THE INFORMATION PROCESSING APPROACH TO COGNITION

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Of the many alternative approaches available for understanding cognition, the one that has dominated psychological investigation for the last decade or two is information processing (IP). For better or worse, the IP approach has had an enormous impact on modern cognitive research, leaving its distinctive imprint on both the kinds of theories that have been proposed and the kinds of experiments that have been done. Its influence has been so pervasive, in fact, that some writers have argued that IP has achieved the exalted status of a "Kuhnian paradigm" for cognitive psychology (Lachman, Lachman, & Butterfield, 1979). It is unclear whether or not this claim is really justified, but the fact that it has even been suggested documents the preeminence of IP in modern cognitive psychology.

Whenever an approach so dominates a scientific field, it is important to understand -- or at least to try to understand -- its foundations: the nature of the assumptions that underlie its use. These must be scrutinized for their consistency, plausibility, empirical support, utility, and potential limitations. Only then can one begin to see how the approach is related to others, how firmly it is rooted, why it has taken the field to its present state, and where it is likely to lead in the future. The goal of such an enterprise is essentially to provide a theory of the particular scientific endeavor being analyzed: to capture the activities and intuitions of the approach's practitioners accurately and succinctly. If the practitioners agree that the analysis succeeds in capturing the nature of their beliefs and their work, it can eventually replace vague intuitions with well-defined constructs as the basis for further research.

We believe that the time has come to examine the foundations of information processing in psychology. There has been some work along these lines, but it has come primarily from philosophers and computer scientists rather than from IP psychologists themselves. From IP-oriented philosophers have come formulations of a new philosophical doctrine -- called "functionalism" -- offered as a possible solution to the age-old mind/body problem (e.g., Craik, 1943; Putnam, 1960; Fodor, 1968; Dennett, 1978). From computer scientists have come related proposals that the operation of the human mind can be simulated, or perhaps even duplicated, on modern digital computers (e.g., Newell, 1980; Newell & Simon, 1972, 1976). The trouble is that many cognitive psychologists who consider themselves IP practitioners, ourselves included, find that some of the assumptions made in these arguments are too strong or of the wrong type (or both) to accurately reflect the nature of IP in psychology.

The present chapter represents our attempt to present a principled description of the IP approach as it is practiced within psychology. We try to formulate the assumptions underlying IP in terms that are based as explicitly as possible on how IP theories are constructed and tested by most IP psychologists. The accounts given by philosophers and computer scientists are just too far removed from what psychologists actually do to be certain that their views accurately reflect our own. Perhaps it will turn out that they do -- although we will argue otherwise -- but this certainly is a matter that requires and deserves more serious attention than it has yet received. We must not *assume* that their views are the same as ours, but rather *determine* whether they are or not. One of our principle aims, then, is to analyze the nature of IP with an eye toward clarifying its relation to these other proposals.

In the first half of this chapter we attempt to give a fairly broad characterization of the information processing approach to cognition and the assumptions on which it is based. In the second half we consider the relation of IP psychology to other approaches to cognition, discussing how they agree and how they conflict.

Five Assumptions of Information Processing

We take as our starting point the proposition that the intuitive basis of the IP approach is a theoretical analogy between mental activity and a program running on a computer. Whatever deeper roots IP psychology might have in communication theory, mathematical logic, or formal linguistics, the idea that the mind works like some sort of computer program is certainly the principal reason for IP's current popularity. The analogy runs roughly as follows. Certain information from the environment (the "input") is available to the mind through sensory systems, much as input information is available to a computer program through peripheral devices such as terminals, card readers, and the like. Some of this information is then manipulated in more or less complex ways by mental operations, much as a computer program manipulates information according to the rules it embodies. Among these mental operations are ones that select, transform, store, and match information arising from the present situation, from memories of past situations, from plans for future situations, or (usually) some combination of these. As a result of such operations, the mind produces information in a different form (the "output") which is expressed as overt behavior, in much the same way that a computer program outputs information through peripheral output devices such as terminals, line printers, and so forth. Interestingly, this general proposal about mental operations was made as early as 1943 by Kenneth Craik, long before modern digital computers were generally available.

Is there anything more to IP theory than this loose analogy? We believe that there is and will try to specify what it is in the remainder of this section. We have structured our discussion around five assumptions that are almost universally held by IP psychologists and are fundamental to their beliefs about how to construct cognitive theories. We list them here without background or discussion as a preview of the analysis we are about to present:

(1) *Informational Description*: Mental events can be functionally described as "informational events", each of which consists of three parts: the *input information* (what it starts with), the *operation* performed on the input (what gets done to the input), and the *output information* (what it ends up with).

(2) *Recursive Decomposition*: Any complex (i.e., non-primitive) informational event at one level of description can be specified more fully at a lower level by *decomposing* it into (a) a number of components, each of which is itself an informational event, and (b) the temporal ordering relations among them which specify how the information "flows" through the system of components.

(3) *Flow Continuity*: All input information required to perform each operation must be available in the output of the operations that flow into it.

(4) *Flow Dynamics*: No output can be produced by an operation until its input information is available and sufficient additional time has elapsed for it to process that input.

(5) *Physical Embodiment*: In the dynamic physical system whose behavior is being described as an informational event, information is embodied in states of the system (here called *representations*) and operations that use this information are embodied in changes of state (here called *processes*).

We do not pretend that this list exhausts the assumptions underlying IP psychology, but they are certainly among the most important ones and form a widely held set of "core beliefs". In the following discussion we try to justify these assumptions, elaborate on their significance, and analyze at least some of their implications. Unfortunately, space does not permit any corresponding discussion of the equally important methodological and empirical aspects of IP psychology.

Assumption 1: Informational Description

Saying that the mind is like a computer program really just means that we can describe both of them in essentially the same way. We don't want to restrict our formulation of the analogy to modern digital computers because many mental processes -- especially ones at the sensory and motor ends -- seem to operate a lot more like "analog" machines than digital ones. Furthermore, we want to avoid using the term "computational" altogether because of its technical meaning in the theory of computability (cf., Johnson-Laird, 1983; Newell, 1980) which we do not want to presuppose. Therefore, we state the first assumption in terms of describing mental processes as something we call *informational events* which we define as follows:

> (1) Mental events can be functionally described as "informational events", each of which consists of three parts: the *input information* (what it starts with), the *operation* performed on the input (what gets done to the input), and the *output information* (what it end up with).

By "mental events" we mean to include not only conscious experiences, but all internal happenings that influence behavior, many of which will not produce any conscious experiences at all. For instance, native speakers seem to be able to parse sentences quite well without any conscious experience of the corresponding mental processes, and yet one will almost certainly need to suppose that there are some internal events of this sort to explain how people understand language. Naturally, we do not mean to *exclude* events of which people are conscious either. The phrase "mental events" in our first assumption is really just a place-holder for whatever events turn out to be necessary to account for what people are able to do and how they do them. The concepts of "information" and "operations" also need to be defined, of course, but we will postpone this lengthier discussion to a later section.

The sort of description proposed in the first assumption can be represented by a "black box" diagram like the one shown in Figure 1A. It is assumed that the output is *determined* by the input together with the operation performed on it, and so one really needs just the first two of the three parts -- input plus operation -- to specify what is going on. If the operation is complicated enough that one cannot describe it directly, the operation can be expressed implicitly by specifying the mapping from input to output. When the operation so defined is ascribed to the human mind, we will call this specification a "mental mapping."

Figure 1

Functional Description. Another aspect of the first assumption that needs to be discussed is the notion of a "functional" description. The intent here is to single out a domain of discourse for IP theories of mind that appropriately reflects the kind of accounts they offer. In this context, *functional* descriptions are to be distinguished from both *physical* and *phenomenological* descriptions. We claim that it is possible to construct theories relevant to psychology at any of these levels and that there are important relationships among them. However, IP psychology is identified primarily with the "middle" level of functional descriptions, and secondarily with how this level relates to the other two levels.

Theories at the physical level are concerned with the nature of material substances and events that take place within brains. Descriptions at this level are given in terms of causal sequences of biochemical events involved in neural firings and interactions. Such descriptions are ultimately reducible, at least in theory, to quantal happenings among countless quarks, or whatever the most microscopic level of physical reality happens to be. Very few, if any, theories in psychology are proposed solely within the physical domain.

Theories at the phenomenological level are concerned with the systematic and principled description of conscious experiences in terms of other conscious experiences. Such experiential descriptions are different in kind from any sort of physical description, a fact which has led philosophers to debate issues about the relation between mind and body for centuries. Phenomenological accounts of mental events were once the primary theoretical goal within psychology, when the "introspective method" reigned supreme. Because the subjective experiences on which they are based are not publicly observable entities, however, true phenomenological theories fell from favor with the advent of behaviorism (Watson, 1913). Since then phenomenological description has played an important, but decidedly supporting, role in psychology. This is true despite the fact that many psychological theories -- particularly in the field of perception -- still have as their goal an account of phenomenal experience. The crucial difference is that, since Watson, psychological theories have seldom been advanced in which the account is given *solely* in introspective terms. Outside of psychology proper, however, important phenomenological theories have been offered by philosophers such as Heidigger (1962) and Merleau-Ponty (1962).

At this point it would be appropriate to give a clear definition of the functional level. Unfortunately, we do not know of a good one -- other than the one implied by the information processing approach -- and so we can only appeal to intuitive notions here. Theories at the functional level are concerned directly with neither material substances nor subjective experiences, but rather with how the brain or mind *works* or *behaves* within the context of the environment. The presumption is that this functional level of description is considerably more abstract and general than the physical level (in the sense that many physically quite different objects can have the same function), and yet this functional description is still tied to physical reality in principled ways. Most psychological theories have at least one foot firmly in this functional level. Even physiological theories, which might seem to be exclusively physical, are usually about the relation between some physical structure and its function, as when researchers attempt to say what a given cell "signals" in the environment (e.g., Hubel and Wiesel's (1968) "edge detectors" and "bar detectors"). Prominent examples of psychological theories couched exclusively or primarily within the functional domain include Skinner's (1953) theory of organismic behavior, Piaget's (1950) theory of cognitive development, Freud's (1933) theory of personality, and the many theories that came out of the "functionalist" school, as well as all modern IP theories.

