6 male subjects and 2 female subjects.

Three pilot subjects, all physics graduate students, were also seen.

Procedure

Sessions consisted of an initial interview focusing on basic questions and reasoning about the origin of the universe, collection of background and biographical information, administration of two visual imagery instruments and, finally, some brief questions about the subject's use of imagery in their work.

Each subject was interviewed/tested once for approximately one hour. All sessions were conducted over the telephone and tape-recorded. Answer sheets (without questions) for the imagery instruments were mailed to subjects in advance, and the tests were administered orally over the phone and answers read back to the experimenter at the end.

Subjects were paid $ 50.

Interview

Following Simon's "think-aloud" approach for extracting protocol data (Ericsson & Simon, 1984) the general approach during the interview portion was to ask subjects to think aloud as they tried to answer questions about the origin of the universe (given the unstructured nature of the questions as compared to most problem-solving, no attempt was made to additionally collect the retrospective reports Simon recommends of how subjects recollect answering the problems). The questions themselves basically consisted of repeated attempts to force subjects to justify or explain the basis of each preceding answer or explanation.

The following instructions (a modified version of the instructions found in Ericsson & Simon, p. 378) were read to subjects at the start of the interview:

> In this first part of the study I am interested in what you think about when you try to answer certain questions about the origin of the universe. In order to do this I am going to ask you to think aloud as you try to answer these questions. What I mean by think aloud is that I want you tell me everything you are thinking from the time you first hear the question until you give me an answer. I would like you to talk aloud constantly from the time I present each question until you have given your answer to the question. I don't want you to try to plan out what you say or try to explain to me what you are saying. Just act as if you are alone in the room speaking to yourself. It is most important that you keep talking. If you are silent for any long period of time I will ask you to talk. Do you understand what I want you to do ?
>
> Good, now we will begin with some practice questions. First, I want you to tell me how many windows are in your house, and tell me what you are thinking as you get an answer.
>
> Good. Now I will give you a more abstract practice question that is more similar to the questions I will

be asking you in the study. Remember to tell me everything you are thinking from the time you hear the question until you're done with your answer. Here's the practice question: Do you think people basically have free will and can choose their own course of action, or do you think everything a person does is caused by some preceding physical state, making free will mostly an illusion ?

Good. Now we'll move on to the study questions themselves. Remember to tell me everything you are thinking from the time you hear each question.

Some or all of the following questions were then asked, with the exact course of the interview determined by the answers given:

1. How do you think the universe began ?

2. [In reply to a Big Bang explanation:] What came before the Big Bang ?

3. [In reply to some sort of Steady State or eternal/ cyclical universe explanation:] What is the original cause of that state (or cycle) ?

4. [In repeated reply to any earlier professed single point of creation or existing state:] What came before that (or what was the cause of that state) ?

5. [Assuming a response that we don't know the answer to that question of what came before or was the cause of

...:] Can you imagine our finding an explanation for this question ? Would such an explanation answer all the relevant questions of physics ? Can you give me an example of what might possibly be such an explanation ? Could any explanation or subsequent explanation answer all such questions of physics ? Would other questions -- philosophical or religious -- remain ? Could we reach a point where all of these questions would also be answered ? (For all of these a "why or why not" follow-up was asked as appropriate.)

6. [Assuming some direct response that the question is solved, either by physics or some professed religious or other belief:] Does that answer fully satisfy you or is there anything disagreeable or vaguely unexplained by it ? Why or why not ? You say you are satisfied with that answer, and that there is simply nothing more to be said -- why doesn't everyone feel the same way ? Would they if they understood enough physics/shared your religious/philosophical beliefs ? Is there perhaps more to know but we somehow can't know it ? Could some more advanced species than us possibly understand truths about this that we can't grasp ?

7. [Assuming some fairly abstract solution that is presented as an answer:] That answer sounds very abstract. Is that really the world or just a useful theory for generating answers to problems ? Is there a sense in which you know it is mathematically correct but it is still

somehow not real, not fully satisfying ? What's missing ? Why do you think that is ? Can you imagine a fully satisfying answer ? Why or why not ? What would one look like ?

8. [Assuming some response that the question is, or we have arrived at a point where the remaining question is meaningless:] Does that leave anything unsatisfied ? Why or why not ? Are people's attempts to find some answer to it just mistaken, a bad habit ? Have we reached a limit where we can't talk meaningfully about this subject any more but there may be more to talk about ?

9. It's been suggested that if the Big Bang is the beginning of space and time, it is meaningless to ask about a cause of it or something before it, since there is no time before it. Do you agree ? Why or why not ? If you agree, does that leave any idea or feeling about a need for explanation that is still not addressed ?

10. It's been suggested that the universe may have originated from a quantum fluctuation occurring in some preceding vacuum, and that a fully developed theory around this idea might present a complete and satisfying answer to how "something" came from nothing. What do you think of that ?

Biographical and background information

The following information was then collected from subjects:

1. Degrees, subjects, dates

2. Area of expertise

3. Self-categorization as theoretical or experimental

4. Self-categorization of level of mathematical expertise for someone in this field (low, medium, high)

5. Religious beliefs; belief in God, divine creation, etc.

Imagery measurements

Subjects were then administered two visual imagery tests. The first of these measured imagery frequency using Cohen and Saslona's IDQ-IHS, the Individual Differences Questionnaire-Imagery Habit Scale (1990, and personal correspondence, October 28, 1991), minus the distracter questions regarding study habits, which would have made individual sessions too long. This scale was constructed by Cohen and Saslona by extracting those items from Paivio's original IDQ (1971) that subsequent testing showed loaded highly on a frequency of imagery factor (Paivio, 1983), and modified by Cohen and Saslona from true/false questions to a 5-point Likert scale to extract more information (as suggested by the revision to the IDQ of Hiscock, 1978). Cohen and Saslona report on unpublished work that shows that the IDQ-IHS has been shown to have good internal consistency and test-retest reliability (p. 103).

In addition, two imagery questions that Paivio's factor analysis (1983) showed to load highly on a "use of images to solve problems" factor (p. 477) were randomly inserted into the IDQ-IHS questions to provide some additional relevant data points.

The IDQ-IHS instructions and questions used appear as Appendix A. The two additional problem-solving questions are questions 2 and 5.

The second imagery test that was administered was Marks's VVIQ, the Vividness of Visual Imagery Questionnaire (1973 and personal correspondence, November, 1991). This test is the most popular measure of imagery vividness and an instrument shown to have relatively good test-retest and split-half reliability (Marks, 1973).

The instructions and questions used for the VVIQ appear as Appendix B.

Imagery usage discussion

Finally, subjects were asked to describe in their own terms their use of imagery in their work and their view (if any) of its importance.

RESULTS

The following describes the interviews, biographical background of subjects, imagery test measurements and imagery discussions, as well as some relationships among those different measurements.

Interview results

This section presents 3 views of the interviews conducted with each subject: (1) a tabular presentation of categorized subject responses, (2) some general summary impressions of the interviews, and (3) a more detailed description of each subject interview, including verbatim excerpts from each interview.

Tabulated results

Each independent relevant belief concerning the ultimate origin of the universe was extracted from the interview recordings and a tabulation made indicating which subjects expressed those beliefs or beliefs nearly identical to them. Any closely related beliefs were then grouped together into a general belief statement and new tabulations made as to how many subjects expressed one or more of the component beliefs in that group. These groups of beliefs, together with those beliefs not placed into a group are shown below with the number and identities (s1, s2, etc.) of subjects expressing the belief or, in the case of a belief group, the number and identities expressing one or more component beliefs (in the latter case, the component beliefs are also shown, together with the subjects expressing each; the group total may not equal the totals of components since a given subject may have expressed more than one component belief):

1. Belief: The problem of the origin of the universe cannot be answered and/or does not even make sense within current-day physics or science.
n = 8 (all subjects)
Component beliefs:

a. This is outside the laws of physics. (n = 4: s2, s3, s4, s5)
b. You can't observe or experiment with what came before the Big Bang, making it not an object for scientific study (n = 4: s2, s3, s7, s8)
c. It makes no sense to talk about it. (n = 3: s3, s7, s8)
d. I can't conceive of what came before the Big Bang. (n = 2: s1, s6)
e. It is not a scientific questions. (n = 1: s3)
f. This stuff is currently unvisualizeable, and I

need a tangible image to be satisfied. (n = 1: s2)

2. Belief: It is possible that this question could be answered sometime in the future or be re-formulated to be more sensible.

n = 6: s1, s2, s4, s5, s7, s8

Component beliefs:

a. We may be able to answer the question in the future.
   (n = 6: s1, s2, s4, s5, s7, s8)
b. We have solved seemingly unsolvable problems in the past. (n = 2: s1, s4)
c. Our intuition can evolve; what seems unsolvable or unsatisfying now may not seem so later. (n = 1: s2)
d. We may be able to decompose the question into intelligible sub-questions in the future.
   (n = 1: s7)

3. Belief: We will never be able to re-phrase or solve this problem scientifically.

n = 2: s3, s6

No components.

4. Belief: There is [however] a valid philosophical or religious question about the ultimate origin of the universe.

n = 7: s1, s2, s3, s4, s5, s6, s7

Component beliefs:

a. It borders on religion/is a valid religious question. (n = 6: s1, s2, s3, s4, s5, s6)

b. It is a valid philosophical question. (n = 3: s3, s6, s7)

c. Saying there is no problem because there can be nothing before the beginning of space-time is contrived, a cop-out. (n = 2: s2, s6)

d. Saying that a quantum fluctuation in a vacuum completely solves the problem is not the end of the story, is contrived. (n = 2: s2, s6)

e. God may have set things in motion. (n = 2: s4, s5)

f. It's a philosophical question but anything is; philosophy has little credence. (n = 2: s3, s5)

g. It points to the current limits of language. (n = 1: s7)

5. Belief: This is simply a meaningless question; asking it is carrying human curiosity too far.

n = 1: s8

No component beliefs.

6. Belief: There are limits to what we can know.

n = 7: s1, s2, s3, s5, s6, s7, s8

Component beliefs:

a. We may not be able to understand everything.

(n = 3: s2, s6, s7)

b. There are always more questions. (n = 2: s1, s5)

c. Science has its limits. (n = 3: s3, s7, s8)

d. One gets caught in an infinite loop of questions. (n = 1: s2)

e. There is always the question of ultimate origin. (n = 1: s7)

A note on the above tabulations: The questions posed aimed to elicit the subjects' thinking on these questions, and were not forced-choice. Nevertheless, if we look at expressed beliefs and their negations we can see that (a) all subjects expressed the belief that the problem cannot be solved today, and no subjects expressed the view that it could; (b) all subjects expressed either the belief that the question could someday be answered (belief 2, n = 6) or that it would never be scientifically answered (belief 3, n = 2), and no single subject maintained both beliefs (though subjects sometimes held related inconsistent beliefs, e.g., in the existence of certain limits, in which case both beliefs are reported above; or responded one way initially, often casually, but then expressed a different belief after repeated questioning, in which case the final expressed belief was generally used); and (c) all subjects expressed either the belief that there is nevertheless a valid philosophical or religious question (belief 4, n = 7) or that there is no such remaining question (belief 5, n = 1), and no single subject expressed both. All subjects but one expressed the belief that there are limits on what we can know (belief 6), though the remaining subject, while not stating this, did not explicitly state that everything could someday be known.

