Changing the Layers of Mind

Technical Report PCG-12

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Running Head: The Layers of Mind

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Abstract

It is common in cognitive science to assume that the mind is composed of layers of programmable machines. The machine of the top layer runs the "end user" program which, roughly speaking, performs the task at hand. Every other machine runs a program that implements the memories and primitive processes of the machine above it in the stack of layers. The bottom machine is actual neuronal "hardware." A natural part of the layering principle in computer systems design is that the layers can be changed. In particular, any layer, except the hardware layer, can be replaced without changing the others. This essay examines the psychological implications of the hypothesis that layers can be changed.

1. Introduction

One can argue that good principles of design for electronic computing systems may also be good principles for neuronal computing systems. Fodor (1975) argues that the mind is a stored program computing system where the programs are learned and the hardware is innately specified. Simon (1969) argues that mental functions must be nearly decomposable and hierarchically arranged. Fodor (1983) argues that the mind is modular, with one module for language, another for imagery, etc. All three hypotheses--programability, hierarchy, and modularily -- are supported by empirical tests, or at least, they could be. The mere analogy to computing systems is not by itself a convincing argument for a psychological principle, although it is suggestive.

Recently, it has become common to assume that a further principle of computing systems is obeyed by the mind. The *layering hypothesis* is that the mind consists of layers of programmable machines. Each machine consists of memories and primitive processes, the operation of which is controlled by the program running on that machine. The machine of the top layer runs the "end user" program which, roughly speaking, performs the task at hand. Every other machine runs a program that implements the memories and primitive processes of the machine above it in the stack of layers. The bottom machine is actual neuronal "hardware." Perhaps connection systems are low in the stack, close to the neuronal layer but not identical to it. Further up the stack are, perhaps, spreading activation or marker-passing systems that employ "localist" or symbolic endings. On the top might be a general problem solving architecture, such as SOAR (Laird, Rosenbloom, & Newell, 1986) or a special purpose architecture for, e.g., processing language.

Although this picture of the mind is not new, a closer examiniation of it reveals that it is incomplete. A natural part of the layering principle in computer systems design is that the layers can be changed. In particular, any layer, except the hardware layer, can be replaced without changing the others. This essay examines the implications of the hypothesis that layers can be changed. In the first section, the computer science rationale for changeable layering is presented. In section two, these implications are extended via the usual analogy of minds and computers.

What is missing from this brief speculative essay is a proper defense of the changable-layers hypothesis. In other work of this kind (e.g., Fodor, 1983; Fodor, 1975; Simon, 1969), hypotheses are supported by showing how they simplify the accounts of numerous psychological phenomena. No such support is ventured here. So what we have here is pure speculation, although its relevance to contemporary debates in cognitive science makes it germane and perhaps even interesting.

2. Layers of Virtual Artificial Machines

It is standard to implement complex electronic computing systems in layers. The bottom layer is the machine's hardware. It usually consists of several types of memory with different capacities and decay rates. There are multiple data pathways and multiple special-purpose processors, often with different timing characteristics. There are usually several clocks and myriads of gates (controlled switches) available to regulate the flowing data. Orchestrating this parallel maze of processing is a program, written in a special language called the "microcode." It is designed to execute another program that is written in a language called the "macrocode." The macrocode program operates on the assumption that there is just one processor, and one (or a few) memories. The microcode program makes this assumption valid. It implements a *virtual* processor and memories, or a *virtual machine* as it is standardly called. The virtual machine is much simpler than the real machine. Moreover, it is designed to be the kind of simplicity that enables simple macrocode programs to perform complex tasks.

On many computers, there are several layers of virtual machines. The lowest layers are written by the computer's manufacturer and come as part of the machine. The middle layers are usually an operating system, such as Unix, and on top of that, an interpreter for a programming language such as LISP or LOTUS 1-2-3. The user's program might itself implement another VM. For instance, a user's C program might implement a LISP interpreter, and the LISP program might implement an interpreter for a production system.

The layering of virtual machines is a good design principle because it permits very complicated tasks to be achieved with layers of simple programs. The programs that implement VMs, which are called *interpreters*, all have a similar structure. They are a single giant loop that runs endlessly. Inside the loop, the most important task is to fetch the next instruction in the macro program (the one being interpreted), then call the subroutines that implement that type of instruction. In addition, the loop may have some general housekeeping tasks that must be done constantly, such as managing memory or checking the state of peripheral devices.

Interpreters are conceptually simple because they are modular. Each type of instruction in the macro language corresponds to one module in the interpreter. The modules are written so that macro instructions can be implemented in *any order*. This independence of order is the key to allowing complex tasks to be simply programmed in the macro language. The program writer does not need to worry about fine-grained interactions among the macro instructions, because there are guaranteed to be none. This leaves the programmer free to consider only large-grained interactions--those that are intended to occur.

A second important feature of layering is that it allows changing virtual machines. Typically, there are only two useful applications of this ability:

- *Changing the bottom layers and leaving the top.* This is useful when the same user programs need to be run on different hardware. For instance, many different hardware manufactures provide appropriate lower layers for interpreting the UNIX operating system. This allows UNIX programs written on other machines to be executed on theirs.
- *Changing the top layers and leaving the bottom.* This is useful when the same hardware is needed for different applications. For instance, one application might be best handled with a program written in LISP, while another application program is better suited for implementation in Prolog. By changing the top few layers, one can change a LISP virtual machine into a Prolog virtual machine.