Information and Operations. What distinguishes IP theories from most other functional theories in psychology is its further claim that the appropriate type of functional description is *informational*: that is, mental events are to characterized in terms of information and operations that relate information.[1] This is the point at which we should present a rigorous yet uncontroversial definition of information and operations. Unfortunately, we cannot do this because the nature of information and operations is one of the least understood and most problematic aspects of the whole IP enterprise. This may seem surprising given how heavily the entire theoretical approach seems to rest on them, but the most basic concepts in science often prove to be the most difficult to analyze explicitly.

The situation is especially peculiar with respect to "information" in that, at first glance, it might seem as though there is a readily available formalization in Shannon's (1948) mathematical theory of information. But Shannon's conception of information is not what we meant when we talked about information in the first assumption and not, we suspect, what any other IP theorist means by it either. To see why, one needs only to consider the general nature of Shannon's formulation of information: it is a unidimensional quantity (measured in "bits") which expresses the reduction in uncertainty by a receiver about a source via a message transmitted through a noisy communication channel. Even without the mathematical details it is easy to see that this is not what the first assumption is about. As many commentators on the mathematical theory of information have also noted (e.g., Cherry, 1957; Dretske, 1979; Garner, 1962) Shannon's conception of "information" refers only to the *amount* of something as measured in bits, whereas "information itself" is about the *something* that gets measured in these bits. What IP psychologists mean by information is far more closely related to the content of the "messages" and the whole communication context that surrounds them than it is to the "amount of reduction in uncertainty". Shannon's theory is really about the *informativeness* or *surprise value* of messages rather than about their actual *information content*. This means that we are almost back to where we started: we know that information is not the same as Shannon's measure of informativeness, but we still don't know what it is or how it is related to his formulation. This is a rather embarrassing situation, but one that accurately reflects the present state of affairs in IP psychology.

As we are using the terms, information is an abstract construct in theoretical descriptions of mental events. We have used it in this way to reflect the pervasive belief among IP psychologists that IP theories are *abstract*, *functional* entities that do not depend on at least certain physical characteristics of the events being described. But we still need to define this level of abstraction and to say how it arises in the IP paradigm.

The key to understanding the abstractness of the IP level lies in the abstract nature of information itself. This abstraction can be intuitively demonstrated by examples in which two physically very different signals can carry the same information about some referent state of affairs. For example, Paul Revere and his co-conspirator agreed that information about the arrival of British troops was to be carried

[1] We say "most" because there are some examples of functional theories based on informational descriptions that are, nevertheless, not instances of IP theories. The most notable example is James J. Gibson's (1966, 1979) theory of ecological optics in which informational descriptions play the central role, but which does not conform to the additional assumptions of IP.

by the number of lights hung in the church window ("one if by land and two if by sea"). However, the *same information* could have been equally well transmitted by the opposite arrangement ("one if by sea and two if by land"), or by the color of a single light ("red if by land and blue if by sea"), or by the number of cannon shots fired, or, indeed, by any other pair of signals that Revere could have distinguished from his vantage point on the opposite shore, provided that he and the signal-sender had agreed on the signals and their corresponding interpretations in advance. There is an important sense in which all of these alternative signals -- one light, two lights, red light, blue light -- would have been *informationally equivalent* under the corresponding scenarios, despite their wide variety as different physical events; the reason is that they all "stand for" or "represent" the same referent event. This informational equivalence is, by definition, more abstract and general than mere physical equivalence. It is a form of *functional equivalence* because it is concerned with the extent to which different events could be substituted for each other and still "work in the same way" or "cause the same outcome". It is in precisely this sense that IP descriptions are more abstract that the physical events they describe. The abstract functional nature of IP descriptions thus lies in the nature of information itself, specifically in the abstract equivalence relation defined by substitution.[2]

Mapping Theories. At this point in our development of IP theory the whole operation performed by the human mind is conceived as a single, complex function that maps input information to output information. Informational theories of mind can be and have been proposed at this highly abstract level. We call such theories "informational mapping theories" or simply "mapping theories".[3] They specify *what the mapping is* in a systematic and well defined way without claiming to specify *how this mapping is accomplished*. In other words, mapping theories make no psychological claims about what goes on "inside the mental black box"; they merely describe the result of the mapping performed from inputs to outputs.

Despite this limited goal, mapping theories of large domains can be notoriously difficult to construct and are correspondingly rare. In part this is because precise specification of the mapping often requires extensive use of formal mathematical tools such as algebra, geometry, formal grammars, predicate calculus, computer programming, and the like. Another difficulty lies in the vast scope of a mapping

[2] Whereas in this example Revere and his partner had to agree explicitly on the informational correspondence between events and signals (and hence the interpretation of the signals by Revere), the same cannot literally be true for informational theories of mind, since there are no parties to do the agreeing. Instead, the role of agreement in this example must be played by some other method of arriving at a conventional interpretation: namely, some *process of selection*, such as evolution in cases of innately given interpretations (e.g., simple unlearned reflexes) or learning in cases of organism-acquired interpretations. In informational theories of mind, interpretations of signals carrying information about the world must be *achieved* through some process that provides feedback about the appropriateness of the chosen interpretation. Thus the informational correspondence is "agreed" upon by what *works*: which interpretation is evolutionarily successful or which one leads to desired outcomes in the learning situation. The end result is the same as if an agreement had been made between the environment and the organism: the signals carry information about the environmental events that is largely independent of their specific physical nature.

[3] Mapping theories are very similar to what Marr (1982) has called "computational theories". We find his label unfortunate because it strongly suggests that the mapping is accomplished by some sort of computation. If the mapping theory really makes no claim about *how* the mapping is accomplished, calling it "computational" seems to prejudge an important issue that lies outside the mapping theory itself. We will discuss these issues in more depth later in the section on "Computationalism".

theory for the entire range of human performance. Therefore, it is not surprising that the available examples attempt to define the input-output mapping only for some modest subdomain of human mental abilities: e.g., Chomsky’s (1965) transformational grammar theory of linguistic syntax, Horn’s (1975, 1977) differential geometric theory of perceiving shape from shading, Johnson-Laird’s (1983) predicate calculus theory of syllogistic reasoning, Leeuwenberg’s (1971, 1978) symbolic coding theory of shape perception, Longuet-Higgins and Prazdny’s (1980) theory of optical flow, Marr and Poggio’s (1979) "computational theory" of stereoscopic vision, and Ullman’s (1979) theory of motion perception, to name some of the most prominent examples. If the scope of the mapping theory is sufficiently narrow, of course, then it can be defined simply by enumerating the input-output correspondence: e.g., the mapping theory of naming the capital letters of the alphabet in a particular type font can be specified completely by a list of 26 ordered pairs. Such simple mapping theories are usually not stated explicitly because they are intuitively obvious.

Since mapping theories do not attempt to specify *how* the mapping from inputs to outputs is accomplished, scientific interest in them centers on their formal rigor, predictive accuracy, and ecological validity. Unfortunately, it is often unclear just how accurately the specified mapping predicts the mental mapping because the theorist makes the "competence assumption": an assumption that the theory specifies the mapping independently of any "performance" or "resource" limitations (cf., Chomsky, 1965). This strategy can be justified on the grounds that if one does not care *how* the mapping gets done, the theory need not -- indeed, should not -- take such considerations into account. However, the fact that such limitations usually do affect the observed mapping weakens the empirical implications of the mapping theory and, therefore, makes it hard to test. The problem is that it is difficult to discriminate cases in which the inaccuracies arise simply because the competence assumption is inappropriate versus cases in which they arise because of fundamental inadequacies in the mapping theory itself.

Mapping theories are also often judged by criteria of ecological validity as well. The reason is that if a theory concerns only *what* mapping is performed, it is important that the mapping be one that applies, at least in principle, to a wide range of realistic stimulus situations. If not, it is unclear what the importance of the theory is for understanding human behavior. Unfortunately, the criteria for deciding how valid a theory is ecologically are seldom well defined, and judgments usually rest on vague intuitions about the superficial similarity between the conditions to which the theory applies and the naturally occurring conditions in the ecology of the organism. Ecological criteria are usually taken to be less critical in evaluating theories that attempt to specify *how* the mapping occurs. Such theories are taken to be primarily about the internal mechanisms they postulate, and so application to simple (and seemingly ecologically invalid) situations are valued for the additional scientific rigor they often permit in empirical tests.

To the above list of mapping theories one might wish to append some important related theoretical efforts that are similar in kind, but miss one of the critical attributes of rigor, accuracy, and ecological validity. James J. Gibson’s (1950, 1966, 1979) "ecological optics" theory of spatial perception was clearly in the spirit of a mapping theory by our definition -- i.e., he tried to specify the mapping from proximal stimuli to perceptual responses -- and had strong claims to validity by ecological criteria, but only infrequently did it achieve the requisite level of rigor to specify the actual mapping (e.g., Gibson, Olum &

Rosenblatt, 1955). Naturally, when a mapping theory is not well enough defined to determine the mapping unambiguously, its accuracy is correspondingly difficult to evaluate, and this has been a problem with many of Gibson's proposals. Other possible candidates for mapping theories come from "normative" theories, often adopted wholesale from other disciplines. They are usually rigorous, but often turn out not to give a very good account of human performance, even taking the competence assumption into account. Examples of this type include mathematical logic as a theory of human reasoning (e.g., Inhelder & Piaget, 1958; Henle, 1978; see Johnson-Laird, 1983, for a critique), mathematical information theory as a theory of human performance (e.g., Fitts & Posner, 1967; Garner, 1962), and Bayesian probability theory as a theory of human inference (e.g., Edwards, 1965; 1968; see Kahneman & Tversky, 1973, for a critique).[4]

The relatively small number of currently viable mapping theories should not be taken as evidence that they are unimportant. Indeed, their advocates have argued that they are absolutely critical to the enterprise of understanding the mind and that the lack of such theories is largely responsible for psychology's slow progress (cf., Chomsky, 1965; Gibson, 1966, 1979; Marr, 1982). IP psychologists are interested in them -- or should be -- because, even though they do not *propose* internal mechanisms, they strongly *constrain* possible mechanisms and are testable. The constraints arise from the fact that knowledge about the mapping eliminates or makes implausible an enormous set of possible mechanisms. Their testability derives from the fact that they are directly tied to empirical reality at both the input and output ends, and so can be compared directly to human behavior. The importance of mapping theories in psychology is confirmed by inspecting the foregoing list. Even in cases where they have clearly failed as psychological theories, testing them to find out when and how they go wrong has produced important results that have strongly affected further theorizing. For example, the ways in which formal logic (cf., Johnson-Laird, 1983) and Bayesian probability theory (cf., Kahneman & Tversky, 1973) have failed as theories of human performance have led later theorists to more accurate formulations.