General interview results and impressions

This section describes some of the general results and themes that were present in the interviews.

1. In response to the first question about how the universe began, all subjects led off with the statement that the Big Bang was their current view of the origin of the universe, with many subjects going on at some length about it and offering significant detail. No subjects initially expressed the opinion that the (ultimate) origin of the universe was unknown or not today a valid scientific problem. Rather, all subjects immediately interpreted the question as a straightforward scientific problem whose current best answer was the Big Bang.

2. When asked what came before the Big Bang, all subjects quickly offered some form of the belief that this was not a valid scientific question -- "it's not known," "that's the limit of current-day physics," etc. Some subjects qualified this by saying that that was the current situation, while

others simply and flatly said that the problem was outside of science (though typically retreated after later questioning to the more qualified view).

Many subjects quickly offered that the question was more properly a part of or bordered on philosophical or religious questions, though only a few indicated they had seriously thought about it or considered the question significant, e.g., one subject said that, since it was not part of science, one's view of that question today was simply a matter of "taste." Other subjects clung at least for a while to the idea that this was simply a non-scientific question, or that, scientifically speaking, there was nothing before the Big Bang, and that that was all there was to it.

When asked if this view of the problem was satisfying, most subjects indicated that it was not completely so. However, interestingly, no subjects indicated this was a burning or particularly significant question for them. Rather, the lack of satisfaction expressed was usually tentative (at least or especially at this early stage of the interview), almost an afterthought, and sometimes explained away by the admission that science, after all, has its limits.

For some subjects this problem of understanding what came before the Big Bang was related to the difficulty of producing a testable hypothesis, or having anything to observe. Without observation or experimentation, these subjects felt there could be no science, and hence no scientific problem. These subjects had essentially a "black box" view of science: there were observations and laws derived from them that let you put numbers into equations and predict results. There was, in this model, little role for questions of meaning or ultimate significance, even if these same subjects accepted that such questions might have some validity outside of science. While some subjects did not mention the importance of observation or espouse this black box view of science, no subjects contradicted it.

A few subjects immediately saw and raised the conceptual problem of identifying a fundamental cause, raising concerns of "infinite loops" and endless questions about what came before.

3. When pressed about whether there was nevertheless a valid philosophical or religious question, almost all subjects (n = 7) expressed the view that there was, even if it was not today within science. However, it often took repeated questioning for subjects to leave the scientific perspective and consider the problem seriously from a philosophical or religious perspective, sometimes even if they had originally stated in an offhand manner than the question was more philosophic than scientific. Two subjects

placed very low value on this (e.g., s3: "You can never prove anything in philosophy or ... religion.... Religion and philosophy can basically say anything.") but most seemed (at least eventually) to attribute some weight or force to the philosophic/religious puzzle that remained, though the amount varied from subject to subject.

The one subject who has been tabulated as not expressing the belief that a valid philosophical or religious question existed was not completely unequivocal about this. However, such equivocation as there was came mostly in response to fairly repeated pushing, and did not seem to be the subject's true view. Also, the amount of support for viewing this as a valid question was, even then, qualitatively less than from any other subject.

No subject suggested there was a clear philosophic or religious answer today to these questions. The two subjects who mentioned God as a possible solution did not offer this as a definitive explanation but rather as a possible explanation for whatever philosophic/religious question might remain after future scientific successes.

4. The question about whether there might someday be a solution to this problem evoked some confusion or conflict in all subjects except s8 (the one subject who fairly consistently denied the existence of a substantive

problem). This often recalled conflicts over the earlier question of what came before the Big Bang, and took the form of subjects being more tentative (including those who had been very confident up to that point), sometimes changing their mind, or actually holding what appeared to be inconsistent beliefs. Here's a quick run-down of the kind of conflict that was observed, by subject:

> Subject 1: Couldn't conceive of an answer but explicitly thought that that collided with intuition, that maybe there could be an answer if we saw the world a different way.

> Subject 2: Had faith and a positive desire that there could be an answer, as there has been for other problems, but kept running into the unique limitations of this problem (e.g., what set these laws in motion); still, said his mind resisted copping out.

> Subject 3: Very dismissive of the problem initially: sounded relatively satisfied, the idea of a quantum fluctuation seemed like a possibility, saw a philosophical problem but a fairly trivial one. But then, after 20 minutes, slowed and got more tentative, and said the solutions discussed only seemed to push the problem further back.

Subject 4: Saw the problems as practical, thought it might be solved in a billion years; then said the question of who put it there would remain; and then later said that maybe there could be a solution after all.

Subject 5: Thought it possible to solve, but, after probing, started to ramble and become somewhat confused about the problem being discussed.

Subject 6: Thought maybe 'nothing' was the whole answer, but then, on reflection, thought that couldn't be it, that 'nothing' was a cop-out; then thought maybe she wasn't the right person to answer the question.

Subject 7: Thought the question well-posed philosophically, that progress was possible; after 15 minutes, however, thought the question could never be answered, but then, finally, thought that maybe it just barely could, that the limitations were just those of today.

Abstracting from the above, we can see two general classes of responses: (1) subjects who fairly directly perceived an unresolved conflict between current scientific doctrine (which they generally accepted, and which rules the problem out of bounds) and their intuitions or desires about the extent and solvability of this problem; and (2) subjects who generally started responding within a relatively narrow scientific perspective (that was, given current doctrine, largely indifferent to or dismissive of the problem, or perhaps hopeful of an eventual solution) but then, usually after 15 or 20 minutes, became more tentative and open to the difficulties of the problem, almost as if their habitual scientific manner had been worn down and they were seeing the difficulties of the problem for the first time, or perhaps facing it anew without the defense of their training and work.

In both cases the conflict was apparently sufficiently unresolved to have many subjects embrace one position and then another, only to perhaps return back to an earlier one, while other subjects became obviously confused, or engaged in some form of self-doubt about their ability to competently answer the question.

Ultimately, most subjects (n = 6) expressed and seemed to maintain (however slightly) the belief that, despite their current scientific assessment of the question as meaningless or unsolvable, it might indeed be answered in the future. None of these subjects had any particular expectation of what such a solution might look like (though some referred to Stephen Hawking's theories), or even much confidence that this would be the case (there was some variation here, with one or two subjects willing to throw out time periods -- "a hundred years" -- after which there might be some more insight, but all subjects were essentially non-specific about future success). Rather, there was simply the belief that it could happen, substantiated primarily by the fact that "anything is possible," or that difficult problems had been solved before (a few subjects explicitly mentioned other difficult problems that had been solved despite seeming very hard at the time). This belief in a possible future solution was expressed (inconsistently ?) even by the one subject who saw not only no valid scientific question today but not even a meaningful philosophic or religious question, though such a possibility of an eventual solution (to an eventual problem) was considered to be little more than a possibility.

Such beliefs in at least the technical possibility of a solution to this problem were all the more remarkable in light of the fact that most subjects expressed some view that science had its limits, or that there were questions that could not be solved; and, obviously, these sentiments arose in response to discussion about understanding the origin of the universe. It appears, however, that, although subjects believed in the limitations of science, the power of past scientific success was too great for them to label this (or perhaps any particular) problem as unsolvable; science may have its limits, but we cannot, as it were, know what it is those limits prevent us from doing.

The limitations of science were, in fact, frequently seen as a good thing, with several subjects mentioning that they hoped all questions could not be answered, since that would be the "end of science," a distinctly uninteresting and unappealing state of affairs for them. (Again, the impossibility of knowing which questions are unsolvable seems implicitly important here; if one know certain questions to be unsolvable, they would not be very good subjects of investigation, and would hardly help keep the scientific endeavor going).

5. Most subjects seemed unfamiliar with or uncomfortable focusing on what they saw as the essentially non-scientific (at least today) question of the origin of the universe. Many subjects kept drifting back to related but narrower and more directly scientific questions, or otherwise had trouble staying focused on the questions at hand. Some subjects openly expressed or conveyed by their tone or speech their disdain for what they might be forced to admit were valid philosophical or religious questions.

6. There was some use of visual language during the interviews ("picture," "can't see anything there," etc.),

but as the tabulated results show only one subject volunteered the statement that visualization was directly connected to problem difficulty. (More information on the role of visualization came out when subjects were directly asked about their use of imagery during the imagery usage discussion at the very end of the session; these results are reported below.)

Psychological processes in interview responses

A principal hypothesis of this study was that a psychological individual difference factor -- visual imagery frequency and/or vividness -- would be related to subject perception of the unsolvability of the problem of the origin of the universe because of an underlying connection between adequate physical explanation and imagability. One subject did specifically mention the need for, and difficulty (if not impossibility) in this case, of an adequate visualization for satisfactorily solving this problem, and a few subjects made at least some use of visual language. However, there was no clear or general relationship observed in the interview portion of the study between difficulties in imaging a possible solution and perceived problem unsolvability.

However, the hesitation, inconsistency or outright reversal of opinions (or combinations of these) described in the previous section and that was seen to some degree in nearly all subjects suggests the presence of some significant psychological process(es) beyond a simple problem solving effort motivated by the study setting, even if this process is not obviously connected to subjects' use or vividness of visual imagery in thinking about this problem. What, we may ask, is going on psychologically as subjects struggle with such obvious difficulty or lack of consistency to voice their opinions on the questions asked ? We can make the following observations:

1. Most subjects approached what initially appeared to be directly scientific questions (e.g., How do you think the universe began ?) at least initially and often for some time with the scientific style and assumptions one would think appropriate for such questions and which we would in any case expect to be habitual as a result of their scientific training and/or professional work, possibly further motivated by the knowledge that they were solicited for this study specifically because of that scientific training, e.g., when asked how the universe began, several subjects launched into fairly lengthy and detailed explanations of the Big Bang and the events immediately following it. However, the questions posed are better described as, and sooner or later came to be seen more

accurately as meta-scientific (e.g., Is a solution to this problem possible ? Is such a possible solution completely satisfying ? etc.) This shift in the nature of the questions being asked and the need to draw on information or opinions outside of their scientific training per se might by itself reasonably be expected to produce some hesitation and uncertainty in subjects as they re-oriented their thinking over the course of the interviews.

2. The repeated questions about what came before the Big Bang revealed a further and less easily resolved conflict in that, for all subjects but one (s8) there was, sooner or later, a perceived inconsistency between scientific doctrine -- which subjects indeed believed made the question of what came before the Big Bang meaningless or unanswerable (or at least non-scientific) -- and their meta-scientific (or directly philosophic) beliefs or intuitions that a meaningful question remained. The belief in scientific doctrine was typically dominant (as might be expected through sheer force of habit as well as conscious belief and motivation) and often made more difficult the eliciting of the meta-scientific beliefs and intuitions, which in some cases had apparently not been given much consideration before; in other cases, though, the subject was aware of and explicitly stated the conflict, e.g., subject 2 slowed when asked what came before the Big Bang, said that that couldn't be determined and that there was

"no justification in logic" for an answer but said that he had "faith" that the "artificial boundary" could be broken, adding that he has the "intuition that time exists outside this universe," but that that intuition "may be false."

