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An Estimate of How Much People Remember, Not of Underlying Cognitive Capacities

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In my paper "How much do people remember? Some estimates of the quantity of Learned Information in long-term memory," I tried to measure the amount of knowledge that people acquire and retain through experience. These were described as "black box" measurements of "functional information contents," explicitly defined in the paper as "the amount of information transmitted from input to output with delay." In his paper "Estimating human cognitive capacities: A response to Landauer," (1988) Lawrence Hunter scathingly criticizes me for not providing upper bounds on underlying "component capacity" or "cognitive processing capacity." In my paper, I had tried to make it clear that I did not intend to estimate such capacity bounds, offered some reasons why attempts to do so would be fruitless at this time, and discussed the interest and utility of the average information content estimates that I did provide.

When an author is criticized for not addressing the same questions that the reader would have liked answered, it is hard to know what to do. It is tempting to merely apologize for the reader's disappointment, or to urge more careful reading. But it would be unfortunate if my estimates of remembered information were construed as something they are not, and Hunter's response proves that it is possible to misunderstand them rather dramatically. Let me try again.

First I will briefly review what I did in the work reported in the paper, what the results mean and how they might be used. Then, I will comment, also briefly, on the alternative research goals proposed by Hunter. Finally, I'll discuss a few technical points.

WHAT WAS AND WAS NOT ESTIMATED IN LANDAUER'S 1986 PAPER

As people go through life they remember a certain amount of what they see, hear, read, think, and so forth. Later, they use this information as the basis of many cognitive acts, skills, and processes. My aim was to get a rough idea of how much information people actually accumulate; how much, measured in bits, is available after a certain number of years of life. To get such

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estimates, I used data on the rate at which people acquire new information; in the paper, I analyzed experiments on learning from reading text and from looking at pictures. These were the "black box" measurements. I simply looked at how much information people could exhibit about the world, after such experiences, that they could not before. This was accomplished by measuring changes in the ability to perform tasks that would reflect any knowledge that had been gained. The performance measures were turned into information theoretic quantities specifying the amount of reduction in uncertainty about the aspect of the world experienced in the learning situations that was preserved over time. I called these "functional" memory estimates because they are of the amount of information preservation needed to perform tasks and have nothing to say about how the information might actually be represented and retrieved. A wide variety of different measures and different learning experiences resulted in remarkably consistent estimates of about 1 or 2 bits per second of information acquired during concentrated study. Estimates were also obtained for the rate at which information is lost over very long periods of time. Integrating the gain and loss rates allows one to plot the growth of information over time, and leads, for example, to the conclusion that roughly 10^9 bits have been accumulated, on the average, by midlife.

What is this an estimate of? What does it mean? How can it be used? To be as precise as possible, it is an estimate of the amount of information accumulated as a result of attentive experience over time by an average person. Among many potential theoretical uses for such approximate numbers are the following: Suppose someone wanted to construct a complete model of an adult human. How much information gained from experience should the model be assumed to acquire, exhibit, and utilize? Something on the order of 10^9 bits. Suppose someone proposed building an expert system that can do everything a typical 30-year-old human can. How much information of the kind people acquire during life will the knowledge engineer need to put into it? If the information is measured in a comparable way, it is on the order of 10^9 bits.

The obtained estimate is of the average quantity of acquired information, measured in a certain way. It is *not* an estimate of the maximum processing or storage capacity of the human mind or brain. It is not an upper bound on anything interesting that I can think of. In particular, it was not intended to be and should not be taken as an upper bound on the size of a program or its data structures or of the hardware underlying any real or theoretical cognitive processor. Nor is it an estimate of the computational power needed to run such a processor.

The estimate is plausible as a very low lower bound on the total component information storage capacity of brains or devices that seek to simulate humans. But because such systems would have so much more to do than

simply record new information in a compact code, and because they might do all the things they do in very "inefficient" ways, the estimate is probably of little interest as a bound on underlying capacity requirements. The estimate simply was not intended to and does not impose useful constaints on the size or power of the "machine." What it does provide is an estimate of the average value of a potentially interesting parameter of mind. Expressed as a constraint, it means only that one should probably not assume that adult humans have learned much more or less, as evidenced by the ability to recall and recognize aspects of previous experience, than about 10^9 bits of information. Nevertheless, it is a very interesting number. It reflects how much people acquire in a lifetime of learning. Therefore, it probably comes close to what many people would want as an answer to the question, "how big is human memory?"

SHOULD SOMETHING ELSE HAVE BEEN ESTIMATED?