Notice that there is nothing about mapping theories that is unique to the IP approach. They are certainly *consistent* with it (cf., Marr, 1982), but the relationship is a weak one. Gibson, for example, was a strong advocate of what we are calling mapping theories, yet he was openly opposed to and critical of the IP approach. Some of his followers in ecological psychology are even more adamant about their opposition (e.g., Turvey, 1977; Shaw & Bransford, 1977). What these theorists primarily object to is IP's further assumption that a psychological theorist should *decompose* the mental mapping by postulating a structure of internal events that purport to describe *how* it is achieved. We now turn our attention to this second critical assumption of the IP approach.

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[4] Given the indeterminacy mentioned above in determining whether inaccuracies in the mappings are due to errors introduced by the competence assumption or more fundamental errors in the theory, there is a certain unavoidable element of personal judgement in deciding whether a given theory is an instance of a "good" mapping theory or belongs in this category of "inadequate" normative theories. There seems to be a correlation with the theory's age: older mapping theories are more likely to be thought inadequate, probably just because they have been more thoroughly tested. Chomsky's (1965) transformational grammar theory, for instance, would now be thought by many to be an inadequate "normative" theory rather than a psychologically interesting mapping theory.

Assumption 2: Recursive Decomposition

Perhaps the most central assumption of IP theories is that any unitary informational event can be described more fully at a more specific (or "lower") level by decomposing it into simpler informational events. We state this conjecture as the assumption of *recursive decomposition*:

(2) Any complex (non-primitive) informational event at one level of description can be specified more fully at a lower level by *decomposing* it into (a) a number of components, each of which is itself an informational event, and (b) the temporal ordering relations among them which specify how the information "flows" through the system of components.

Informational theories that make use of this assumption are true *IP theories* (or "process models") because they make claims about what is inside the "black box" of the mind. This level of theory corresponds to what Marr (1982) has called the "algorithmic" level. Unlike mapping theories, which only specify *what* the mental mapping is, IP theories try to specify something about *how* that mapping is accomplished. Such IP theories are usually represented graphically by drawings such as those shown in Figures 1B and C. We will call these *IP flow diagrams*.[5] For instance, Figure 1B shows a possible flow diagram for the unitary operation depicted in Figure 1A. It is typical of first-level IP flow diagrams proposed as theories of mental structures involved in cognitive tasks (e.g., Atkinson & Shiffrin, 1968). Each of the components at this level has its own "primitive" description in terms of the three functional parts of a informational event: (a) its input information, (b) the operation that gets performed, and (c) the output information that results.

A flow diagram is only an *incomplete* representation of an IP theory, however, because it does not show precisely what input-to-output mapping is accomplished by the operations depicted in the flow diagram. What is needed to complete the theory is a "mini-mapping theory" for each of the internal informational events postulated in the diagram or, equivalently, a direct description of the operation. In many cases the mapping theory of the components is so trivial that it does not really need to be spelled out. However, in many other cases the mapping claimed for the hypothesized components is very complex and does need to be explicitly defined, although theorists often fail to do so. The primary difference between these "mini" mapping theories for components within an IP theory and "pure" mapping theories that stand alone at the highest (undecomposed) level is that the former are only indirectly tied to empirical reality, whereas the latter are directly tied to it. For this reason the IP theorist has a substantially more freedom in postulating "internal inputs" and "internal outputs" for hypothetical informational events inside the head than the pure mapping theorist has for defining the nature of "external inputs" and "external outputs".

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[5] We purposely avoid calling them "flowcharts" because of its more restricted, technical meaning in computer science as a device for specifying "transfer of control" in a serial computer. The IP flow diagrams we use here are intended to be a more general representation of how information flows over time through a system of processing components, more or less like a "time-lapse photograph" of the dynamic IP system in action. There are many difficult and technical issues involved in specifying just what these diagrams mean, but we will avoid them here and rely on an intuitive understanding of them, fully realizing that this will need to be specified further at some later time.

The decomposition assumption states that operations can be broken down into a flow diagram. Because this does not exclude operations that resulted from previously decomposing a higher-level operation, it implies that the decomposition of operations into flow diagrams can be performed *recursively*. For instance, Figure 1C shows how one operation in the structure shown in Figure 1B, short-term memory, might be further decomposed into a flow diagram of still simpler operations (Baddeley, 1976). Naturally, any of the other operations shown in Figure 1B could be similarly decomposed, although we have not shown this in our diagram.

The recursive nature of decomposition implies that a tree graph can be constructed to represent the hierarchical embedding of flow diagram components, as shown in Figure 1D. The vertical dimension reflects what we have been referring to as "height" ("high level" versus "low level" operations) or "specificity" ("general" versus "specific" descriptions), and the horizontal dimension simply enumerates the components that belong to each level of flow diagram. Later we will use this conception to clarify the relation between IP theories and computer programs that simulate them.

The Role of Primitives. It it clear that without some stopping rule the decomposition assumption could, in principle, be applied recursively *ad infinitum*. We have included an implicit stopping rule in our second assumption through the concept of a "complex (non-primitive) informational event", since only these can be further decomposed. By implication, then, a *primitive* informational event *cannot* be further decomposed. We have intentionally left this stopping condition vague because there are at least two plausible and well-used strategies for defining such primitives, one based on "software" considerations and the other on "hardware" considerations. They broadly characterize two styles of theorizing that coexist relatively happily within the IP approach, a "computational" or "software" one based on choosing primitives for computational plausibility and a "physiological" or "hardware" one based on choosing primitives for their neurological plausibility.[6] There is, in addition, a third strategy for dealing with the conditions under which to stop decomposing, and that is simply not to worry about it. Many IP psychologists, perhaps even most of them, are quite satisfied to work at a level which is well above any ultimate "primitives" and leave theorizing at such a "low" level to other theorists.

The computational strategy is to base the stopping rule on "software primitives": choose some set of simple, well understood, primitive IP operations *a priori* and stop when these are reached. For instance, Newell and Simon (1972) define a plausible set of primitive IP operations which are equivalent in power to a universal Turing machine (Newell, 1980), and IP theories have been proposed in terms of just such primitives (e.g., J. R. Anderson, 1976, 1983; Just & Carpenter, 1977; Newell & Simon, 1972). This approach has the logical advantage of definiteness: one does indeed know just what the conditions for stopping are. However, it has the disadvantage of potential inapplicability: one does not know beforehand whether these conditions will ever be reached. In choosing a given set of primitive operations it is

[6] The distinction between "computational" and "physiological" approaches is *not* precisely aligned with the disciplines of computer science and psychology, respectively. Some computer scientists have proposed theories that are essentially "physiological" in our sense (e.g., Feldman, 1981; Hinton & Anderson, 1981; Marr & Poggio, 1976; 1979). Conversely, some psychologists have proposed theories that are "computational" in our sense (e.g., J. R. Anderson, 1976; 1983). Still, there does seem to be a tendency for psychologists to favor the physiological strategy and computer scientists to favor the computational one.

important to know, for example, that they are logically *sufficient* to capture the full range of mental capabilities one wishes to describe. Using a set that has the same computational power as a universal Turing machine is obviously a good place to start, but as we will discuss later (see the section "On Computationalism"), there is no way of knowing *a priori* that even this will turn out to be sufficient.[7] If the primitives chosen are insufficient, any theory based on them will necessarily fail. Even assuming that the primitives are logically sufficient, they should also be the psychologically correct primitives. Different sets of primitives can yield quite different IP analyses of the same behavior, so choosing the wrong set in advance will produce the wrong theory.

The physiological strategy is based on "hardware primitives": stop when the hypothesized IP operations are functional descriptions of known physical components in the device being described. This approach can be illustrated by analogy to "black box" problems in physics. The student presented with the box knows beforehand that the electrical components inside the mysterious container are things like resistors, capacitors, transistors, and the like, each of whose functional descriptions he or she supposedly knows well. When a "theory" of the contents of the box is specified as a circuit in which each hypothetical component has the functional description of a resistor, capacitor, transistor, or whatever, then the "bottom" has been reached. Naturally, the student cannot really *know* until the box is opened that it does not contain some far more complex circuit -- such as a microcomputer that simulates the hypothetical simple circuit -- but as long as the functional characteristics of the physical components are known in advance, there must be at least one correct answer in terms of the functional descriptions of these hardware primitives.

The strategy of hardware primitives has much to recommend it. It is necessarily applicable because the functional description of the hardware *must*, by definition, be applicable to describing its behavior. By the same token, it must also be logically sufficient to account for the capabilities of the device, since that is how the device actually does it. There are several potential problems, however. One is that the level of hardware primitives may be considerably "lower" (more specific and detailed) than that of software primitives. For example, in modern digital computers hardware primitives are much lower level than the software primitives found in the languages that people typically use to program them. If this is so, using hardware primitives will unnecessarily increase the complexity of the "bottom level" IP description.

A potentially more serious problem is that psychologists probably are not yet in the same position as a physics student with a "black box problem" in that we do not really know what the brain's critical

[7] Many theorists believe that a set of primitives equal in power to a universal Turing machine *must* be sufficient to capture the nature of mental events (e.g., Newell, 1980; Johnson-Laird, 1983). Their belief rests on the intuition that "Turing's thesis" is correct. Turing (1936) proposed that any scientifically well defined procedure (usually called an "effective procedure") could be carried out by some Turing machine. If so, one can conclude that if the nature of mind can be captured by an effective procedure, then any set of primitive equal in power to those of a universal Turing machine will be sufficient to capture the nature of mind. Turing's thesis remains a conjecture, however. The fact that no one has yet discovered a well defined procedure that is beyond the capabilities of a universal Turing machine does not mean that no one ever will. We may currently be in much the same position that geometers were for many centuries when Euclid's geometry was thought to be the only one. In the last two centuries, however, many non-Euclidean geometries have been discovered. Perhaps there is an enormous class of as-yet-undiscovered effective procedures that are beyond the scope of Turing machines. The fact that none have yet been encountered is only weak evidence that Turing's thesis is correct.

physical units are with respect to mental function. The most obvious candidate is, of course, the neuron. However, the important structures might ultimately turn out to be much smaller, such as molecular processes at synaptic membranes, or much larger, such as complex Hebbian cell assemblies (Hebb, 1949). There are at least a few cases in which there is currently good agreement between an IP description and a known physiological structure, all of which do currently point to the neuron as the basic physical unit of processing. However, most of these examples come from fairly peripheral sensory systems -- such as color vision (De Valois & De Valois, 1975) and spatial vision (De Valois & De Valois, 1980) -- and the relevant unit of processing might conceivably be quite different for more complex cognitive operations.