The reasoning behind the hypothesized connection between imagery frequency/vividness and belief in unsolvability would also seem to apply to the relationship between visual imagery and the extent to which subjects believed there to be a valid (unsolved) problem there at all: given a basis for physical explanation in imagable constructs, frequent or more vivid imagers would presumably be more sensitive to the lack of adequate image-based explanation contained within the mathematics of the Big Bang (as well as more pessimistic about eventual solvability because of the difficulty of finding any other image-based solution). Viewed another way, a measure of one's view of the problem as unsolvable is obviously influenced by the extent to which one considers the problem substantive (or already solved!). As a result, given the somewhat unexpected unanimous belief that science indeed says there is nothing before the Big Bang, and, in that sense, declares the problem solved (or a non-problem) and the variation in the extent to which individuals nevertheless perceive there to be a valid (unsolved) problem we can use that variation as a further component of a more broadly conceived "unsolvability" measure in the correlational studies with the visual imagery measures presented below.

3. The repeated questions about whether a complete solution would ever be possible provoked for nearly all subjects a second conflict between two inconsistent, but, in this case, both meta-scientific beliefs: that a complete solution to this problem was not possible, and that, on the other hand, one could not say that any specific problem was beyond the reach of science. The latter belief was, as might be expected, more accessible and dominant, if somewhat superficially maintained. For example, subject 4 said the question could never be answered completely, but then added, somewhat emptily, that maybe there'd be enough physics to tackle the question in "a million years"; subject 2 said that physics teaches the importance of analogy, and since similar hard problems had been solved, it might happen here -- but he couldn't really see how.

4. In general there was considerable macro-level uniformity in the meta-scientific views expressed about problem existence/unsolvability (despite the measurable variations in the strength of these views), suggesting a possible common factor underlying them. Although their was no obvious role that visual imagery played in the interviews, it is worth pointing out that this does not rule out visual imagery as being that factor, since the hypothesis in

question does not require any explicit mention or use of imagery in reasoning about this problem, but only differential sensitivity to unsolvability based on underlying imagery competencies. Further, a very strong relationship between visual imagery and problem unsolvability might actually suggest that basic visual imagery competencies would be sufficient to produce fairly uniform views on problem existence/unsolvability (as were found here), providing good confirmation of that relationship only in the differences revealed in rank order correlations or in extreme or infrequent cases.

Interview details

Below are detailed descriptions of each of the interviews, including information about the tone and general state of mind of each subject on these questions. Selected literal excerpts are presented as well. Subjects are presented in numerical order. The first 7 subjects thought the question of what ultimately came before the Big Bang non-scientific (as all 8 subjects did) but still valid or well-posed in some sense. Subject 8 is the lone subject who did not consider the question meaningful in any way (at least today).

Each subject is identified by subject number, followed by a brief description of the subject's experience level, self-categorization as experimental or theoretical (many volunteered "observational" as a third option, since this better characterizes the work of most observation-based astronomers, who cannot really be said to "experiment" with their objects of study), self-categorization as to relative mathematical expertise (low, medium, high) and gender.

Subject 1 (4th-year graduate student, experimental, medium math, female):

When asked what came before the Big Bang, this subject expressed the view that that could not be imagined or really conceived of, while at the same time feeling that that was a limitation of tools or science, and not an absolute limitation on what was true, or could be known. Unlike most subjects, the subject then immediately started to struggle in a groping and tentative way with what she saw as a clash between science (or mathematics) and intuition, and voluntarily suggested that religious or philosophical questions remained:

> I can't conceive of anything that came before it.... I can imagine finding an answer to things that I find inconceivable ... but, well, I don't know if imagine is the right word.... I can't really imagine it... There's always religious questions.... I don't have the tools to imagine it but if there was some way of understanding the world in a way different than the

> way we see it then maybe there'd be a way of understanding what came before the Big Bang.

The subject expressed this sense of scientific limits consistently throughout the interview. When asked about whether an answer would be possible in the future, she fairly quickly gave the response that it was a possibility but only that, saying "maybe God could explain it." When then asked as to whether that would indeed answer all questions, she indicated how slight she viewed that chance by quickly stating that she thought that you could probably never get a final answer to this question, that there would always be more questions:

> If we understood what was here before our universe we would then have more questions about whatever that was.... There'd always be more questions.

<u>Subject 2</u> (4th-year graduate student, experimental, medium math, male):

This subject was very confident, and began with the statement that, having taken lots of relevant courses, the (first) question of how the universe began did not throw him. He went into some detail, including the statement that he "immediately think[s] of a small point."

When asked what came before the Big Bang, he slowed down considerably and said that that couldn't be done, that the laws we have now don't work for that problem, that we "must speculate," and that "confusion reigns." He also quickly volunteered that some people would invoke God at this point, but that that wouldn't end the questioning:

> I feel like that's the sort of question which in some ways isn't possible to model.... One tries to invoke things like God, what came before Him and you sort of get caught in this logical, infinite loop trying to figure out what happens before a given event.

Despite the above, the subject was hopeful, saying that, though there was "no justification in logic," he had, as part of his "belief structure," a "faith" that we could "break this artificial boundary." This hope, however, kept running into what seemed to be the limits on this particular problem. For example, the subject pointed to mathematics, saying that, as it can describe an intuitive picture, so it can also describe an unintuitive picture, leaving open the possibility that intuition could then evolve to follow where the theories had led. He said this happened for him in quantum mechanics, that he went from no intuitions about it to some sort of intuitive understanding. However, when asked to (in effect) confirm that he was saying it would or at least could also happen in cosmology, there was a long pause, after which he said that physics teaches the importance of analogy, and that since this has happened in the past, he must admit it could happen here; but he couldn't really see how.

Part of the reason for this appeared to be the apparent impossibility of ever being able to test an ultimate cosmological hypothesis in a way comparable to the experimental confirmation of quantum mechanics. He emphasized that a fully satisfactory answer must be associated with "testable" results, something mentioned by a number of subjects.

Nevertheless, the subject repeatedly affirmed at least the meaningfulness of the problem. When asked if some theory based on quantum fluctuation in a vacuum preceding the Big Bang might be a complete explanation, he allowed the possibility of such a theory though added "but what set these laws in motion ?" Similarly, when asked whether the Big Bang, as the beginning of time itself, in fact made the question of an earlier event meaningless, he indicated that that was true but that the question was meaningless only because there was "no context." The question, he said, is nevertheless "well-posed," and "[his] mind resists copping out." The tension with a science that today cannot address the problem and suggests the problem may not even be meaningful remains close at hand, however; the subject stated that "I have the intuition that time exists outside this universe, but that may be false" (though his suspicion of the falsity of that particular intuition does not seem to extend more generally to the suspicion that there is no valid problem there at all to solve about the origin of the universe). At this point the subject, in halting speech, volunteered (as if to further explain his uncertainty and clash between science and intuition) that he accepts the idea that he might "not [be] capable of understanding everything," adding that the ideas of Godel (who proved the incompleteness of ordinary arithmetic) came to mind.

The subject also volunteered that, in any case, a purely mathematical solution would not be good enough. He said that, while he has friends for whom "equations are enough," he required some visualization of the underlying concepts: "just the equations don't do it for me." This was the one subject who volunteered during the interviews that visualization was necessary for conceptual understanding.

<u>Subject 3</u> (Ph.D., 1985, observational, high math, male):

Subject 3 was one of those who initially stayed fairly strictly within the confines of science, nodding towards a possible philosophical question but initially giving it very little weight, and only much later backing off of the scientific perspective and giving the difficulty of the problem greater due. Even then, however, the subject stayed fairly much within the scientific perspective, making this subject the least accepting of the significance of this philosophical question of those 7 (of the 8) subjects who at least admitted the existence of such a question.

When asked at the start what came before the Big Bang, this subject stated more than once that it didn't make much sense to talk about what came before the Big Bang:

> That's outside of science.... It's a philosophical or religious question.... I think strictly speaking that scientists would say there was nothing before the beginning ... and that's it.... As a human being ... you still think about it.... I don't think there are really limits on a philosophical question.... I think in science you do have limits.

This subject then expressed the importance of observation and testing for anything scientific, stating that "you have to be able to experiment," and that this gave "only science" the ability to be definitive, adding that you can never prove anything in philosophy, that science was just a "black box" into which you put in numbers and got answers (implying deeper understanding was not the point), etc. The subject offered that (lay) people don't have a problem with the universe being finite in extent (which is fairly dubious) but only with there being no "before," but that the latter was as much a fact as the former.

When asked if he was personally satisfied with this, the subject repeated that one couldn't help thinking about it, but actually sounded quite satisfied that, despite such random thoughts, the matter was closed. He offered at this point that there was "enough to investigate in the first second... an infinite amount... enough to keep [him] ... happy," suggesting by his tone that investigation into what came before the Big did not much tempt him, and was perhaps wasteful given all the tractable problems one could address.

The subject was then asked what he thought about the theory that the Big Bang might have arisen from a quantum fluctuation in a preceding vacuum. The subject said that was a possibility, and connected it to some other theories (about "baby universes") he had mentioned, elaborating with additional technical detail. The subject was then asked whether a fully developed quantum cosmology, should that be produced, might in fact solve the problem completely and fully, answering any imaginable questions about the origin of the universe. At this point, about 20 minutes into the interview, the subject rather doubtfully said "yeah, I don't know," and then laughed, stating that that would only push the problem further back. When then asked again if this was (now) a problem outside of science, the subject for the first time hesitated and said he didn't know, though he continued to phrase the problem in scientific terms (e.g., in terms of a finite or infinite universe, "baby" universes breaking off from larger ones, etc.). When asked if he was therefore saying a complete answer was at least possible, he responded unequivocally that he hoped not (and presumably thought not), that "there'd be nothing left to do." When pressed, he said it was a philosophical question, but with little of the offhand dismissal that this judgment produced at the beginning of the interview.

It was clear, though, that the subject did not move naturally towards or enjoy this philosophical view of the problem, preferring to stay immersed in what science had to say and could profitably study about the problem, and still treating the non-scientific aspects of the problem disdainfully (because they could not be definitively solved), if not as dismissively as before.

The subject finally offered that we'd never understand everything, a position that only this and one other subject consistently maintained. However, even after making this admission, the subject again showed his embrace of the scientific endeavor and, in a sense, his disdain (vs. the real perplexity or awe shown by some other subjects) for this hard limit by stating again that it would be "very boring" if we ever did, negating the import of the limit by implying that he'd just as soon have it and be assured of problems to tackle.

<u>Subject 4</u> (recent Ph.D., theoretical, medium math, male):

When asked what came before the Big Bang, this subject said that "that's an interesting question," that, mathematically, "there doesn't have to be an answer" and that science starts to break down at that point. He fairly quickly raised the possibility of a cycle of creation and destruction, but as quickly observed that that doesn't really answer the question, adding that philosophy and religion come into play and that, for now, it was a matter of "taste." Throughout this opening set of statements the subject was calm and matter of fact, and while pushing the question out of physics and into philosophy or religion, there was no particular sense that the question was permanently unsolvable:

> The question would be valid to ask ... where it started ... like what put this whole thing in motion. I think it starts to border on the religion question. You run into problems with present-day physics.

The subject was then asked whether there could ever be a possible solution to this problem in science even though it was today not a question that science could address. His initial response focused, as did that of several other subjects, on the need of science to perform observable experiments, stating that it was a "tough question" because you would need such very high energies to, in effect, perform experiments comparable to what happened at the origin of the universe, and it was unclear that, as a practical matter, such energy requirements could be met (in fact, the subject then said they could not, and that the universe was unique in that respect). There was little concern, though, for any inherent conceptual problem. The subject did say that there was a problem with quantum mechanics breaking down at the point of the origin of the universe, but he nevertheless felt that the problem was, "in principle," solvable some day if somehow the question of energy requirements could be met or sidestepped.