3. Layers of Virtual Mental Machines

If the mind is like a computer, then good design principles for computers should be good design principles for minds. The preceding section described one good design principle, the layering of VMs. Assuming that Nature has designed our the minds well, the mind too should have layers of VM, and moreover, some of those layers should be changeable. The analogy between layered computers and layered minds is quite direct. Electronic hardware corresponds to neuronal tissue. The next layer up might be appropriately modelled by a connection system of the distributed kind. The next level up might be a localist connection system. Perhaps several layers higher, the mind has several VMs--perhaps a VM something like Berwick's (1985) Lparisfal for language, a VM like Kosslyn's (19) screen for imagery, and a VM like SOAR (Laird, Rosenbloom, & Newell, 1986) for general problem solving.

This view of the mind may not be particulary startling. I think that most cognitive scientists already believe the mind is organized as multiple layers. Indeed, there have been several investigations of how a program written for a connection system can implement a serial, von Newman-style VM (see, e.g. Rumelhart, Smolensky, McClelland and Hinton, 1986) .

However, a tacit assumption of the layered view of mind is that the mind consists of a single, unchanging stack of virtual machines, from neurons on up to e.g., a production system. But this static view of the layers of mind implies that one of the biggest advantages of electronic VM layers is not utilized by the mind--the ability to change layers. It seems much more plausible that the mind can swap VMs, and does so whenever it is useful.

Just as in computing systems, there may be two kinds of utility: changing the top layers and changing the bottom layers. Changing the top layers is useful when a person's task changes. The mind might swap in Kosslyn's machine while doing an imagery task, and Newell's machine while doing a problem solving task. Changing the bottom layers is useful when the memory resources available for a task change. This latter ability might seem rather useless, since it is a safe assumption that the internal memory resources (e.g., short-term memory, long-term memory) change very slowly, if it all. However, if lower VM are in charge of utilizing external memory resources, such as a piece of scratch paper or a blackboard, then memory resources can change rapidly, so the ability to switch the lower VM layers might in fact be useful.

Indeed, it seems possible to use this notion of changing the external memory resources as test of the changeable layers hypothesis. Suppose that the mind uses one lower VM for mental arithmetic and another for regular written arithmetic. There is a second, higher VM for executing the arithmetic algorithm. The lower VM implements the algorithm's primitives (e.g., "what digits are in the hundreds column?"). These assumptions predict that if a subject learns to do both addition and subtraction on paper, then learns how to do mental addition, the subject can immediately do mental subtraction. This massive transfer is caused by swapping out the VM for writing and swapping in the VM for mental "writing", which was learned with the addition program. If VM cannot be swapped, then the three learning episodes generate three program/primitive combinations. To master mental subtraction would require learning a new program/primitive combination. Such static, unchanging VM layers predict less than immediate transfer.

Unfortunately, the situation is not nearly so simple. Current theories of transfer (Kieras & Bovair, 1985, Singley & Anderson, ress) hold that the amount of transfer is proportional to the number of productions shared between the old procedure and the new procedure, and transfer is measured by saving in learning time. In these studies, there is only one old procedure, and it does not completely overlap the new procedure. Consequently, some productions in the new procedure must be learned afresh rather than being transferred from the old procedure. In the hypothetical experiment under discussion, there are two old procedures, a written subtraction procedure and a mental addition procedure. If these procedures are represented as homogeneous sets of productions, then the new procedure would be constructed by taking half its productions from each of the two old procedures. This would predict a complete savings in learning, which would be consistent with the expected result that mental subtraction could be acquired immediately. Thus, the prediction of massive transfer can be obtained without swapping layers.

However, this unchangable-layers account for the putatively massive transfer breaks down when analyzed more closely. Transfer is a form of analogy, and in all current theories of analogy, there is some search involved in finding appropriate old knowledge that can be used as the source of the analogy. To perform the transfer in this hypothetical experiment, the search would have to decide which productions to get from the written subtraction procedure and which to get from the mental addition procedure. If this search takes any resources at all, transfer would be less than immediate. However, the search would become trivial (and hence consistent with the expected experimental findings) if the production sets for the old procedures were divided by a boundary line, so that productions below the line dealt with the medium for storage (i.e., the paper or the mind) and the productions above the line dealt with the arithmetic algorithm. This is just exactly the layering hypothesis, instantiated in a production system formalism.

In summary, the empirical discrimination between the hypotheses of layered versus unlayered production sets rests on finding out just exactly how immediate the transfer is in the experiment under discussion. If it is virtually instantaneous, then the layering hypothesis is supported. So the situation is actually an empirically delicate one.

4. Summary

This essay has assumed, along with much of the cognitive science community, that the mind consists of layers of virtual machines. This assumption is part of the continued tradition of treating the design principles for good computing systems as serious hypotheses about the mind's design.

The point of the essay was to suggest (and only suggest) that *all* of the principle of layered computing systems be taken seriously, and in particular, that the ability to *change* a layer in the stack of virtual machines be considered as a psychological hypothesis. For instance, the top layer might change when the task changes radically, say, from an mental rotation task to a cryptarithmetic task. The bottom layers might change when the memory resources available to the person change.

As shown above, the changable-layers hypothesis does make predictions, especially predictions about transfer, so it is a testable hypothesis. However, it will be a difficult hypothesis to test, as the discussion above indicated.

The layering hypothesis opens up a whole host of issues.

- Where do VM come from? Are they learned?
- What happens while a VM is being swapped? Where does the consciousness (or attention) stand? In a meta-level?
- Does the layering hypothesis allow us to reconcile old controversies, such as the conflict between problem solving architectures, which seem to require arbitrary capacity working memories, and short term memory architectures, with their severe capacity limitations?
- Does compiling from one layer down to the next explain practice effects, such decreasing competition for resources and decreasing cognitive penetrability?
- Does learning a new VM explain how people can recover from some neurological tramas?

My hope is that the mind is much simpler than we ever thought. We only thought it was complex because we tried to model it without using enough layers, which is about as hard as trying to write a Tower of Hanoi problem solver in microcode.

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