Still, many IP theorists do seem to use a "hardware primitives" rule, at least implicitly, in that they couch their theories in terms of excitation and inhibition among processing elements more or less like individual neurons or neural pathways (e.g., Feldman, 1981; Hinton, 1981; Marr, 1982; McClelland & Rumelhart, 1981; Palmer, 1983; Palmer & Bucher, 1981; Posner, 1978; Rumelhart & McClelland, 1982). It is perhaps not too surprising that these physiologically oriented theories tend to be of relatively peripheral mental operations such as sensation and perception, processes about which at least something is known of the corresponding neural hardware. Computationally oriented theories tend to be of more complex, central processes like memory, language understanding, and problem solving, processes about which relatively little of importance is yet known with respect to the hardware involved. The principle exception to this generalization comes from recent attempts by some physiologically oriented theorists to explore the potential capabilities of quasi-neural devices for higher-level cognitive processes like memory and categorization (see Hinton & Anderson, 1981, for a good sample).

Complexity Reduction. The rationale for decomposing mental operations into well formed flow diagrams is to specify the nature of a single *complex* operation in terms of information flow among a number of *simpler* operations. In principle, at least, the decomposition should "factor out" some portion of the complexity *implicit* in a mental operation when it is considered as a unitary informational event by making it *explicit* in the flow relations among a number of simpler operations. This is what we mean by "complexity reduction": with each lower level of description the internal complexity of the component operations should decrease. Generally speaking, this reduction comes at the cost of more components and more complex flow relations among them. However, the goal is to make complexity explicit, so the net effect of decomposition is to reduce the unwanted commodity: implicit complexity. In effect, as one proceeds down the decomposition tree (see Figure 1D), more and more of the complexity is accounted for by the arrows between the boxes (the part made *explicit* in the flow diagram) and less and less by the "mini" mapping theories of the boxes themselves (the part still *implicit* within the operations).

The assumption that decomposition reduces implicit complexity probably *should* have the same status within IP as the previous three, but it does not for several reasons. The primary problem is that being rigorous about it would require well-defined measures of IP complexity both for mapping theories (i.e., the internal nature of the unitary operations) and for IP flow diagrams (i.e., the ordering relations among these unitary operations). No such measures of either kind are currently in use or, to our knowledge, have ever been suggested. Most IP practitioners probably do believe, at least implicitly, that something like this complexity reduction assumption applies to IP theories because they feel that they understand more about what is going on after an operation has been decomposed than they did when it was a unitary, unarticulated event. This intuition depends heavily on the initial unitary operation being more complex than the several operations into which it is decomposed. Without any well defined measures of informational complexity, however, it is difficult to tell for any given IP theory whether such beliefs are really justified.

Emergent Properties. One effect of decomposition not captured by the notion of complexity reduction is that the resulting component operations are not only quantitatively simpler than the initial one, but *qualitatively different* from it. For instance, what would be described as a unitary operation at a high level as a memory search operation ("look for a target, T, in list, L") is radically recast in terms of the information flow among its component operations: data retrieval ("get the next element, E, from list L"), pairwise comparison ("compute the similarity, S, of E to T"), decision ("is S greater than some critical value, C?"), and conditional control ("if so, return positive; otherwise, go to start"). Notice that although each lower level operation does something quite specific that is easily described on its own, none of them does anything like "search sequentially through a list". Only when they are configured into an appropriate flow diagram do they, *together*, perform a search operation. "Search" does not really exist in any of the lower level components individually; it *emerges* only when they are put together in the proper flow relations. Strictly speaking, then, it is appropriate to speak of a "search" taking place only at the higher level of description where what is happening is conceived as a unitary event.

Thus we see that higher level IP descriptions sometimes contain *emergent properties* that lower level descriptions do not. It is the *organization* of the system specified by the flow relations among the lower level components that gives rise to these properties. There is nothing mysterious in this. It is equally true in physical systems where systemic "macro" properties arise only in large systems of elements with different "micro" properties. As a simple example, the gaseous, liquid, and solid states of matter arise only in aggregations of many molecules, since no single molecule, by itself, has the properties of being gaseous, liquid, or solid (cf., Putnam, 1975; Searle, 1983); such properties depend on the relations among many molecules. Even better physical analogies can be found in complex human artifacts like stereos, automobile engines, and telephones: the properties of the object as a whole are qualitatively different from those of its smaller physical components. It seems entirely appropriate to conceive of emergent properties in IP systems in essentially the same way; there is no magic involved, just the configural interaction of different subsystems in ways that produce different properties at the systemic level.

Assumption 3: Flow Continuity

Information processing theories postulate decompositions of mapping theories into psychologically meaningful components. Not just any decomposition will do, of course, since the ordering or "flow" of information among components imposes certain important constraints. These constitute the third assumption of IP, concerning the syntax of IP flow diagrams:

(3) All input information required to perform each operation must be available in the output of the operations that flow into it.

This assumption is perhaps so obvious that it almost goes without saying; it is really just a corollary to the decomposition assumption. In terms of flow diagrams, it states that the input for each "box" consists of the output of all the other "boxes" that lead directly to it by forward-going arrows. If this information is not sufficient for the operation to occur, then the flow diagram is not "well-formed", and the theory it represents is logically deficient in the sense that it could not actually carry out the operation it purports to describe. To determine whether such flow constraints have actually been met, the IP flow diagram of an IP theory must be supplimented with a "mini" mapping theory (in the sense described earlier) of each hypothesized operation. In reality, most IP theorists give, at best, a rather vague, verbal description of the input-output characteristics of the components, and it is often hard to determine whether the flow continuity constraint has been met from such verbal statements. As Newell and Simon (1963) have argued forcefully, this problem can be solved by supporting the theory with a computer simulation, since the program necessarily specifies a "mini" mapping theory for each operation in the flow diagram. Unfortunately, simulations are seldom actually done, and some residual amount of "handwaving" invariably remains in any verbally stated theory. (Later we will discuss the relation between simulation programs and IP theories in greater depth.) Flow diagrams that meet the flow-continuity requirement, insofar as this can be determined, constitute IP theories of the unitary informational event at some lower level of description.

Assumption 4: Flow Dynamics

Some additional assumption is needed to specify the temporal properties of information flow within the system. Here we try to specify some of the most general constraints in terms of the assumption of *flow dynamics*:

(4) No output can be produced by an operation until its input information is available to it and sufficient time has elapsed for it to process this input.

The dynamics of information flow are particularly important in psychology because they often play a central role in empirical tests of the theory. We have attempted to capture only the constraints that (a) processing cannot begin until at least some input information is available and (b) that every operation takes some amount of time, no matter how small.[8] Beyond these two notions, flow dynamics are pretty much up to the theorist and the constraints imposed by the proposed flow diagram.

The most frequently made additional assumption about the time course of processing is that each operation in the flow diagram constitutes a discrete *stage* (Sternberg, 1969a). In stage theories, each operation has a specific duration (plus or minus random variability) that depends on parameters determined by the input information. Before the end of this time interval the operation has no output, and at the end its output is assumed to be fully available as input to the next operation. This notion of discrete stage theories gained immense popularity with the success of Sternberg's (1966, 1969b) work on memory scanning and his formulation of the additive factors method (Sternberg, 1969a). In one form or another stage models have dominated IP theories of flow dynamics ever since.

Other conceptions of flow dynamics are not ruled out, of course; they just make things more complicated. Norman and Bobrow (1975) suggested that a more flexible and realistic conception of information flow was needed than stage theories provided, and proposed the hypothesis of "continuously available output" as an alternative. McClelland (1979) developed a specific mathematical theory of this type which he aptly called "cascade processing". In cascade theory, each operation begins to produce some output almost as soon as it gets some input, and certainty in the result increases over time as more and more input is received from preceding operations. Whether this more complex conception of information flow actually provides a more accurate model of IP dynamics than does stage theory is currently unclear, but the formulation of alternatives to stage conceptions of flow dynamics has been an important theoretical development. Even if stage processing does turn out to be correct, the crucial evidence will undoubtedly come from explicitly testing its assumptions against those of well-defined alternatives (e.g., Meyer *et al*., 1984; Miller, 1982).

Among the most important issues related to flow dynamics is whether a given pair of operations are executed sequentially (serial processing) or simultaneously (parallel processing). This is specified in the

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[8] Some mathematical models have been proposed which assume an exponential distribution of completion times (e.g., Townsend & Ashby, 1983). Taken literally, this implies that stages can take no time at all. Because this distributional assumption is generally made for reasons of mathematical convenience rather than psychological validity, we do not see such models as real contradictions of the assumption that all operations take some finite amount of time: if an otherwise equally attractive alternative were available that did *not* allow for the possibility of "instantaneous" processing, we presume that it would be used in preference to exponential models.

information flow diagram by the obvious conventions: a "chain" of arrows from each operation to the next (serial) or several arrows diverging from a point and leading to several operations at once (parallel). Although this distinction is quite clear theoretically, it turns out to be much harder to pin down experimentally than was initially suspected (see Townsend, 1971, 1972; Townsend & Ashby, 1983). The problem is that many different versions of serial and parallel process models can be constructed and, depending on which additional assumptions are made, some serial models make predictions that are not empirically distinguishable from some parallel models, and vice versa.