The subject was then reminded about his earlier statement that this was a matter of taste and asked if he was indeed saying that the problem could at some point not be a matter of taste but be solved. He answered that he did, that in one or two billion years, we would know whether the universe would expand forever or contract, etc. and the question could be answered.

The subject was then reminded of the point that there seemed to be an ultimate question of what or who put things in motion, and was asked whether that too could be answered. The subject first replied that, while it started to "border on the religious question" that, yes, there might be some framework for answering the question in the future. However, for the first time (some 15 minutes into the interview), the subject then said that that still wouldn't answer the question of "who put it there," and that that question could never be answered:

> That question will never be answered completely because obviously if you ... have nothing then presumably you won't get a lot of something.

Inconsistently, however, the subject then turned around and offered that, maybe in "a million years" there might be enough physics to tackle this problem.

The above shows the difficulty this and some other subjects had both in keeping focused on the question of an ultimate and complete explanation, rather than even slightly (but decisively) more tractable physical questions, and on deciding whether that question was in fact permanently unsolvable. In part this seemed for this subject (and others) to reflect a genuine uneasiness over whether there really were such unknowable questions (as reflected by the professions of possible solutions in the future, even if these couldn't be imagined), while at other times it seems more to reflect the subjects' natural predilection to focus on more tractable, less-than-ultimate problems and not concede anything as permanently unsolvable (as evidenced by the eventual admission by most subjects of an inherent limitation on what could be known even as they continued to drift back to questions that perhaps could be answered or espouse the possibility of future solutions to the problem at hand).

It may also be that some of the ambivalence shown by this subject was due to heretofore unarticulated religious beliefs, since, when next asked about the possibility of a complete explanation based on a quantum fluctuation in a vacuum, the subject replied that, if things were set up like that, then "God set it up" and just put things in motion, not worrying about any of the resulting details. When pressed as to whether God was a necessary part of the explanation for the origin of the universe, however, the subject replied that He was but (only) at present, which is consistent with his view that the question might someday be addressed by physics (though, again, he also expressed the thought that it could never be addressed).

<u>Subject 5</u> (recent Ph.D., theoretical, medium math, male):

This subject had the most explicit religious beliefs of any subject (and also had the most rambling and difficult to comprehend musings about relevant or possible scientific theories, not because of the difficulty of them per se as much as a lack of coherence; this may be due in part to this subject taking much more seriously than others the instructions to think aloud). In response to the first question of what came before the Big Bang, the subject said that there was no answer within science, that, as a Christian, he would say that the arbitrary starting point may have been caused by God, but that anything before that was just not in the realm of science. When asked if an answer could ever be found, he initially said no, repeating that it was not a scientific question; but then, after a pause, said that there was perhaps one possibility:

> That's not within the realm of science.... There's a certain arbitrariness which is not within the realm of science. I don't think there could ever be a scientific answer to that.... There is one possibility ... not within the near future.... I do not believe it will be within our grasp even within a few hundred years....

This "one possibility" was never fully explained, but related to the abstract possibility of an equation with no "free variables," i.e., one in which all values were fixed. The subject went on at length about the possibilities pro and con for such a scientific or mathematical solution before finally ending up (as the above quotation shows) on the side of thinking it was not possible, though this did not seem to be a very firm conclusion.

At this point the subject offered that:

> I think every religion has an answer.... I would say ... philosophy is totally ... doesn't have any credence at all.... Whatever philosophy would say there's nothing to back it up.

The subject added that any scientific answer would be too complex to accept (which is slightly different than his earlier statement that none would be possible). It then became clear that the subjects' musings had become focused more on the possibility of some all-encompassing theory of physics (referred to in physics as a "TOE" or "theory of everything") rather than the potentially narrower problem of the origin of the universe. When this was pointed out to the subject and he was asked to focus on the possibility of a solution to the narrower problem of origination, he responded that, yes, that was a "much simpler" problem and one that it was possible to someday solve.

When then pressed about whether such a solution would really end the cycle of potentially endless questions, he slowed and started rambling again about very abstract technical problems, without seeming to ever come to an answer. He mentioned Hawking's theories and said that they were "very weird."

The question was then re-posed to him as why there was something rather than nothing. His response to this was that it was "almost philosophical," and that there would, indeed,
never be a scientific answer to that (though he earlier said there was such a possibility, and he presumably retained certain religious beliefs that were relevant to the question).

<u>Subject 6</u> (M.S., astronomer, observational, medium math, female):

This subject was fairly low-key, and was one of those to quickly embrace the difficulty of the question of the origin of the universe, admitting that she had considered the problem. She also was one who quickly saw a valid philosophical problem, though, like most other subjects, she vacillated some on the prospect of a scientific answer. She also had more critical views of the practice of science that the other subjects (perhaps because of her status as a working staff practitioner rather than a more academically oriented Ph.D.). Here are her initial comments about the question of what came before the Big Bang:

> It's certainly something I think about and talk about with other scientists.... It's very much a philosophical question.... I think it's an area where ... most of us don't really want to tread because ... it borders on the religious....

The subject then added that maybe the answer was that there was simply nothing before the Big Bang. However, after a short pause the subject then said that, no, she guessed she didn't think we'd ever find an answer, indicating that some questions have no answers and are just "too big to think about." When then asked if she thought there was a valid philosophical question there, she quickly asserted "absolutely" (this apparently being the resolution of her tension that there was a question to answer but, after reflection, no scientific answer forthcoming), adding that that was where a solution might come from. She then added that "I don't think that the answer will necessarily come from science," but qualified that with the statement that, if there were such an answer, it wouldn't be in the next 100 years.

The subject was then asked to clarify whether she thought there could ever be a scientific answer to this question. After a long pause, she said that, sometimes in science a difficult question is explained away by an exotic answer, perhaps so the answer would not be challenged. She said she could perhaps give such an answer but she would be "bullshitting." She herself thought that for questions like this the simplest answers are often correct, and, after some reflection, said she guessed she couldn't really conceive of one, making her one of just two subjects who did not seriously maintain that a scientific solution was at least possible (though the vacillation is clear).

She was then reminded of her earlier response that perhaps the answer was that there was nothing before the Big Bang (which she had also earlier moved away from, but now sounded still equivocal about), and asked to clarify whether or not that could be the answer. After a pause, she said she thought that such an answer would be a "cop-out," but was clearly still somewhat equivocal, adding that, though this was her view, she felt she was "dancing around" the answer, and that the questions were perhaps better posed to particle physicists than to astronomers like herself.

This subject shows clearly the tension some subjects felt between official doctrine (which states, for the most part, that there is nothing before the Big Bang, not even time) and the problems or intuitions that subjects felt still remained (though they could conceive of no solution for them), though it often required persistent questioning and/or some visible effort to admit that (effort which, for this subject, was accompanied by some amount of hostility to the official doctrine and/or perceived official practices). The subject was also quite open about something observed in but not directly expressed by other subjects: that physicists or astronomers would just as soon stay from these problems precisely because they seem to be outside of science and border on philosophical or religious questions.

<u>Subject 7</u> (ABD, theoretical, high math, male):

This subject stayed fairly faithful to the idea that what came before the Big Bang could not be meaningfully talked about today, that there was a problem with, specifically, the language of such questions, but that he found this less than completely satisfying:

> I guess I don't think that question makes sense since I don't know how to define time before the Big Bang, because I think that the Big Bang was essentially the origin of what we call time.... I wouldn't say [that's] completely satisfactory.... Right now it's very difficult to frame a ... well-posed question that might be answered.

When asked whether there was a valid philosophical question there, the subject replied that he thought discovering the existence of life on other planets would have philosophical implications. This was not, of course, the question that was being asked (and perhaps reflects the lack of familiarity or focus of this and other subjects with the question at hand). When the question was then repeated and clarified to pertain to the question of what came before the Big Bang, the subject agreed that this was a valid philosophical question, and tied it to the problem of how to talk about what came before the Big Bang:

> I think it's well-posed philosophically... in the sense it's putting the finger on precisely where our language breaks down.

The subject added that he hadn't really considered this question much before (confirming the above observation about the subject's familiarity with the problem) though he had considered the problem (apparently related in his mind) of why we live in the number of dimensions that we do (this can perhaps be viewed as a somewhat similar but less "ultimate" question about why things are the way they are).

When asked what he thought about there being no time before the Big Bang (which he had himself raised before) and hence no possibility of a cause, he concurred, repeated that the questions were simply meaningless, but again qualifying that by saying that that was how it was today, the way we currently understand those things. When asked if there could ever be a context in which these questions could be answered, he replied that the questions would not be so much answered as replaced by other better-posed questions. He then said he hoped we would never get to a final answer, because that would be the "end of science," a theme echoed by other subjects.

At this point, after some further questioning and some 15 minutes into the interview, he offered that we would not, in fact, ever be able to fully answer that question:

> I think there'll always be a question ... of what is the ultimate origin ... of the universe. I don't see any evidence that we will ever be able to give a complete answer of [sic] that question ... but we might be able to ... continue to push that back further.... I think science has its limitations.

These limitations stemmed from the need to be able to experiment (also a commonly expressed viewpoint), however, rather than (implicitly) from more directly conceptual grounds. Nevertheless, this admission was, if not directly inconsistent with his earlier view that there was (only) a problem in the language of these questions given today's scientific context, a clear change in emphasis from the more circumstantial nature of the problems as he had earlier presented them, suggesting that such absolute limits were not prominent in his thinking.

<u>Subject 8</u> (1st-year graduate student, theoretical, high math):

This subject was the only subject to generally deny the presence of not only a well-posed scientific problem (at least today) but of any philosophical or religious problem as well. At the same time, this subject displayed some of the equivocation or inconsistency found among several of the subjects.

When first asked what came before the Big Bang, the subject immediately answered that that was unanswerable, and probably not even meaningful because it was inherently unobservable:

> I think that's an unanswerable question.... It's one of those things that like ... Wittgenstein said: if you can't speak about it you got to pass over it in silence.... It's completely unobservable.... In science unobservable is probably not meaningful.... You'll never know whether you're right or you're wrong and so it's one of these pointless exercises ... so many words wasted....

The subject added that he wouldn't deny that the question was interesting, but that it was in the realm of metaphysics, by which he meant "fun, but meaningless."

Despite the firmness of the above, when the subject was explicitly asked whether there could be some future answer, he said that that was "entirely possible", but apparently only for the abstract "it's happened before" sort of reason cited by others, adding that it was very unlikely:

> I wouldn't be surprised if 50 years in the future ... somebody comes out with a ... theory that seems to explain all the facts and have some relevance in the realm before the Big Bang.... I won't rule it out ... but just because you can't rule it out doesn't mean it's ... probably going to happen.... It's within the realm of possibility but little more.

When asked whether he could give any glimpse of such a possible answer, he said no, because it "wouldn't be observational" (indicating again that the possibility was purely technical). When asked about there being no time before the Big Bang and therefore no possible causes, he said that, yes, that was exactly what he meant, that there was nothing there, that it was meaningless to say anything else, and that that was the "probable answer" (the word "probable" again letting him hedge slightly on the question about being permanently unanswerable).