Hunter would apparently like an estimate that "reflects the quantity of computational resources necessary for supporting a human-like memory," or one that provides a "constraint on a theory of such a memory." He seems to have two rather different things in mind, both very different from the estimates I obtained. First, he would like "memory" to include the ability to refine categories, generate expectations and plans, focus attention on salient aspects of the environment, and otherwise "bring previous experiences to bear on new situations." His proposed definition of memory is at odds with conventional usage in psychology, philosophy, and computer science where the meaning usually agrees fairly well with dictionary definitions of memory as the ability to recall, reproduce, or recognize previous experiences (e.g., *Webster's Third International Dictionary,* 1981; or the *McGraw-Hill Dictionary of Scientific and Technical Terms,* 1984). Worse, it begs many important questions about the relation of processes such as inference, planning, and judgment to memory as such. For example, Hunter would apparently have us answer by fiat the question of whether memory and inference are separate or integral processes. I would prefer to leave such questions to research. It seems more promising to think such thoughts as "here is the amount of information people will have remembered from experience, here are some of the things that they are able to do with it, and some of the things they are not. Now how can we account for all that?"

Secondly, Hunter would like an estimate that would set limits on the underlying computer-memory, including all of the logical "database" machinery such as indexing and organization, that it might require. I have to agree that this would be nice, if it could be done. But given that we have no good theory in sight of how such processing is carried out in the mind, there appears to be no realistic way to approach this question.

Similar remarks would apply to the goal of setting limits on the hardware capacity of the brain. Not knowing how the brain works in the storage and processing of information, there is no available route to estimating its capacity. (The brain may not even have a fixed maximum capacity. As a library can add shelves, the brain might keep on growing storage capacity as needed.) I did describe some speculations, clearly labeled as such, on this issue. But they were presented merely as illustrations of how one could use information about functional holdings in considering the consequences of hypothetical storage mechanisms.

TECHNICAL COMMENTS

Hunter objects to my measurement of the information gained from reading on the ground that people retain more than the surface form of text. Of course they do. The measure was based on the ability of people to guess the correct words to fill in ones missing from text they had previously read. That the ability to do this reflects much more than surface recollection is clear from the fact that people got 43% of such words right when they had never seen the text before (the necessary control condition for measuring information gain). Indeed, the more one knows about what was said, and its implications, the more likely the correct word is to be guessed. In principle, any information that is derivable from the experience of having read the sentence can be recruited to make a better guess as to what the word was, and will be correctly reflected in the information transfer measurement. To see why this is true, consider why one word, or variant of a word, rather than another word, is in the text in the first place. Only if the two words were absolutely identical synonyms would the choice between them, and thus their differential recall, be a purely "surface" matter.

Only if the information gained from reading, perhaps by inference, were stored in some way that would prevent it from being used efficiently for guessing the right word—if somehow the language producing system were decoupled from other useful functions of memory and comprehension—would the probability of putting in the right word fail to reflect information gained from the text. This is a possibility that cannot be rejected out of hand. However, to alter the functional information gain measure it would be necessary that some other effect of having read the word in the passage be present in the person's behavior that is not highly correlated with the ability to restore the original word. For example, a large number of different performances would reflect the fact that one remembers $2+2=4$. But this would not necessarily mean that more information had been acquired at the time it was learned. One needs to distinguish between the power of the processes for utilizing information and the question of how much information has been acquired. Unfortunately, I have found no way to assess the

possibility of "hidden" information. However, it seems highly unlikely that large amounts of information that are both uncorrelated with the ability to guess the words of the original text and unavailable in trying to make such guesses are lurking about undetected.

SUMMARY

In summary, Hunter is right that I have not provided any estimates that will set upper bounds on the amount of component information processing or memory storage capacity underlying human cognition. And he is right that it would "muddy the already clouded waters of cognitive theory" further to take my estimates as having that meaning. I surely hope no one other than Hunter did so, or will in the future.

On the other hand, if the estimates are properly interpreted as what they are, approximations of the amount of information gained by people from their experience, then they may constitute a useful piece in the puzzle of understanding human cognition. They provide a guide both to how much acquired knowledge needs to be accounted for in the mechanisms we propose for human memory and how much should be assumed as a basis for the memory-dependent skills and processes we seek to explain.

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REFERENCES

Hunter, L. (1988). Estimating human cognitive capacities: A response to Landauer. *Cognitive Science, 12,* 257–261.

Laudauer, T.K. (1986). How much do people remember? Some estimates of the quantity of learned information in long-term memory. *Cognitive Science, 10,* 477–493.

McGraw-Hill dictionary of scientific and technical terms (3rd ed.). (1984). New York: McGraw-Hill.

Webster's third new international dictionary of the English language unabridged. (1981). Springfield, MA: Merriam-Webster.