This points out a problem in testing IP models, a problem that we suspect may be far more general than this particular example. It may be quite difficult to produce rigorous tests of large classes of alternative IP models (e.g., serial versus parallel) because pairs of models in the different classes make the same or insufficiently different predictions when they are examined in detail. The moral may well be that rigorous tests require comparisons between much more detailed classes of models than are usually considered.

Assumption 5: Physical Embodiment

Earlier we argued that information and operations are abstract, functional entities that exist in the domain of IP descriptions. Now it is time to acknowledge fully that information processing actually takes place in the concrete physical world of mechanical, electronic, optical, and biochemical devices and to say something about how abstract information and operations relate to the physical reality of this material world. Clearly they need some physical "vehicles" in the dynamic real-world event that is being described in terms of information and operations. We make explicit the intuitions that information and operations are carried by some physical "medium" or "substrate" in the fifth assumption of the IP approach, that of *physical embodiment* (or "implementation").

> (5) In the dynamic physical system whose behavior is being described as an informational event, information is carried by states of the system (here called *representations*) and operations that use this information are carried out by changes in state (here called *processes*).

Notice that as we are using the terms, *representation* refers to the physical system that "carries" (or "contains" or "embodies" or "instantiates") information, and *processes* refer to the physical processes that "carry out" (or "perform" or "embody" or "instantiate") the operations. Thus, "information" and "operations" exist in the formal domain of *IP descriptions* of events, whereas "representations" and "processes" exist in the physical domain of objects and events in the world *when these are viewed as information processing*. Thus, we do not mean to imply that representations and processes are *merely* physical objects and events, but physical objects and events under an informational and operational description.

We have not yet said anything about what makes these systemic states count as representations that carry information about some other state of affairs. This is an important metatheoretical question within the IP framework, and some work has been done explicitly on it (e.g., Bobrow, 1975; Newell, 1980; Rumelhart & Norman, 1984; Palmer, 1978). The prevailing notions are that representations are defined by (a) being *used* as a surrogate for some referent world and (b) preserving the abstract informational structure of that referent world. These two aspects can be easily demonstrated in how a standard road map acts as a representation of the roads, towns, and spatial layout of the geographical region it depicts.

To *use* the map as a surrogate of the region, one needs to establish a correspondence (or mapping) from geographical objects to map objects and geographical relations to map relations. In an actual road map, this correspondence is spelled out in the "key" and the various labels attached to map-objects. If a representation is to *work* as a surrogate, however, it also has to be reasonably accurate. This is where preserving structure comes in. Structure is preserved when the the truth of statements about the referent world is reflected by the truth of the corresponding statements about its representation. For instance, true statements about the lengths of roads, directions of roads, distances between cities, and so forth correspond to true statements about the corresponding map entities: the lengths of lines, directions between lines, and distances between small circles. Together, these two aspects of representation allow a model to be used as a surrogate of the world.

Unfortunately, space does not permit us to present even a small subset of the issues involved in deciding what sorts of internal representations people use in perceptual and cognitive processes. The reader is referred to Palmer's (1978) presentation for a more complete analysis of the nature of representation in IP theories and to Rumelhart and Norman's (1984) discussion for a survey of issues and specific assumptions that have been made in recent IP theories.

Flow Diagrams versus Programs as Psychological Theories. We have proposed that IP theories are well-formed information flow diagrams plus mini-mapping theories of the operations within them. We now want to consider how this view of IP is related to the well known claim that running computer simulation programs are IP theories of the mental processes that they simulate (e.g., Newell & Simon, 1963). Superficially, at least, they seem to be compatible, since they are both in the same line of theoretical analogy. Although they are definitely related, we see them as distinct claims, at least in the sense that IP theories are descriptions whereas programs are the things described.

According to the present view, a running simulation program is only an IP theory by virtue of the fact that it too can be described by a flow diagram plus mini-mapping theories of its components. If there were one unique flow diagram associated with each program, then there would be no difficulty. However, any program can be described by (or is compatible with) many different flow diagrams at different levels of specificity. In fact, programs are often written by constructing a sequence of hierarchically embedded flow diagrams at more and more specific levels of detail (e.g., as shown in Figure 1). Therefore, important problems arise in deciding *which* flow diagram corresponds to the theory allegedly embodied in the program.

The important theoretical issue for the simulation theorist concerns which flow diagrams he or she takes to be psychologically meaningful. For instance, there is a level of description (i.e., a flow diagram) that corresponds to the sequence of elementary logical operations the digital computer actually executes when it runs the simulation in "machine language". Almost nobody would take this level of description to be psychologically meaningful, and yet it is the most obvious level of flow diagram to identify with "the program". At a higher level, there is the flow diagram that reflects the statement-by-statement sequence of operations specific to the higher-level programming language that the simulationist used: Lisp, Fortran, Pascal, APL, or whatever. It is very unlikely that even this level of description is psychologically meaningful, although it has been claimed that certain languages are much closer to the elementary IP operations of the mind than others (see Newell & Simon, 1963).

At some still higher level of description the operations represented by the flow diagram become plausible components of a psychologically reasonable IP theory of the mind. A simulationist might well want to claim, for example, that high level flow diagram components like searching through a network structure from several nodes simultaneously (as in "spreading activation" theories) or matching one feature list against another for similarity *actually happen* in the mental process simulated by the program. Even in a high-level programming language, such components usually involve large chunks of "code" that include many *ad hoc* details, such as the programming tricks required to mimic parallel processes on serial machines. Clearly the latter are *not* part of the IP theory the simulationist had in mind, whereas the former, large-scale components of the higher level flow diagram *are* part of the theory. Thus, decisions about which components are psychologically real determine what level of description of the program constitutes the IP theory it embodies. Since there may be higher-level flow diagrams that the theorist also wants to claim are psychologically meaningful, the theoretical interpretation of the program corresponds to drawing a line across the hierarchy of flow diagrams to separate those components that are psychologically meaningful ("above" the line) from those that are implementational details ("below" the line). The reason for wanting to keep the higher level flow diagrams as part of the psychological theory, of course, is that they may well be correct even though lower-level ones are wrong.

This way of viewing simulation programs also makes clear one of their principle drawbacks as cognitive theories: the constraints of writing a complete, runable program require the theorist to specify much more than he or she actually needs to specify for the IP theory. This includes everything in the hierarchy of flow diagrams that exists "below the line". As anyone who has ever written a simulation program soon realizes, enormous amounts of time and energy must be expended in figuring out how to get the machine to do what is required, even though many of the details of how this gets done are not really part of the theory. The payoff for this additional work is the assurance that one's theory is actually capable of performing the task simulated and that one really has mini-mapping theories of each component operation in the flow diagram.

In summary, we are arguing that a simulation program *implies* an IP theory, but is ambiguous about just what that theory is. Once the theorist has identified the level of flow diagram that separates meaningful theoretical statements from mere programming details, the theory attached to the simulation becomes clear. We view this analysis as a clarification of the program-as-theory idea rather than as a contradiction. We agree wholeheartedly with much of the spirit and the motivation behind the program-as-theory movement, such as specifying vague verbal theories more precisely and allowing their adequacy to be tested rigorously. Our objection is merely that simulation theorists should be more careful than they often have been in separating their program as it runs on a computer from their theory of the mental processes it simulates.

Relations to Other Views of Cognition

We stated at the outset that one of our primary goals in trying to specify IP theory was to clarify its relation to other views of cognition. Having now stated explicitly at least some of what we believe are the principal assumptions underlying IP theory, we are in a position to contrast it with some other noteworthy approaches to cognitive theory in the history of psychology: cognitivism, behaviorism, and ecologism. We then turn our attention to some more contemporary views of cognition that are closely related to IP: computationalism (or "weak AI"), functionalism, and Turing-machine functionalism (or "strong AI"). Our initial intuition that IP is different from and weaker than these other contemporary views turns out to be correct when the underlying issues are examined carefully. IP is not so weak as to be meaningless or unfalsifiable, but it does make fewer substantive claims about the nature of human mentality than these related proposals.

Cognitivism

It is important to be clear at the outset that IP psychology, as described here, is *not* the same as "cognitivism", but a specific brand of it. As the term is used in psychology, "cognitivism" refers to a very broad theoretical position in which it is assumed that behavior can only be properly understood by postulating internal "cognitive" (or "mentalistic") states such as percepts, attitudes, beliefs, goals, memories, images, plans, and the like. This explicitly cognitivist stance was formulated vigorously by Tolman (1932) in response to the explicitly anti-cognitive viewpoint expressed in Watsonian behaviorism (Watson, 1913, 1925). Prior to this time, psychological theory was certainly "cognitive" in the sense we have defined, but it was only implicitly so. It took the challenge of the behaviorist alternative to bring the cognitivist viewpoint into focus.

Information processing is certainly an explicitly cognitivist approach in that it encompasses theories based on such hypothetical internal states. However, IP goes well beyond simple cognitivism in making further assumptions about the specific *form* that such theories should take. It is these further assumptions -- described here in terms of informational description, recursive decomposition, flow continuity, flow dynamics, and physical embodiment -- that distinguish IP theories from other cognitive theories. Indeed, there are many cognitivists who simply do not ascribe to one or more of these assumptions, preferring to work within a looser (or at least different) set of theoretical constraints that are nevertheless quite "cognitive". Historically prominent examples include Freud, Piaget, Vygotski, Wertheimer, Kohler, Koffka, Bartlett, and, of course, Tolman. Thus, IP is correctly viewed as a proper subset of cognitivism: all IP psychologists are cognitivists, but not all cognitivists are IP psychologists.

Behaviorism

The relation between IP and behaviorism is far more complex, since (a) there are several different brands of behaviorism that need to be distinguished and (b) each brand includes somewhat different proposals with which IP is in agreement on some and opposed on others. Perhaps because IP arose historically as a reaction *against* behaviorism, there is a tendency to see them as diametrically opposed. As is often the case, however, the new approach has much more in common with the one it supplants than is initially acknowledged. This is clearly true of the relation between IP and behaviorism.

As initially proposed by Watson (1913, 1925), the behaviorist approach broke with the then-traditional introspective approach by identifying publicly observable behavior as the central concern of psychology rather than private mental experiences. This general proposal contains at least two quite different aspects which need to be distinguished, however: *methodological behaviorism* and *theoretical behaviorism*. The methodological proposal is that because subjective experiences are not scientifically observable, behavior is the proper object of study in psychology as an objective natural science. With this

IP practitioners invariably agree, at least in the sense that the data on which theoretical issues in IP are decided are objective measures of overt behavior.