The subject was then asked whether there wasn't still a valid question as to why the laws that made this question meaningless obtained (this was not a question posed to other subjects, since no other subjects had gone this far in denying any valid problem). To this he replied that, no, this was a meaningless question; the universe was a "single shot," an experiment that couldn't be run again. Pressed to answer why some people felt you could still, and always, continue to ask "why," he said:

> It's just carrying the human curiosity [too far].... If you start reducing backwards and backwards ... very quickly ... you're going to come to some explanation like ... two electrons tend to repel each other and you ask why and you just say that's the way it is, there's no inherent explanation for it.... You come to the point where you get sort of the fundamental level of explanation ... beyond that you can't really go ... we will never be able to determine why or why not.

Biographical and background information

The follow biographical and background information was collected for each subject. All subjects were graduate students and/or working staff (teaching and/or research) at either the Harvard or MIT departments of physics or Harvard's Center for Astrophysics at the Smithsonian Observatory. Orientation was recorded as experimental, theoretical, observational or some combination of these. Mathematics expertise was subject-evaluated compared to other people in their field as low, medium or high. The section on religious beliefs is a brief synopsis of pertinent views expressed.

Subject 1 (female):

B.S., physics, 1989, M.S., physics, 1991; 4th-year graduate student in physics

specialty: atomic physics

orientation: experimental

math expertise: medium

religious beliefs: none in particular ... has a "cultural religious" belief (Jewish)

Subject 2 (male):

B.S., physics, 1988, M.S., astronomy, 1991; 4th year graduate student in astronomy

specialty: solar and atomic physics

orientation: experimental

math expertise: medium

religious beliefs: spiritual; not an atheist but no particular beliefs

Subject 3 (male):

B.S., physics, 1980, M.S., astronomy, 1983, Ph.D., physics, 1985

specialty: clusters of galaxies

orientation: observational and theoretical

math expertise: high

religious beliefs: "non-specific"

Subject 4 (male):

B.S., electrical engineering, 1987, M.S., physics, 1989, Ph.D., physics, 1992

specialty: astrophysics, supernova remnants; cosmology

orientation: theoretical and experimental

math expertise: medium

religious beliefs: believes in God

Subject 5 (male):

B.S., mathematics/physics, 1985, M.S., physics, 1987, Ph.D., theoretical physics, 1992

specialty: cosmology

orientation: theoretical

math expertise: medium

religious beliefs: Christian, Protestant evangelical; "not fundamentalist, not charismatic"; believes in God

Subject 6 (female):

B.A., M.S., astronomy, 1992

specialty: high energy astrophysics, clusters

orientation: observational

math expertise: medium

religious beliefs: no organized religion, but "wouldn't say [she] was an atheist"

Subject 7 (male):

B.S., physics/mathematics, 1984, M.S., physics, 1987;
ABD, physics

specialty: mathematical physics, high-energy theory,
string theory

orientation: theoretical

math expertise: high

religious beliefs: "don't really believe in a personal
God ... not very well thought out.... I believe
in
sort of underlying structure in the universe."

Subject 8 (male):

B.S., applied math and physics, 1991, 1st-year
graduate
student in astronomy

specialty: theoretical physics, quantum mechanics

orientation: theoretical

math expertise: high

religious beliefs: non-religious, atheist

Imagery measurements

Table 1 presents the individual results of the Individual Differences Questionnaire-Imagery Habit Scale (IDQ-IHS) and

VVIQ tests for each subject, as well as the scores for the two additional questions inserted into the IDQ-IHS to explicitly measure use of imagery in problem-solving.

Table 1

Imagery Measurements

S	IDQ-IHS[a]	Imagery in[b] problem-solving	VVIQ[c]
1	4.60	4.50	1.40
2	4.87	4.50	1.60
3	4.27	5.00	2.60
4	4.27	5.00	1.63
5	4.12	5.00	2.40
6	3.93	4.00	2.25
7	4.00	4.00	2.20
8	3.67	1.50	2.25
min	3.67	1.50	1.40
max	4.87	5.00	2.60
M	4.22	4.19	2.04
SD	0.38	1.16	0.44

[a]Range 1 (low usage) to 5 (high usage)

[b]Based on 2 questions; range 1 (low usage) to 5 (high usage)

[c]Range 1 (high vividness) to 5 (low vividness)

Imagery usage discussion

Independent statements about the use of imagery in the subjects' work were extracted from the interviews and interview notes and nearly identical statements were then grouped together. Three types of responses emerged, with each subject falling in just one of the groups:

1. Statement: Imagery is very important in my work; visualizing the problem is solving 90% of it.
n = 5: s2, s3, s4, s5, s7

2. Statement: Imagery usage depends on the problem; I use it when building something or for motion problems, but not for more mathematically-oriented problems.
n = 2: s1, s6

3. Statement: Imagery is not very important in my work; I rarely use it.
n = 1: s8

Data relationships

Two approaches were followed for evaluating relationships among the data collected for each subject, especially the target relationship between problem unsolvability and imagery usage/vividness. The first approach is essentially non-statistical and focuses on the discrete, often dichotomous explicit statements about the problem of the origin of the universe and related matters (e.g., is there a valid non-scientific problem there or not) and, given the general uniformity of the views expressed, examines extreme or infrequent views in light of other equally obvious differences among subjects in imagery usage/vividness or any of the other data collected (e.g., that a subject who alone expressed a certain view had the lowest score on a particular measure).

The second approach is statistical and attempts to go beyond the general uniformity of subject interview responses and extract whatever additional information is to be had about the target relationship (as well as highlight the possible influence of other factors) by producing a single ordinal measure for the degree of belief in problem unsolvability, as well as a similar single measure for imagery usage/vividness. Given the small sample size and relatively open-ended interview format, this unsolvability measure consists of a simple ranking of the subjects with regard to degree of belief in problem unsolvability, and the subsequent analysis focuses on rank order correlations and observations between this and other measures. These analyses supplement -- sometimes supporting and sometimes refuting -- the discrete and more direct (if more isolated) results of the first approach, though the small sample size and exploratory nature of the study as a whole limit the sophistication and conclusiveness of these analyses.

Discrete data analysis

1. The 7 subjects who expressed the view that there was a valid philosophical or religious question to be asked about the origin of the universe evidenced a range of backgrounds, measured and reported imagery usage and measured imagery vividness. This suggests that, at some level and to some greater or lesser extent, viewing this question as not solved or solvable within current science but still meaningful is not dependent on any of these background or imagery factors.

2. Only one subject -- s8 -- felt fairly strongly that the question of the origin of the universe was a meaningless problem -- not only not a valid scientific question but not really a valid philosophical or religious question. This subject had the lowest (least usage) scores on the IDQ-IHS and the two questions regarding use of imagery in problem solving. Similarly, this subject alone expressed the view in the imagery discussion that imagery was basically not important to his work. (On the other hand, the subject's score on the VVIQ was only slightly higher (less vivid) than average -- within 0.5 standard deviations.)

There are also some potentially interesting biographical facts about this subject: (a) he was the least experienced in the study (a 1st-year graduate student), and (b) was one of three subjects with high math expertise. Also, although they are not factors that as clearly distinguish the subject from the rest of the subjects, it is of potential significance that this subject (a) considered himself theoretical, and (b) said he was an atheist. We will see some data that bears on these differences in the correlational studies below.

All of these factors combined tend to suggest that certain, relatively infrequent traits -- including, in particular, very low imagery usage -- may be conducive to or even necessary for the relatively rare view that the question of the origin of the universe is not a valid problem. Of course, the fact that this subject was the least experienced in the study may also be significant, and point more to an explanation rooted in professional immaturity (or lack of expertise, though the latter seems less likely given that the basic formal background seemed to be there for this subject as for all others).

3. Only two subjects -- s3 and s6 -- did not explicitly embrace the view that this question could someday be solved. These subjects were not especially similar to each

other, or very different from the rest of the subjects on any of the imagery or background factors. The significance of these subjects' position is also reduced by the fact that they did not so much express a significantly stronger relative pessimism about problem solvability but rather only failed to express the fairly weak and non-specific belief about a future possible solution that other subjects expressed.

4. One can observe that there is some relationship between imagery usage as reported in the interview and as measured on the IDQ-IHS or problem-solving questions, with only s1 clearly showing high instrument scores of usage but reporting relatively low use of imagery in her work (though the subject did report context-dependent use of imagery in problem-solving; this is, of course, what the problem-solving questions measure, though frequency usage on the IDQ-IHS does not appear to have carried over to across-the-board usage in the subject's work).

Statistical analysis

1. Two judges (the author and one other, a clinician with course work in college physics) reviewed interview responses and ranked subjects in terms of degree of belief in problem unsolvability. As discussed above, this concept was broadened somewhat to consider beliefs in the non-

existence of the problem (i.e., a belief that the problem was already solved by science and/or not really valid -- beliefs more commonly expressed that was originally anticipated) as beliefs in the solvability of the problem, making the overall judgment more closely one of problem forcefulness/unsolvability vs. problem insignificance/solvability. This fits with the original study hypothesis linking unsolvability with high imagery usage/vividness in that the underlying hypothesized requirement of imagability for adequate scientific explanation (solvability) could reasonably be expected to make frequent/vivid imagers as dissatisfied with the non-imaged-based abstractions that currently rule the problem out of bounds as they are pessimistic about a future non-image-based solution, while poor visualizers would be less sensitive to both the difficulties of current doctrine or the difficulties of any future solution.

Both judges were unaware of the subject scores on the various imagery measures with the exception of the author being aware that s8 had the lowest scores on the IDQ-IHS and questions about imagery in problem solving; however, this is of little consequence, since this subject so clearly ranked at the bottom of the list on degree of belief in problem significance/unsolvability. There was some initial disagreement about the ranking of some subjects, but discussion between the judges produced a consensus. (It would have been possible at that point to have instead employed a 3rd judge, but, given the varied and often twisting course of the interviews, it was not obvious that that would have directly resulted in agreement with either of the first two judges, and the lack of initial agreement, though indicating limitations in the measure or interview methodology, would not seem to present particular problems here given the lack of knowledge about and objective scoring of the imagery measures.)

A composite imagery ranking was produced using the sum of the scores for each subject of the 3 paper-and-pencil imagery measures (first inverting the VVIQ score so that a higher score indicated more vivid imagery, putting it in line with the IDQ-IHS and problem-solving questions on which higher scores indicated higher imagery usage). This composite could be considered to have over-valued the (two-question) measure on imagery in problem-solving. However, as the correlations reported below indicate, removing this component does not significantly change the results, and weighting a measure on the specific use of imagery for problem-solving is arguably appropriate.

Table 2 presents the ranking of each subject on problem unsolvability, the composite imagery usage/vividness rank and the actual composite imagery score, as well as Spearman's rank correlation coefficient between the unsolvability and imagery ranks, which can be seen to be a moderately strong 0.83 ($p < .02$).

Table 2

Rank order correlation of unsolvability and composite imagery scores

S	Unsolvability.[a] rank	Imagery[b] rank	Imagery[c] score
1	1	2	13.70
2	2	1	13.77
3	6	5	12.67
4	3	3	13.64
5	5	4	12.72
6	4	7	11.68
7	7	6	11.80
8	8	8	8.92

$r_s = 0.83$, $p < .02$

[a]Rank 1 = most unsolvable, rank 8 = least unsolvable

[b]Rank 1 = highest imagery usage/vividness, rank 8 = lowest

[c]Range 3.0 (least imagery usage/vividness) to 15.0 (most imagery usage/vividness)

2. Rank order correlations were also formed between the unsolvability measure and other combined (by addition; VVIQ inverted) imagery measures (IDQ-IHS and problem-solving questions, IDQ-IHS and VVIQ and, finally, VVIQ and problem-solving questions) and between the unsolvability measure and each of the individual imagery measures, as well as intercorrelations among the individual imagery measures themselves. These correlations, together with the preceding correlation between unsolvability and the full composite imagery measure (included here for comparison) are presented in Table 3. Full product-moment computations were performed because of the presence of tied ranks (ranks were assigned in those cases by averaging). The correlations between unsolvability and combined IDQ-IHS/VVIQ and between unsolvability and combined VVIQ/problem-solving questions were statistically significant ($r = 0.81$ and $r = 0.79$ respectively, $p < .02$ for each), as was the correlation between unsolvability and the IDQ-IHS by itself ($r = 0.78$, $p < .05$). The correlation between unsolvability and the VVIQ just missed significance at the .05 level($r = 0.69$, $p < .10$). All other correlations were not statistically significant, including intercorrelations among the imagery measures.

Table 3

Additional unsolvability and imagery correlations

Relationship	Correlation
Unsolvability and IDQ-IHS/VVIQ/problem-solving	0.83**
Unsolvability and IDQ-IHS/VVIQ	0.81**
Unsolvability and VVIQ/problem-solving	0.79**
Unsolvability and IDQ-IHS/problem-solving	0.43
Unsolvability and IDQ-IHS	0.78*
Unsolvability and VVIQ	0.69
Unsolvability and problem-solving	0.37
IDQ-IHS and VVIQ	0.53
VVIQ and problem-solving	- 0.17
IDQ-IHS and problem-solving	0.60

**$p < .02$

* $p < .05$

3. The additional data collected on each subject (e.g., religious views, level of math expertise, etc.) is, with perhaps the single exception of experience level, not sufficiently detailed or differentiated for statistical analysis. However, an analysis of experience level is possible, and several other observations can be made connecting these factors to the above rankings:

a. The rank order correlation between unsolvability and experience level as measured by years since beginning graduate study (there were no particular gaps in experience among subjects) is 0.55. This correlation is not statistically significant, and tends to support the view that unsolvability is not primarily a matter of subject experience or professional maturity.

b. The 3 subjects who categorized themselves as having "high" math expertise -- s3, s7 and s8 -- are the 3 subjects ranking lowest on unsolvability (i.e., viewing the problem as already solved, a non-problem or solvable), supporting a similar observation made in the discrete analysis with regard to this factor.

c. The 3 subjects who included "experimental" in their self-categorization of professional orientation were the 3 subjects ranking highest on unsolvability (the other subjects categorized themselves as theoretical and/or observational), supporting an earlier suggestion regarding a connection between a theoretical (or at least non-experimental) orientation and problem solvability.

d. The 4 subjects who reported some explicit belief in God -- s2, s4, s6 and s5 -- ranked 2nd through 5th consecutively on unsolvability. This offers some support for the reasonable idea that a belief in God may be connected to or even to some degree be sufficient (though not necessary) for believing in the relative significance and unsolvability (at least in non-religious terms) of the problem.

e. The two female subjects ranked 1st and 4th in problem unsolvability.

f. The responses of subjects in the imagery usage discussion regarding the importance of imagery in their work did not provide any particular new information in conjunction with the unsolvability rankings.

DISCUSSION

The goals of this study were to explore the opinions and reasoning of knowledgeable subjects on a potentially unsolvable problem -- the question of the origin of the universe -- and to examine a possible relationship between these opinions and visual imagery. On the first of these points, there was considerable uniformity: All subjects reflected the current view in physics and cosmology that the universe began with the Big Bang. In addition, all subjects expressed the view that the question of what came before the Big Bang could not be addressed by current day science. All subjects but one thought that there nevertheless remained a valid philosophical or religious question, though there was some variation on the quickness with which these subjects left the scientific perspective, and their view of the significance of this residual question. Finally, all subjects but two expressed the view that a future physics could perhaps address this problem more completely, though for almost all this view seemed to represent more a general faith in continued scientific progress or the belief that anything was possible, and not any particular sense that a solution would be forthcoming. Indeed, subjects seemed to have no particular sense that the question would actually be solved, and 7 of 8 subjects expressed some belief in there being limits on what we can understand.

The uniformity of the stated responses (despite measurable variations in the strength of responses) is quite striking, and in contrast to the view one might form from reading well-known dissenters, or, more generally, from tracking the progress of cosmology in the popular press, which sometimes seems to suggest that the solution of the problem of the origin of the universe is at hand, if only one had the expertise to grasp it.

From these responses we may tentatively conclude that the question of the origin of the universe is, within today's science, viewed by knowledgeable subjects as unsolvable, or even meaningless, though this later categorization must be quickly qualified by the near unanimous opinion among the subjects that the problem is in fact meaningful if we step outside the restrictions of currently understood physics. Attempting to deny the problem because of such restrictions was considered "contrived," or a "cop-out" by some subjects.

For most subjects the stated nature of this unsolvability was that current physical law simply does not apply if we go back to the moment of the Big Bang (or the moment before it), making the question of what came before the Big Bang literally not a part of current physics. However, it is clear from the interviews that subjects did not view this as a mere formal limitation to be bridged by incremental expansion of physical law. Rather, when pressed on the question of what ultimately came before the Big Bang subjects generally volunteered that this was more a question for philosophy or religion and not one to be readily resolved by expanded scientific effort. It seemed, indeed, that the question of what might have come before the Big Bang was only the current incarnation or scientific context of the problem of understanding how there could be an ultimate beginning (such as the Big Bang) without immediately inviting the question of what in some sense preceded or caused it.

As to whether this problem is permanently unsolvable, most subjects did express the belief that the problem might someday be solved within science. However, the lack of specificity and conviction in this belief seem to suggest that this is based primarily on a general faith in science and/or a reluctance to rule anything out as impossible, especially in light of previous difficult problems in science that were later solved. No subjects expressed any substantive basis for seeing how this might actually happen in this case, and most considered it unlikely, if nevertheless abstractly possible. Most subjects also expressed the view that there were limits on what could be known, suggesting some tension between believing that this problem may in fact be unsolvable and the reluctance to cast any specific problem as permanently unsolvable. Future work in this area might try to elucidate the nature of this faith in science and/or reluctance to accept what subjects otherwise seem to substantively view as apparent impossibility/unsolvability.

In any case, the overall consistency of the reasoning this problem produced among knowledgeable subjects who differed on a number of other dimensions, and the failure to offer any serious glimpse of a possible solution can also be viewed as supporting the actual, rather than merely perceived unsolvability of the problem.

The relative uniformity of response makes evaluation of the second objective of the study -- the relationship between such reasoning and visual imagery -- more difficult. The speculation at the outset of the study was that individuals with the most frequent or vivid visual imagery would have the strongest feelings about the unsolvability of the problem, while those with the least frequent or vivid imagery would be more optimistic. No subjects, in turned out, could be said to be optimistic about solving the problem.

However, the one subject who basically considered the problem meaningless from any point of view had the lowest measured image frequency as determined both by the IDQ-IHS and the subjects' own statements of their use of imagery, with the subject reporting, in the latter case, virtually no use of imagery, whereas half the subjects said imagery was central to their work. This belief that the problem is meaningless can be viewed as consistent with a belief in problem solvability (and the link between this belief and the subject's low imagery usage is therefore consistent with the hypothesized link between solvability and low imagery usage/vividness) if we add to our concept of an optimistic view of problem solvability a failure to perceive there being much of any problem there in the first place, either because the problem is not well formed or is already solved. This seems a reasonable refinement, since the hypothesized link between concepts of causation and visual imagery could be expected to not only desensitize less frequent/less vivid imagers to the difficulty of solving the problem but also to reduce in such individuals the perceived need for a causal analysis in the first place, or to more willingly accept that non-image-based formalizations (such as the absolute beginning of space and time provided by the Big Bang theory) dismiss, if not solve the problem.

Viewed the other way around, the expectation that subjects with the most vivid visual imagery would be less optimistic might be reasonably modified to include the idea that such subjects would more clearly perceive the weight and forcefulness of the problem itself, since such individuals are more likely to engage in the visualization processes through which the literature suggests causation is so often considered. For such individuals, the attempt (and failure) to produce visual images for this problem underscore the reality (and intractability) of the problem.

On the other hand, the interviews did not contain many spontaneous references to a failure of imagery in tackling this problem. This may, however, point to the dominance of a scientific mode of reasoning and explanation that was evident in most subjects (e.g., some subjects who said that imagery was "intrinsic" to their work during the imagery discussion had, until that point, made little or no mention of it). This scientific style, as it were, may reduce the visibility of an underlying connection between imagery and perceived problem unsolvability.

Similarly, there is a question as to whether the general uniformity of response with regard to the meaningfulness and unsolvability of the problem does not, in the presence of a reasonable range of imagery usage/vividness scores, suggest that there is in fact no link between unsolvability and imagery. However, it may be that this uniformity is due to imagery competencies that are basic enough (e.g., the basic ability to form and understand visual images at some appropriate level) to be common to most individuals, with obvious differences in stated beliefs visible only at relatively extreme values (e.g., s8's very low imagery usage measures). (The original study expectation that there might be obvious differences in solvability beliefs linked to imagery usage or vividness was based in part on the existence in the literature of a range of views on solvability for this problem, as well as, and perhaps more so, for what seems the conceptually related mind-body problem. However, it may be that such published views, especially for the problem of the origin of the universe, are not that representative of the views of working professionals.)

Although, given the above model, evidence in the form of obvious differences may be observable only at the extremes, evidence in the form of less obvious differences may be available by looking at more subtle measures below the level of dichotomous stated beliefs. The sample size and open-ended nature of the study suggest caution in such an approach, but at least some such evidence can be found in the significant correlation ($r = 0.83$, $p < .02$) between an overall ranking of subjects by degree (vs. mere statement) of belief in problem significance/unsolvability and a composite imagery score formed by summing the 3 objective imagery measures[1]. There were also significant correlations between unsolvability and imagery usage alone as measured by the IDQ-IHS ($r = 0.78$, $p < .05$) and a near significant correlation between unsolvability and the VVIQ measure of imagery vividness ($r = 0.69$, $p < .10$). However, the largest correlation was, interestingly, the 0.83 value produced by using the composite of all 3 imagery measures, none of which correlated significantly with any other. A more careful analysis of the elements of this intriguing composite relationship is beyond the reach of the current data set.

There are possible confounding factors, including mathematical expertise and a theoretical (vs. an experimental) orientation, both of which appeared tied to weaker (lower ranked) beliefs in problem unsolvability and greater satisfaction with current explanations (it is perhaps noteworthy that the higher unsolvability ratings and related higher imagery scores of the self-described experimentalists is consistent with Galton's finding that (experimental) physicists were among the better imagers). The data also suggests a possible role for religious belief.

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[1]Thanks to William Hirst for suggesting this statistical analysis.