There is a more controversial extension of methodological behaviorism: namely, that because conscious experience is inherently unscientific, consciousness should play no role whatsoever in scientific psychology. On these grounds, radical behaviorists avoided all questions about "purely mental events" such as imagery and thought. Practitioners of the IP approach have rejected this extreme position in a number of different ways. First, many IP psychologists use personal introspection as a source of ideas and hypotheses about cognitive events. Of course, these must then be subjected to more rigorous evaluation by measuring observable behavior in others to be scientifically respectable, but this is a standard procedure for much IP work in cognitive psychology. Second, the behaviors that IP psychologists measure are often overt reports of subjective experiences, such as ratings of perceptual or conceptual similarity (e.g., Shepard & Chipman, 1970) or verbal "thinking aloud" protocols while solving a complex problem (e.g., Newell & Simon, 1972). Thus, subjective experiences are considered important enough to warrant explanation, but only insofar as they can be made public by behavioral criteria. Third, IP psychologists are decidedly more interested in and optimistic about the scientific study of "purely mental events" such as imagery, thought, and consciousness. Far from banishing them as inherently unscientific, most IP psychologists have come to view them as valid and important topics that will yield to appropriate scientific methods. During the past decade or two, IP psychologists have made a great deal of progress on the topics of imagery (e.g., Kosslyn, 1980; Shepard & Cooper, 1982) and thought processes (e.g., Newell & Simon, 1972). This has been accomplished within the framework of methodological behaviorism by using objective measures such as reaction times and protocol analysis to anchor these "mental events" in observable behavior. There has lately been a resurgence of interest in consciousness itself, focusing on issues like why some things are conscious whereas others are not (Shallice, 1972, 1978; Mandler, 1975), whether a stimulus can affect IP events without itself becoming conscious (Marcel, 1983a, 1983b; Dixon, 1971), and what sort of IP architecture is needed to account for consciousness (Johnson-Laird, 1983). Still, these projects are deemed sensible only to the extent that they can be grounded in objective behavioral measures, thus conforming in the end to the central tenet of methodological behaviorism.

Theoretical behaviorism concerns the nature of explanation in scientific psychology. "Radical behaviorism" is a theoretical view in which all accounts of behavior are couched in strictly "external" terms of environmental histories (cf., Riley, Brown & Yoerg, chapter of this volume). Internal "mentalistic" constructs that could not be directly observed in behavior were rejected out of hand as improper theoretical objects. It is to this part of radical behaviorism that IP is fundamentally opposed. Indeed, it is this proposal that is rejected by all cognitivists, not just IP psychologists. Within the IP approach the behaviorist rejection of unobservable internal events is specifically opposed to the decomposition assumption, since this is the mechanism by which hypothetical "internal events" are generated in IP theories. (We will shortly consider this issue of "unobservables" in more detail.) These theoretical strictures of behaviorism were too extreme to go unchallenged for long, even among otherwise devout behaviorists, and eventually they led to revisionist movements such as "neobehaviorism" and Tolman’s "purposive behaviorism".

The neobehaviorist movement was initiated by Hull's (1952) introduction of "mediating" stimuli and responses within the organism (e.g., S-r-s-R) that were taken to be "internal surrogates" of observable S-R connections. Here we see a line of reasoning similar to IP's decomposition assumption in which the "primitives" were taken to be minimal associations between stimuli and responses, both external and internal. For this reason, neobehaviorism is an important theoretical precursor to IP. It has even been shown that such mediated S-R theories are formally equivalent to a class of finite automata (Suppes, 1969). There are important *pragmatic* differences between mediated S-R theories and IP theories, however, because the computer analogy brought with it a vast repertoire of concepts from computer science that could be used to specify the nature of the hypothesized internal events. These IP constructs -- including information structures such as lists, arrays, matrices, and so forth, plus operations such as encoding, storing, retrieving, transforming, comparing, deciding, branching, looping, and the like -- are richer and more powerful tools for theorizing about mental events than were the neobehaviorists' simple associations among "covert stimuli" and "covert responses". Still, neobehaviorism accomplished the important step of lifting radical behaviorism's absolute ban on theories that appealed to internal processes in explaining behavior.

Tolman's (1932) "purposive" behaviorism went a step further in allowing openly "cognitive" constructs back into the theoretical arena. He argued convincingly for the importance of goals, hypotheses, plans, cognitive maps, and the like in understanding the behavior of rats as well as man. As we noted previously, Tolman's theoretical views are actually "cognitivist" rather than "behaviorist", although he remained a firm believer in the methodological tenets of behaviorism. We will not discuss the relation between Tolman and IP further here because an excellent discussion of this topic is presented elsewhere in this volume (Riley, Brown & Yoerg).

The Role of Unobservables. We have claimed that the primary difference between the IP and radical behaviorist approaches to theories of mind is the former's willingness -- even eagerness -- to postulate internal mental structures in accounting for observable behavior versus the latter's unwillingness to do so. If the IP approach is preferable to this radical form of behaviorism, the use of unobservable constructs in psychological theory must be justified. We will do so by appealing to the well documented use of unobservable entities in other sciences and by examining a few successful cases within psychology itself.

There is a long and important history to the use of unobservables in the natural sciences, and it includes some of the most profound discoveries of the last several centuries. Examples abound of scientists proposing initially unobservable constructs on the basis of purely "behavioral" research and later having their theories confirmed by more "direct" observation. Biologists such as Mendel proposed the existence of genes that carry hereditary traits on the basis of measured regularities in the characteristics of offspring, and this happened long before DNA was actually observed within cell nuclei. Physicists like Rutherford deduced the internal structure of atoms from measuring the scatter that resulted when they were bombarded by X-rays, again, many years before the existence of these subatomic particles was confirmed more directly. There have also been many important cases in which unobservables were postulated without any presupposition of direct observation: e.g., Newton's hypothesis of gravitational attraction and Darwin's concept of natural selection. More recently physicists have suggested that gravity may, in fact, be carried by an elementary particle, but this conjecture antidated considerably their success as "unobservable" constructs in physics. No one has yet supposed that the process of natural selection will itself turn out to be a directly observable "thing".

From such examples we can discern at least two important factors in the success of unobservables in scientific theories. The first is *adequate description*: the construct must provide a succinct and parsimonious account of results known at the time the theory is proposed. The second is *successful prediction*: they must figure centrally in generating novel hypotheses about the existence of new phenomena in substantially different circumstances, and these predictions must subsequently be confirmed. We submit that unobservable constructs of the sort found in IP theories are at least potentially adequate on both counts.

The criterion of adequate description is, of course, the reason for postulating unobservable constructs in the first place: it "makes sense" of some set of data or relates several different sets of data in ways not previously considered. The rationale for this justification of unobservables in psychological theory was developed quite nicely by neobehaviorists in defending the use of internal variables like hunger and thirst in their theories (cf., Tolman, 1932) and there is no need to restate their arguments here. As we said earlier, the move away from the stricture against unobservables was actually started by the neobehaviorists and merely continued and expanded by IP psychologists. There is certainly no problem in principle with IP constructs providing adequate descriptions of well documented phenomena, and there are several noteworthy successes, such as the two-stage theory of color vision (cf., De Valois & De Valois, 1975) and the spatial frequency theory of spatial vision (cf., De Valois & De Valois, 1980).[9] Neither of these has achieved the status of, say, subatomic particles or gravity in physics, but each has provided a substantial framework for describing a large number of experimental results in its domain.

Successful prediction is the true hallmark of success for any scientific theory. It was repeated successful predictions that really convinced biologists of the existence of genes and physicists of the reality of subatomic particles. Repeated confirmation of a theory's predictions leads eventually to such a dense cluster of results around it that the theory displaces specific results in textbooks. There are at least a few good examples in psychology. For instance, color vision is usually presented in texts on perception almost exclusively by the theory with just a few examples of experimental procedures to give a feeling for the research. The same is generally true of the duplex theory of pitch perception. The situation is quite different in more complex cognitive domains, such as semantic memory and language understanding: each of several competing theories is presented along with a few results that seem to support it, and it is the results, not the theory, that are emphasized as characterizing the domain in question. Such theories are "brittle" in the sense that they break down (or simply do not apply) when seemingly minor changes in procedure are introduced, and they often fail to make successful new predictions or succeed only under certain unusual conditions. There is no reason to suppose, however, that robust IP theories cannot someday be achieved in these areas as they have been in sensory domains; the problems are just a great deal more numerous and complex.

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[9] We are considering that psychophysical theories generally fall within the IP framework. Although much of this work predated the IP movement in cognitive psychology, our position is justified on the grounds that most psychophysically derived theories conform to all five assumptions listed above and to the whole spirit of the IP enterprise. Indeed, it was this kind of connection between IP and sensory processes that Lindsay and Norman (1972) developed so skillfully in their seminal textbook, *Human information processing*.

There is a third possible criterion of success that applies to at least some unobservable constructs proposed in science: *potential observability*. A construct is potentially observable if it is, in principle, capable of being measured directly, even if the means for doing so are not yet at hand. Not all unobservable constructs have this status, of course, as exemplified by gravity and natural selection. In psychology, a distinction has been made between "intervening variables", which do not imply potential observability, and "hypothetical constructs", which do (McCorquodale & Meehl, 1948). Proposed IP components are clearly meant to be stronger than intervening variables, which merely redescribe empirical relations succinctly in somewhat different form. Because intervening variables are not meant to have any reality "inside the black box" (i.e., they claim only to specify *what* the mapping is, not *how* it is accomplished), they only play a role within the IP approach as part of mapping theories. IP theories, however, *do* make substantive claims about what goes on inside the head, so the internal operations they propose must be some species of hypothetical construct. This does not mean, however, that all such internal operations imply the existence of specific, isolable, and identifiable neurological mechanisms that embody them.