Experience level, on the other hand, did not appear to be significantly related to unsolvability beliefs, confirming the expectation that such beliefs and differences in them would, by virtue of their primarily structural dependency on basic cognitive competencies such as imagery ability, not be sensitive to the novice/expert distinction prominent in many other situations.

However, the current study did not collect enough data to examine any of these factors while controlling for the others, and the question of cause and effect is quite open at the moment (e.g., it may be that greater imagery capabilities predispose a physicist both to experimental work and to a dissatisfaction with the constraints of certain non-image-based theoretical constructs).

In any case, this statistical analysis and some of the related findings around explicit stated beliefs still suggest a possible role for one or more imagery capabilities in beliefs about problem solvability. While this may support the posited underlying necessity of imagery for adequate physical explanation and the consequential likely unsolvability of the problem at hand, several factors warrant caution in making this or any other interpretation of the results:

1. The complexity of the beliefs and posited relationships allow for multiple approaches to and

interpretations of the data (e.g., it may be that those who view the problem as insignificant could in fact be said to see it as unsolvable -- so clearly as to dismiss the problem -- rather than as effectively solved).

2. The possible confounding influence of a mathematical/theoretical orientation supports the early concern that a relationship between imagaibility and unsolvability may point not to true problem unsolvability but to the inability of imagers to accept a valid, non-image-based solution.

3. The small sample size not only makes controlling secondary factors difficult but raises questions about how representative of current scientific thinking the sample is; e.g., what relationships might be observed among those critical of the Big Bang theory ?

4. The VVIQ and other imagery measures are, as noted in the literature review, not without controversy in their measurement or interpretation.

Future study in this area might profitably continue both tacks of analysis taken here and address some of the above concerns by (a) securing an adequate number of subjects with a greater range of scientific beliefs and, especially, with some of the minority/extreme views and imagery capabilities discussed (e.g., subjects who believe the problem of the origin of the universe completely solved; who have virtually no visual imagery experiences at all; or who are critical of the Big Bang), perhaps by soliciting subjects with such views explicitly; (b) setting out from the start to explicitly and closely measure some of the different belief components identified in the current work, including the use of standard questions to allow for better quantification and comparison of stated beliefs (vs. the more exploratory goals of the current study); and (c) examining a wider range of imagery capabilities (e.g., imagery control) and attempting to offset some of the known problems in imagery measurement (e.g., through the use of more directed imagery interview questions, additional tests, etc.).

REFERENCES

Adelson, B. (1984). When novices surpass experts: The difficulty of a task may increase with expertise. Journal of Experimental Psychology: Learning, Memory, and Cognition, 10, 483-495.

Ahsen, A. (1990). AA-VVIQ and imagery paradigm: vividness and unvividness issue in VVIQ research programs. Journal of Mental Imagery, 14, 1-58.

Anderson, J.R. (1983). The architecture of cognition. Cambridge, MA: Harvard University Press.

Ashton, R., McFarland, K., Walsh, F., & White, K. (1978). Imagery ability and the identification of hands: A chronometric analysis. Acta Psychologica, 42, 253-262.

Aveling, F. (1927). The Relevance of visual imagery to the process of thinking. British Journal of Psychology, 18, 15-22.

Bartlett, F.C. (1932). Remembering. Cambridge, England: Cambridge University Press

Berger, G.H., & Gaunitz, S.C. (1977). Self-rated imagery and vividness of task pictures in relation to visual memory. British Journal of Psychology, 68, 283-288.

Bernstein, J. (1991, September 26). King of the quantum. New York Review of Books, pp. 61-63.

Betts, G.H. (1909). The distribution and functions of mental
imagery. Teachers' College, Columbia University, Contributions to education, 26, 1-99.

Black, M. (1964). A companion to Wittgenstein's 'Tractatus'.
Ithaca: Cornell University Press.

Boyd, R. (1991). Confirmation, semantics, and the interpretation of scientific theories. In R. Boyd, P. Gasper, & J.D. Trout (Eds.), The philosophy of science (pp. 3-35). Cambridge, MA: MIT Press.

Caramazza, A., McCloskey, M., & Green, B. (1981). Naive beliefs in "sophisticated" subjects: misconceptions about
trajectories of objects. Cognition, 9, 117-123.

Carey, S., & Diamond, R. (1980). Maturational determination of the developmental course of face encoding. In D. Caplan (Ed.), Biological studies of mental processes (pp. 60-93). Cambridge, MA: MIT Press.

Ceci, S.J., & Liker, J. (1986). A day at the races: A study of IQ, expertise, and cognitive complexity. Journal of Experimental Psychology: General, 115, 255-266.

Charness, N. (1979). Components of skill in bridge. Canadian
Journal of Psychology, 33, 1-16.

Chase, W.G., & Simon, H.A. (1973). The mind's eye in chess. In W.G. Chase (Ed.), Visual Information Processing (pp.

215-181). New York: Academic Press.

Chi, M.T.H., Feltovich, P.J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. Cognitive Science, 5, 121-152.

Churchland, P. (1984). Matter and consciousness. Cambridge, MA: MIT Press.

Cohen, B.H. & Saslona, M. (1990). The advantage of being an habitual visualizer. Journal of Mental Imagery, 14, 101-112.

Cooper, L.A., & Shepard, R.N. (1975). Mental transformations in the identification of left and right hands. Journal of Experimental Psychology: Human Perception and Performance, 1, 48-56.

deGroot, A.D. (1965). Thought and choice in chess. The Hague: Mouton.

deKleer, J. & Brown, J.S. (1981). Mental models of physical mechanisms and their acquisition. In J.R. Anderson (Ed.), Cognitive skills and their acquisition (pp. 285-309). Hillsdale, NJ: Erlbaum.

Dennett, D.C. (1978). Toward a cognitive theory of consciousness. In D.C. Dennett (Ed.), Brainstorms (pp. 149-173). Cambridge, MA: MIT Press.

Dennett, D.C. (1991). Consciousness explained. Boston, MA: Little, Brown.

DeSoto, C., London, M., & Handel, S. (1965). Social reasoning and spatial paralogic. Journal of Personality and Social Psychology, 2, 513-521.

diSessa, A. (1982). Unlearning Aristotelian physics: A study of knowledge-based learning. Cognitive Science, 6, 37-75.

diSessa, A. (1983). Phenomenology and the evolution of intuition. In D. Gentner & A. Stevens (Eds.), Mental models (pp. 15-33). Hillsdale, NJ: Erlbaum.

Doan, B.D. (1981). Belief among academics in free will and in the veracity of scientific judgement. Unpublished doctoral dissertation, McGill University, Montreal.

Ericsson, K. A. & Simon, H. A. (1984). Protocol analysis: Verbal reports as data. Cambridge, MA: MIT Press.

Ernest, C. H. (1977). Imagery ability and cognition: A critical review. Journal of Mental Imagery, 2, 181-216.

Flanagan, O. (1984). The science of the mind. Cambridge, MA: MIT Press.

Fodor, J. (1983). The modularity of mind. Cambridge, MA: MIT Press.

Forisha, B.L. (1978). Mental imagery and creativity: Review and speculations. Journal of Mental Imagery, 2, 209-238.

Forisha, B.L. (1981). Patterns of creativity and mental imagery in men and women. Journal of Mental Imagery, 5, 85-97.

French, P.A., & Sternberg, R.J. (1988). Expertise and intelligent thinking: When is it worse to know better. In R.J. Sternberg, (Ed.), Advances in the psychology of intelligence, Vol. 5 (pp. 157-188). Hillsdale, NJ: Erlbaum.

Galton, F. (1883). Inquiries into human faculty and its development. London: MacMillan.

Gasper, P. (1991). Causation and explanation. In R. Boyd, P. Gasper, & J.D. Trout (Eds.), The philosophy of science (pp. 289-297). Cambridge, MA: MIT Press.

Gentner, D. (1982). Are scientific analogies metaphors ? In D.S. Miall (Ed.), Metaphor: Problems and perspectives (pp. 106-132). Brighton, England: Harvester Press.

Goethe, W.v. (1978). Theory of colours (C.L. Eastlake, Trans.). Cambridge, MA: MIT Press.

Griffitts, C.H. (1927). Individual differences in imagery. Psychological Monographs, No. 172.

Grunbaum, A. (1989). The pseudo-problem of creation in physical cosmology. Philosophy of Science, 56, 373-394.

Gur, R.C., & Hilgard, E.R. (1975). Visual imagery and the discrimination of differences between altered pictures simultaneously and successively presented. British Journal of Psychology, 66, 341-345.

Hadamard, J. (1945). The psychology of invention in the mathematical field. New York: Dover.

Harre, R. (1988). Modes of explanation. In D.J. Hilton, (Ed.), Contemporary science and natural explanation: Commonsense conceptions of causality (pp. 129-144). New York: NYU Press.

Hawking, S. (1988). A brief history of time. New York: Bantam Books.

Heidbreder, E. (1933). Seven psychologies. New York: Appleton-Century-Crofts.

Heuer, F., Fischman, D., & Reisberg, D. (1986). Why does vivid imagery hurt color memory ? Canadian Journal of Psychology, 40, 161-175.

Hiscock, M. (1978). Imagery assessment through self-report: What do imagery questionnaires measure ? Journal of Consulting and Clinical Psychology, 46, 223-230.

Hollenberg, C.K. (1970). Functions of visual imagery in the learning and concept formation of children. Child Development, 41, 1003-1015.

Huttenlocher, J. (1968). Constructing spatial images: A strategy in reasoning. Psychological Review, 75, 550-560.

James, W. (1890). The principles of psychology. New York: Henry Holt.

Kaiser, M.K., Jonides, J., & Alexander, J. (1986). Intuitive reasoning about abstract and familiar physics problems. Memory & Cognition, 14, 308-312.

Katz, A.N. (1983). What does it mean to be a high imager ? In J. Yuille, (Ed.), Imagery, memory and cognition (pp. 39-64). Hillsdale, NJ: Erlbaum.

Keil, F.C. (1989). Concepts, kinds, and cognitive development. Cambridge, MA: MIT Press.

Koedinger, K.R. & Anderson, J.R. (1990). Abstract planning and perceptual chunks: Elements of abstract planning in geometry. Cognitive Science, 14, 511-550.

Kohler, W. (1947). Gestalt psychology. New York: New American Library

Kosslyn, S.M. (1980). Image and mind. Cambridge, MA: Harvard University Press.

Kosslyn, S.M., Seger, C., Pani, J.R., & Hillger, L.A. (1990). When is imagery used in everyday life ? A diary study. Journal of Mental Imagery, 14, 131-152.

Krellenstein, M. (1987). Reply to "Parallel computation and the mind-body problem". Cognitive Science, 11, 155-157.

Kuhn, D. (1989). Children and adults as intuitive scientists. Psychological Review, 96, 674-689.

Kuhn, T.S. (1962). The structure of scientific revolutions. Chicago: University of Chicago Press.

Kuhn, T.S. (1977). Concepts of cause in the development of physics. In T.S. Kuhn (Ed.), The essential tension (pp. 21-30). Chicago: University of Chicago Press.

Lakoff, G. (1987). Women, fire, and dangerous things. Chicago: University of Chicago Press.

Larkin, J.H. (1983). The role of problem representation in physics. In D. Gentner & A. Stevens (Eds.), Mental models (pp. 75-98). Hillsdale, NJ: Erlbaum.

Larkin, J.H., McDermott, J., Simon, D.P., & Simon, H.A. (1980). Expert and novice performance in solving physics problems. Science, 208, 1335-1342.

Larkin, J.H. & Simon, H.A. (1987). Why a diagram is (sometimes) worth ten thousand words. Cognitive Science, 11, 65-99.

Leslie, A.M. & Keeble, S. (1987). Do six-month-old infants perceive causality ? Cognition, 25, 265-288.

Lewis, C. (1981). Skill in Algebra. In J.R. Anderson (Ed.), Cognitive skills and their acquisition (pp. 85-110). Hillsdale, NJ: Erlbaum.

Lightman, A.P. (1989). Magic on the mind: Physicists' use of metaphor. American Scholar, 58, 97-101.

Lightman, A.P., & Brawer, R. (1987-1989). The cosmology interview project. (Available from the Niels Bohr Library, Center for History of Physics, American Institute for Physics, New York, NY.)

Lightman, A.P., & Brawer, R. (1990). Origins: The lives and worlds of modern cosmologists. Cambridge, MA: Harvard University Press.

Marks, D.F. (1973). Visual imagery differences in the recall of pictures. British Journal of Psychology, 64(1), 17-24.

McCloskey,, M., Caramazza, A., & Green, B. (1980). Curvilinear motion in the absence of external forces: Naive beliefs about the motion of objects. Science, 210, 1139-1141.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A.L. Stevens (Eds.), Mental Models (pp. 299-324). Hillsdale, NJ: Erlbaum.

McGinn, C. (1989). Can we solve the mind-body problem ? Mind, 391, 349-366.

McKeithen, K.B., Reitman, J.S., Rueter, H.H., & Hirtle, S.C. (1981). Knowledge organization and skill differences in computer programmers. Cognitive Psychology, 13, 307-325.

McKeon, R. (1966). The basic works of Aristotle. New York: Random House

Medin, D.L. & Ross, B.H. (1989). The specific character of abstract thought: categorization, problem solving, and induction. In R.J. Sternberg, ed., Advances in the psychology of human intelligence, Vol. 5. Hillsdale, NJ: Erlbaum.

Miller, A.I. (1984). Imagery in scientific thought. Cambridge, MA: MIT Press.

Munitz, M.K. (1986). Cosmic understanding. Princeton: Princeton University Press.

Murphy, G.L., and Wright, J.C. (1984). Changes in conceptual structure with expertise: Differences between real-world experts and novices. Journal of Experimental psychology: Learning, Memory, and Cognition, 10, 144-155.

Paivio, A. (1970). On the functional significance of imagery. Psychological Bulletin, 73, 385-392.

Paivio, A. (1971). Imagery and verbal processes. New York: Holt, Rhinehart, and Winston.

Paivio, A. (1983). Factor analysis of a questionnaire on imagery and verbal habits and skills. Canadian Journal of Psychology, 37, 461-483.

Patel, V.L. & Groen, G.J. (1986). Knowledge based solution strategies in medical reasoning. Cognitive Science, 10, 91-116.

Pear, T.H. (1927). The relevance of visual imagery to the process of thinking. British Journal of Psychology, 18, 1-14.

Penrose, R. (1989). The emperor's new mind. New York: Oxford University Press.

Poincare, H. (1908). Science and method. New York: Dover.

Proffitt, D.R., Kaiser, M.K., & Whelan, S.M. (1990). Understanding wheel dynamics. Cognitive Psychology, 22, 342-373.

Pylyshyn, Z. (1984). Computation and cognition. Cambridge, MA: MIT Press.

Reisberg, D. & Chambers, D. (1986). Neither pictures nor propositions: The intensionality of mental images. In _Eighth Annual Conference of the Cognitive Science Society_ (pp. 208-222). Hillsdale, NJ: Erlbaum.

Reisberg, D., Culver, L.C., Heuer, F., & Fischman, D. (1986). Visual memory: When imagery vividness makes a difference. _Journal of Mental Imagery_, 10, 51-74.

Richardson, J.T. (1980). Mental imagery and stimulus concreteness. _Journal of Mental Imagery_, 4, 87-97.

Rock, I. (1983). _The logic of perception_. Cambridge, MA: MIT Press.

Roe, A. (1951). A study of imagery in research scientists. _Journal of Personality_, 19, 159-179.

Roncato, S. & Rumiati, R. (1986). Naive statics: Current misconceptions on equilibrium. _Journal of Experimental Psychology: Learning, Memory, and Cognition_, 12, 261-377.

Schoenfeld, A.H., & Hermann, D.J. (1982). Problem perception and knowledge structure in expert and novice mathematical problem solvers. _Journal of Experimental Psychology: Learning, Memory, and Cognition_, 8, 484-494.

Schmeidler, G.R. (1965). Visual imagery correlated to a measure of creativity. _Journal of Consulting Psychology_, 29, 78-80.

Shaver, P., Pierson, L., & Lang, S. (1974). Converging evidence for the functional significance of imagery in problem solving. Cognition, 3, 359-375.

Shaw, G.A. & DeMers, S.T. (1986). The relationship of imagery to originality, flexibility and fluency in creative thinking. Journal of Mental Imagery, 10(1), 65-74.

Shimony, A. (1991). Metaphysical problems in the foundations of quantum mechanics. In R. Boyd, P. Gasper, & J.D. Trout (Eds.), The philosophy of science (pp. 517-528). Cambridge, MA: MIT Press.

Shoham, Y. (1990). Nonmonotonic reasoning and causation. Cognitive Science, 14, 213-252.

Slee, J.A. (1980). Individual differences in visual imagery ability and the retrieval of visual appearances. Journal of Mental Imagery, 4, 93-113.

Thagard, P. (1986). Parallel computation and the mind-body problem. Cognitive Science, 10, 301-318.

Wallas, G. (1926). The art of thought. New York: Harcourt & Brace.

Wellman, H. & Gelman, S.A. (1988). Children's understanding of the non-obvious. In R.J. Sternberg, ed., Advances in the psychology of human intelligence, Vol. 4. Hillsdale, NJ: Erlbaum.

White, B. Y. (1983). Sources of difficulty in understanding Newtonian dynamics. Cognitive Science, 7, 41-65.

Winograd, T. (1975). Frame representations and the declarative-procedural controversy. In D.G. Bobrow & A.M. Collins (Eds.), Representation and understanding: Studies in cognitive science (pp. 185-210). New York: Academic Press.

Wittgenstein, L. (1961). Tractatus logico-philosophicus (D.F. Pears & B.F. McGuinness, Trans.). New York: Routledge & Kegan Paul. (Original work published 1921)

Yates, J., Bessman, M., Dunne, M., Jertson, D., Sly, K., & Wendelboe, B. (1988). Are conceptions of motion based on a naive theory or on prototypes ? Cognition, 29, 251-275.

Zajonc, A.G. (1976). Goethe's theory of color and scientific intuition. American Journal of Physics, 44, 327-333.

Appendix A

This section asks questions about the frequency and use of your visual images. Please indicate your answer to each of the questions by circling a 1 if you strongly disagree with the statement or a 5 if you strongly agree, or some value in between to indicate an intermediate state of disagreement or agreement.

1. I often use mental images or pictures to help me remember things.

strongly disagree 1 2 3 4 5 strongly agree

2. By using mental pictures of the elements of a problem, I am often able to arrive at a solution.

strongly disagree 1 2 3 4 5 strongly agree

3. My thinking often consists of mental pictures or images.

strongly disagree 1 2 3 4 5 strongly agree

4. I find it difficult to form a mental picture of anything.

strongly disagree 1 2 3 4 5 strongly agree

5. I often use mental pictures to solve problems.

strongly disagree 1 2 3 4 5 strongly agree

6. When remembering a scene, I use verbal descriptions rather than mental pictures.

strongly disagree 1 2 3 4 5 strongly agree

7. I never use mental pictures or images when trying to solve problems.

strongly disagree 1 2 3 4 5 strongly agree

8. I often enjoy the use of mental pictures to reminisce.

strongly disagree 1 2 3 4 5 strongly agree

9. I can close my eyes and easily picture a scene I have experienced.

strongly disagree 1 2 3 4 5 strongly agree

10. I think that most people think in terms of mental pictures whether they are completely aware of it or not.

strongly disagree 1 2 3 4 5 strongly agree

11. I can easily picture moving objects in my mind.

strongly disagree 1 2 3 4 5 strongly agree

12. I do not form a mental picture of people or places when reading of them.

strongly disagree 1 2 3 4 5 strongly agree

13. When someone describes something that happens to him or her, I sometimes find myself vividly imagining the events that happened.

strongly disagree 1 2 3 4 5 strongly agree

14. I have only vague visual impressions of scenes I have experienced.

strongly disagree 1 2 3 4 5 strongly agree

15. Listening to someone recount his experiences does not usually arouse mental pictures of the incidents being described.

strongly disagree 1 2 3 4 5 strongly agree

Appendix B

This section aims to determine the vividness of your visual imagery. The items of the test will possibly bring certain images to your mind. You are asked to rate the vividness of each image using the 5-point scale given below. For example, if your image is "vague and dim" then give it a rating of 4. After each item write the appropriate number in the space provided. Throughout the test, refer to the rating scale when judging the vividness of each image. Try to do each item separately, independent of how you may have done other items. You may keep your eyes open or closed.

Ratings:

1 Perfectly clear and as vivid as normal vision

2 Clear and reasonably vivid

3 Moderately clear and vivid

4 Vague and dim

5 No image at all, you only "know" that you are thinking of the object

Ratings: 1 Perfectly clear and as vivid as normal vision

2 Clear and reasonably vivid

3 Moderately clear and vivid

4 Vague and dim

5 No image at all, you only "know" that you are thinking of the object

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For questions 1-4, think of some relative or friend whom you frequently see (but who is not with you at present) and consider carefully the picture that comes before your mind's eye.

1. The exact contour of face, head, shoulders and body.

   Rating ______

2. Characteristic poses of head, attitudes of body, etc.

   Rating ______

3. The precise carriage, length of step, etc. in walking.

   Rating ______

4. The different colors worn in some familiar clothes.

   Rating ______

Visualize a rising sun. Consider carefully the picture that comes before your mind's eye.

5. The sun is rising above the horizon into a hazy sky.

   Rating ______

6. The sky clears and surrounds the sun with blueness.

   Rating ______

7. Clouds. A storm blows up, with flashes of lightning.

   Rating ______

8. A rainbow appears.

   Rating ______

Ratings 1 Perfectly clear and as vivid as normal vision

2 Clear and reasonably vivid

3 Moderately clear and vivid

4 Vague and dim

5 No image at all, you only "know" that you are thinking of the object

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Think of the front of a shop which you often go to. Consider the picture that comes before your mind's eye.

9. The overall appearance of the shop from the opposite side of the road.

   Rating ______

10. A window display including colors, shapes and details of individual items for sale.

    Rating ______

11. You are near the entrance. The color, shape and details of the door.

    Rating ______

12. You enter the shop and go to the counter. The counter assistant serves you. Money changes hands.

    Rating ______

Finally, think of a country scene which involves trees, mountains
and a lake. Consider the picture that comes before your mind's eye.

Rating ______

13. The contours of the landscape.

    Rating ______

14. The color and shape of the trees.

    Rating ______

15. The color and shape of the lake.

    Rating ______

16. A strong wind blows on the trees and on the lake, causing waves.

Rating ______