We believe that IP operations are potentially observable in the brain in just the same sense that programs are potentially observable in Turing machines. If the program is "hardwired" into the machine, it is *physically observable* in the wiring of its circuits. If it is implemented on a general purpose machine, it is *functionally observable* in the behavior of the machine, but not physically observable in the sense of dedicated hardware components. In the latter case, the hardware constitutes the *architecture* on which the programs run, but this architecture only weakly constrains the programs that can run on it. In the case of the brain, peripheral operations seem to take place on "dedicated hardware" where there is some distinctly physical reality to its functional components. More central "cognitive" operations may well take place on a more general-purpose architecture. Most IP theorists who try to account for complex cognitive events find it hard to imagine that the brain has enough distinct neural circuits for all of the necessary mental processes to be realized in dedicated hardware.

In summary, there is no good reason to avoid unobservable constructs in psychological theory and several good reasons to use them as needed. The natural sciences provide ample precedent for this, and psychology itself includes some successful examples. The kinds of unobservable constructs that appear in IP theories are, in principle, capable of both adequate description and successful prediction. Some may even be potentially observable in the "hardware" of the brain, although this is not a necessary claim.

Ecologism

Ecological psychology has been proposed, at least in part, as an alternative to IP psychology (e.g., Gibson, 1979; Shaw & Bransford, 1977). It is not easy to summarize the ecological approach, partly because it is not yet well defined, and partly because ecological psychologists themselves capture their approach partly in terms of negating the IP approach as they see it. Here we will briefly discuss the ecological approach and examine its relation to the foregoing view of IP.

Generally speaking, ecological psychologists reject the computer program metaphor and the appeal to representations and processes as explanatory concepts in theorizing about perception and cognition. Rather, they view the organism from an evolutionary perspective -- i.e., as a system whose primary purpose is self-survival and adaptation -- and organisms in their environments as mutually constraining systems.

Ecological psychology is primarily derived from J. J. Gibson's approach to perception (1950, 1966, 1979). Gibson viewed perception as a biologically adaptive activity, and emphasized the dynamic interaction between organisms and their environments. The centrality of the role that the environment plays in Gibson's view of perception was aptly and succinctly captured by Mace (1977): "Ask not what's inside your head but what your head's inside of".

Gibson asserted that there is information in complex patterns of stimulation available to the organism, corresponding to the important distal objects and events in its environment. This significant information is to be found in "higher-order" variables that remain invariant over the visual transformations taking place as the organism actively explores the world around it. In his theory of "ecological optics" Gibson tried to identify and specify these invariants. According to his theory the active perceptual system "picks up" this information without the involvement of logical processes using specific knowledge about the world. This approach lead him to the notion of "direct" perception.

One way to understand the idea of direct perception is in the historical context within which it was initially proposed. Gibson believed that perception was direct in the sense that, contrary to the Helmholtzian notion of "unconscious inference", it does not involve *epistemic* mediation. As we understand it, this argument does not necessarily deny that representations and processes play a role in perception, but only that it does not make use of *explicit* forms of knowledge and *logical* inference processes of the sort associated with thought, memory, and problem solving.[10] We do not see this view of direct perception as incompatible with the basic tenets of IP. As evidence for this, it is entirely possible to construct a "data driven" IP theory of perception that does not rely on explicitly represented "facts" or logical "deductions": Marr's (1982) theory is one prominent example, at least up to the point at which patterns are identified as instances of known types. Such IP theories can easily be seen as consistent with this weak interpretation of direct perception.

There is, however, a stronger interpretation of direct perception that seems to strike at the heart of the IP approach by rejecting the decomposition assumption. The goal of ecological optics is to specify the mapping from proximal stimuli to perceptual responses, and its content is that this can be done by correlating physical invariants in the dynamic optic array with perceptual responses. Thus Gibson's theory is not concerned with the *mechanisms* that enable an organism to do this, except that the perceptual system detects the invariants by some sort of physiological "resonation" (Gibson, 1966). It is in this sense -- namely, the lack of interest in specifying the nature of internal mechanisms -- that Gibson rejects,

[10] We refer here to "explicit" knowledge and "logical" inference to distinguish the classical position of "unconscious inference" from some modern theories that seem to make use of knowledge and inference of a very different sort. One interesting example is Marr and Poggio's (1976) model for computing global stereopsis: the excitatory and inhibitory connections among the binocular processing units actually embody knowledge of the world (that the visual world is generally continuous in depth, at least over local regions) and of light (that because most surfaces are opaque, each point on an image generally comes from just one depth plane). Even so, this model does not seem to be in the spirit of Helmholtzian "unconscious inference", but more like a sort of "resonance" process of which Gibson might have approved. The difference between classical "unconscious inference" and this type of computational theory seems to be that the knowledge in the former case is explicit, whereas in the latter case it is implicit, and that the rules of inference in the former case conform to the standard logical conception, whereas in the latter case they do not.

if not the decomposition assumption itself, certainly the motivation behind it. Ullman (1980) presents an extended critical analysis of this view, and the interested reader is referred to his paper and the many commentaries that follow it for more information.

From the IP point of view, Gibson’s theory is an important attempt at formulating a mapping theory of perception, since he was occupied almost entirely with *what* the mapping is to the exclusion of *how* it might be achieved. Thus, although his theory is *incomplete* from an IP standpoint, it is entirely compatible with the IP framework, since an ecological mapping theory of perception is the logical starting point for an IP theory of perception (see Marr, 1982). From Gibson’s point of view, however, IP theories of perception are not compatible with his ideas, since he believed that psychological theories of internal mechanisms were irrelevant to understanding perception. Recent followers of Gibson’s ecological approach claim that Gibson did recognize that information pick up involves processes, but in his hints to resonating, optimizing, and the like, they read that these processes have to be different from those suggested by a general purpose device such as the modern digital computer (Carello, Turvey, Kugler, & Shaw, 1982). This assertion may constitute an argument against the computer program metaphor, but not necessarily against the IP approach as presented here.

It should be clear at this point that we do not see ecological psychology as incompatible with the basic tenets of IP. Why then, do ecological psychologist so often present their view as a reaction against IP? The answer to this question requires differentiating between theoretical principles of IP on the one hand, and common practice of IP psychologists on the other. As noted above there are not many mapping theories in psychology, and most current IP models focus almost exclusively on the internal structure (representations and processes) proposed to accomplish the mapping without any attempt to specify the ecological constraints that support the mapping in the first place. There have been some recent attempts among IP theorists to remedy this situation (e.g., Marr, 1982; Bregman, 1981; Shepard, 1981), but it is generally a criticism well taken. In summary, there is a clear difference in emphasis between the ecological and IP approaches as typically practiced, even though they are not theoretically as conflicting as they are often assumed to be.

Computationalism

As we have seen from the foregoing discussion of cognitivism, behaviorism, and ecologism, the most controversial assumption of the IP approach is that mental events are decomposable. For this reason, it would certainly be reassuring if somehow one could *prove* that this were true. As it turns out, a closely related problem has been studied by mathematical logicians in the "theory of computability" (see Johnson-Laird, 1983, for a psychologically motivated introduction). From this work by Church, Turing, and others, we know at least something about certain *conditions* under which an operation is decomposable. It turns out that *if* the mental mapping is an example of what is called a "computable function", then it can indeed be decomposed into a set of primitive functions that are combined according to well specified rules, just as would be required for the decomposition assumption to be unequivocally true.

Probably the best known definition of a computable function is due to Turing (1936): a function is computable if it is the input-output mapping of a machine (now called a "Turing machine") that reads binary symbols from and writes binary symbols to an indefinitely long tape. The sequence of logical steps by which such a function is computed in such a machine is called an algorithm, and there are many different algorithms that can result in the same computable function. Indeed, it turns out that there are many different sets of "primitive functions" and rules for combining them which are, in principle, capable of generating the set of all computable functions: Turing machines, recursive functions, lambda calculus (Church), Post canonical systems, Markov processes, and others (cf., Newell, 1980). So if the mental mapping is actually computable, then the job of IP psychology amounts to discovering what the mind's primitive IP functions are and how they are composed into the larger, more complex algorithms of the human mind (see previous section on "The Role of Primitives"). Mental architecture is probably quite different from that of standard universal Turing machines (or modern digital computers), and a psychologically more plausible formulation has been described by Newell (1980).

We can now say that the decomposition assumption would be true if the mental mapping is a computable function. But is it? There are many functions that are not, so perhaps it is one of these. Unfortunately, no way is currently known to determine this analytically because there is no well defined method for determining whether an arbitrary function is computable or not. The only alternative is to try to show that it *is* by finding an algorithm that "simulates" the mind. The goal is to program a computer so that it passes Turing's test: to behave so much like a person that experts cannot distinguish its behavior from that of a real person (Turing, 1950). Because such a program would, by definition, be a well defined composition of primitive IP operations, its existence would prove by demonstration that mental decomposition is possible. Since an infinite number of other algorithms will produce the same computable function, there would still be the problem of finding the *right* decomposition, but at least we would know that such a decomposition exists. Psychologists would presumably play a central role in determining which of several alternative decompositions is correct.

This line of reasoning suggests an approach to cognitive theory which we will call "computationalism" (or "simulationism"). Its proponents assume that the mental mapping is indeed a computable function, at least as a working hypothesis, and proceed to try to attain the goal presumed possible. Their method is to write computer programs (which are, by definition, computable) that try to simulate human behavior. Searle (1980) has called this sort of approach "weak AI": the programmer views the modern computer as an important tool for discovering things about the nature of mentality, but does not assume that the programmed machine actually *has* mental states. Later we will contrast this view with "strong AI" in which the computer is presumed actually to *have* the mental states that it simulates.

The primary difference between computationalism and IP concerns the logical relation between the assumptions of computability and decomposability. As we have said, computability implies decomposability, but does decomposability imply computability? It turns out that it does not, because the mental mapping, as a whole, may not be computable, yet it still may be possible to decompose it meaningfully into an IP theory. Perhaps the easiest way to see this is to suppose that there is one small part that is not computable, and that this part can be isolated in its own "black box" as an uncomputable primitive within the system. Then it is clear that the system could be decomposed in this way, even though its overall input-output mapping would not be computable. Indeed, there might be many such uncomputable components in the mind, but their existence does not necessarily preclude successful decomposition.

It is not obvious just what this sort of analysis would be like, but Dreyfus (1979) and Searle (1983) have recently offered arguments suggesting that something like this might be true. They allow that some of human knowledge and mental operations may indeed be analyzable into component pieces -- what Searle calls "the Network" -- and this part may well be compatible with computationalism. However, they also argue that there will necessarily be some residue of complex yet fundamental skills, presuppositions, and stances toward the physical world -- what they call "the Background" -- that will defy all attempts at computational analysis. In truth, their reasons for claiming this are not entirely clear and have not yet had much impact on the beliefs of most computationalists. However, the critical point for the present discussion is that even if Dreyfus and Searle did turn out to be right and computationalism wrong, mental decomposition would still be a potentially valid assumption for cognitive psychology and IP a potentially useful approach to solving at least some of its problems. Its usefulness would depend on how much decomposition were possible before the intractable "Background" were reached, and how much would have been learned about the nature of mind as a result.

The possibility of decomposition without strict computability clarifies the relation between IP and weak AI (computationalism). Classical computationalists start with certain precisely stated primitive functions and shows how to *compose* them into more complex functions. The resulting complex function is necessarily computable by definition. IP psychologists start with a complex function, which may or may not be computable, and proceed by trying to *decompose* it into flow diagrams. The components of these flow diagrams may or may not be themselves computable. Thus, computability is a *sufficient* condition for decomposition, but not a *necessary* one. Weak AI therefore places stronger constraints on a theory of mind than does IP. By the same token, of course, weak AI is less likely than IP to be correct.

We see, then, that IP psychologists are not necessarily committed to believing that the mind will ultimately be simulable on an appropriately programmed digital computer, because, strictly speaking, IP does not imply computability. This conclusion is consistent with the fact that serious doubts exist among a substantial subset of IP psychologists that mental events will ever be fully simulated on the sort of digital computers that are currently available. Perhaps someday different machines will be developed that will change such opinions, but they may also change the very definition of computability.

Functionalism

Functionalism was proposed by philosophers as a possible solution to the mind/body (or mind/brain) problem (e.g., Fodor, 1965; Putnum, 1960).[11] It assumes that the necessary and sufficient conditions for mentality are to be found in the functional organization of the brain rather than in its particular physical embodiment. This implies that any device that has the same functional organization as the human brain literally *has* mental states in exactly the same sense that people do. This includes all aspects of mentality, including intentionality, consciousness, and internal experiences.

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[11] The modern philosophical doctrine called "functionalism" should not be confused with the older psychological school also known as "functionalism" which is associated with the work of James, Hall, Cattell, Dewey, Woodworth, and others. There is little, if any, connection between them.

The initial intuitive basis for this claim comes, once again, from the computer analogy. There is an important sense in which the same program (software) can be run on many different digital computers (hardware). The analogous implication for the mind/body problem is that the same "mind" might potentially be instantiated on a wide variety of physically different devices. The essence of functionalism, then, is that systemic organization defines the necessary and sufficient conditions for having mental states, and brains are merely the one material form in which this particular organization has been realized so far. Nothing in principle prevents other sorts of objects from having the same mental states people do, provided that they have the right sort of organization.

It is certainly true that many IP psychologists seem to reject the *spirit* of functionalism by taking certain aspects of neurology very seriously in their theorizing. For instance, several psychological IP theories have been proposed that rest importantly on neurological or quasi-neurological constructs such as excitation and inhibition (e.g., Hinton & Anderson, 1981; Posner, 1978), aftereffects due to priming (e.g., Posner, 1978), and even hemispheric specialization (e.g, Friedman & Polson, 1981). On closer examination, however, these proposals do not really conflict logically with functionalism. If true, they would only imply that brain properties like activation, inhibition, aftereffects, and so forth play some functional role in the nature of mind, and that for another physical object to have the same mental states it would presumably need to have the same functional properties. These might easily be realized in nonbiological objects such as a computer. Thus, even if such theories were correct in detail, they would not strictly imply that it is the *physical* properties of the central nervous system that are responsible for their role in mental events. However, these examples do demonstrate rather convincingly that many IP psychologists do not really "buy the functionalist line" that the hardware of the brain is uninformative about the nature of mind.

A stronger argument against the claim that IP is equivalent to functionalism can be made on strictly logical grounds. It turns out that IP is weaker than functionalism, and the principle reason is that because IP theories are descriptions, they require only that some, not necessarily all, aspects of what makes an event "mental" can be captured by the flow diagrams. There may be certain aspects that are not captured, and these may be considered necessary conditions for something literally *having* mental states as opposed to merely *simulating* them. The most obvious candidate for such a mental aspect is consciousness: qualitatively different phenomenal experiences might be necessary for something literally to *have* mental states, and yet IP theories might not be able to capture this aspect of mentality. One could be an IP theorist and a true dualist at the same time, for instance. Such a person would believe that whereas IP flow diagrams specify the functional organization of the brain, internal experiences are required for it literally to have a mind, and these are quite independent of the specified functional organization. It is also possible, of course, that IP theories *will* be able to characterize consciousness in terms of flow diagrams, at least those aspects of it that are scientifically approachable, and several IP psychologists have proposed such theories (see Johnson-Laird, 1983; Marcel, 1983b; Shallice, 1978).

The important point in understanding the relation of IP to functionalism is that the validity of the IP approach does not stand or fall in terms of whether it captures *all* aspects of mental events, whereas functionalism does. Naturally, IP psychologists hope that IP theories will turn out to account for everything, but not many would feel that it had failed if it turned out to leave some mysteries unsolved. In this case, the "correct" flow diagram theory of the mind would turn out to be merely a *necessary*, but not *sufficient*, condition for having the sort of mental states that people do. It would be devastating to a functionalist, however, if it turned out this way. For example, Searle (1983, Epilogue) has argued against functionalism by suggesting that consciousness is inherent to specific biological processes occurring in brains, but this is not necessarily an argument against the IP approach as described above. In defense of functionalism, however, it should be noted that there is presently no scientific evidence in support of Searle's materialist, biological view, only his own intuitions. Consciousness may well turn out to be a problem whose solution will be found entirely within the realm of functional organization.

Turing-machine functionalism (or "Strong AI"). If a properly programmed computer has the same functional organization (i.e., implements the same algorithm) as the human mind, then it follows from functionalism that the machine would literally have a mind in exactly the same sense that people do. Indeed, this would be true of any machine implementing the same algorithm, including one made of electronic, mechanical, optical elements or whatever. This conjunction of computationalism and functionalism is usually called "Turing machine functionalism" (e.g., Block, 1978; Block & Fodor, 1980; Fodor, 1980) and sometimes "strong AI" (Searle, 1980). Note that it would not be sufficient for the computer merely to duplicate the input-output mapping function of the human mind because many different algorithms (and, therefore, different functional organizations) can produce the same mapping.[12] Functionalism proposes that it is the *functional organization* that must be the same, and this is a much stronger constraint than just that the *mapping* be the same. For example, if one proposed an IP theory of consciousness which required that two processes run in parallel, a strictly serial computer that merely *simulated* parallelism by switching back and forth between them would not have the organization specified by the theory, even though it would exactly mimic its input-output function. Therefore, it need not be itself conscious, but might well only mimic consciousness. It isn't just *what* gets done that matters, it's *how* it gets done. In any case, it should be clear that IP as characterized here is not equivalent to Turing-machine functionalism, since it does not strictly imply either computationalism or functionalism, much less their conjunction.

At this point we can summarize the foregoing discussion by putting it all into a single framework involving just two issues and the positions taken on them by each approach. The first issue concerns the *analyzability* of mental processes into functional components. The strong position is that mental processes are computable (computationalism and Turing-machine functionalism), and the weak position is that they are merely decomposable (functionalism and IP). Radical behaviorism and Gibsonian ecologism take the more pessimistic position that the question of analyzability itself is entirely misguided.

The second issue concerns the *logical implications* of functional organization for the nature of the human mind. The strong position here is that the functional organization is both necessary and sufficient for having mental states (functionalism and Turing-machine functionalism) and the weak position that it is merely necessary (computationalism and IP). Again, it is possible to hold the more pessimistic position that functional organization is logically unrelated to issues concerning the human mind (radical

[12] I thank Phil Johnson-Laird for pointing out this crucial distinction to me. The example that follows came from him.

behaviorism and ecologism). Thus, the four meaningful conjunctions of the two positions on these two issues define the four principle modern views shown in Table 1. Of these, Turing-machine functionalism is the strongest and IP the weakest. Note that, by the same token, IP is the most general view and is compatible with all three of the other approaches.

Table 1

		SUFFICIENCY		
		Necessary & Sufficient	Sufficient	(Irrevelant)
	Computable	Turing Machine Functionalism	Computationalism	-
ANALYZABILITY	Decomposable	Functionalism	Information Processing	-
	(Irrelevant)	-	-	Behaviorism & Ecologism

Summary and Conclusion

We have presented a metatheoretical view of the IP approach to cognition in terms of five central assumptions that underlie it. The first two assumptions -- informational description and recursive decomposition -- are the most critical. The third and fourth assumptions -- flow continuity and flow dynamics -- further specify the nature of the decomposition assumption, and the final assumption -- physical embodiment -- further specifies the informational description assumption. Together these five assumptions form the basis for constructing IP theories of mental processes in terms of information flow diagrams that represent the component operations and the temporal relations among them. Unless the operations of the flow diagram are taken to be primitives, the IP theory should also include a mapping theory of each operation.

We then contrasted this view of IP to other prominent approaches to cognitive theory: behaviorism, ecologism, computationalism (weak AI) functionalism, and Turing-machine functionalism (strong AI). Many of the differences among these views can be captured, at least schematically, by their stands on two fundamental issues: the extent to which mental processes are *analyzable* into functional components and the logical *sufficiency* of this analysis in accounting for the nature of mental states. According to this analysis, IP is weaker than (but compatible with) computationalism, functionalism, and Turing-machine functionalism.

We believe that IP is currently the most viable theoretical approach to cognition, but this is obviously just our own opinion. We offer the foregoing analysis and discussion in the hope that it gives a clearer conception of the IP approach than has previously been available. Even if IP turns out to be fatally flawed in one or more ways, being clear about the underlying issues can only help in the ultimate goal of understanding cognition. Thus, the four meaningful conjunctions of the two positions on these two issues define the four principle modern views shown in Table 1. Of these, Turing-machine functionalism is the strongest and IP the weakest. Note that, by the same token, IP is the most general view and is compatible with all three of the other approaches.

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