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Estimating Human Cognitive Capacities: A Response to Landauer*

LAWRENCE HUNTER
Yale University

Thomas K. Landauer's (1986) estimate of the capacity of normal human memory is deeply flawed. His estimate neither reflects the quantity of computational resources necessary for supporting a human-like memory, nor provides any constraint on a theory of such a memory. The roots of the problem lie in a misunderstanding of the relationship of previous experience to intelligent behavior and therefore a failure to provide the kind of estimate that could be useful for constructing an AI or psychological theory of remembering.

The word *memory* has two quite distinct meanings. One refers to the accumulated experience of a human being; it is the difference between a naive youth and a wise elder. Human memory is not confined to the ability to recognize previously seen objects or accurately reproduce previously seen texts. It is our memories that allow us to recognize and refine categories of objects or events, to generate reasonable expectations and plans, or to focus attention on salient aspects of the environment, to name but a few of the tasks memory subserves. In short, human memory is the ability to bring previous experiences to bear on new situations.

The other meaning of *memory* is the specifically defined term of information theorists, most commonly encountered in discussions of computers; that is, a device that can maintain one of several possible states as a result of past action, thereby preserving information over time. The smallest unit of memory is the smallest unit of information, or a bit. Any system whose state depends on some past event can be characterized in information theoretic terms, and the amount of information it can transfer from past events to current state can be measured in bits. Landauer's goal seems to be to estimate the number of bits it would take to duplicate the store of experiences of a human being in a way that subserves the same functions as human memory.

As Landauer acknowledges, the relationship between human-like memory and the underlying computer-memory requirements necessary to support it

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Correspondence and requests for reprints should be sent to Lawrence Hunter, Computer Science Department, Yale University, New Haven, CT 06520.

is problematic. Although admitting that "[I]t should be clear there is not a one-to-one correspondence" between human-like memory and the underlying "component capacity," he provides no estimate or means to estimate the relationship between the two. Landauer's observation that "[g]enerally, a database system for textual material will require two or three times as much memory as is represented in the input" is at best irrelevant; any description of that relationship is dependent on a theory of how human-like memory functions.

Landauer wants to measure what he calls "functional memory" capacity. His definition of functional memory, never made explicit, seems to be the quantity of information remembered that is used in the accomplishment of some future task. Landauer wants to eliminate information stored for the purposes of "'internal affairs,' 'bookkeeping,' 'database management,' and overcoming the effects of noise, unreliability, and damage" from his estimate of the number of bits in functional memory. This definition assumes that indexing plays a minor role in human memory, which is in opposition to the views of many memory researchers (Charniak & McDermott, 1985; Schank, 1982; Schank, Collins, & Hunter, 1986). The organization of memory mediates the transfer of information from input to outputs. By eliminating "bookkeeping" and "database management," Landauer seems to intend functional stores to refer only to the content of the experiences remembered, explicitly ignoring the storage requirements of any organization (indexing, packaging, characterization, etc) imposed on those experiences. Human beings remember (even by Landauer's assessment) a large number of experiences; for that store to be useful, relevant previous experiences must be available without exhaustive search through the entire memory. A stored experience may be relevant to a wide variety of future tasks, some in contexts quite different from the original episode. Because Landauer doesn't consider the organization of experience part of remembering it, his functional memory measurement can provide only a lower bound on the component capacity necesseary to implement a memory that supports human-like functionality.

Given the simplicity of the tasks Landauer uses, the lower bounds on underlying component capacity derived are likely to be quite conservative. For example, take his measurement of the information gained by reading. Landauer finds that people who have read a text can fill in randomly deleted words from that text somewhat better than people who have never seen it (63% correct word choices vs. 48%, respectively). It may seem surprising that people who have read a story can recall only 63% of randomly deleted words correctly; it is even more surprising that Landauer believes that this figure is representative of the information that the subjects gleaned from the texts. As has been long established (Clark & Clark, 1977), people remember the surface structure of a text only very briefly, saving instead a representation of its content. The saved representation may include inferences made on the basis of prior knowledge or the understander's goals, and will be indexed well enough to be recognized in analagous situations or be used in future expectation generation or planning (Charniak & McDermott, 1985). The amount of storage necessary to usefully remember understood materials is unknown; it is clearly a good deal more than the 0.4 bits per word of text minimally necessary to account for the improvement in random word replacement observed in Landauer's experiment. At best, this experiment provides a conservative lower bound on the memory elements used by people to accomplish the task.

As Landauer points out, an estimate of storage requirements could bear on elucidating the mechanisms of human memory. Unfortunately, his lower bounds are uninteresting from a theoretical point of view because they provide no plausible constraint on a theory of memory. How then might an assessment of human computational capacity be useful to the cognitive theorist? One of the key insights of artificial intelligence research has been that process theories of mentation must be computationally tractable, that is, they must execute in a reasonable amount of (computational) time and space. Fighting combinatorial explosion (Charniak & McDermott, 1985) is the modus operandi of AI researchers. There are many possibile standards for selecting what constitutes a "reasonable" amount of time and space; because nearly every AI theory is a worst-case exponential algorithm, traditional computer science measures are of limited utility. One promising area to look for specific limits on the amount of time and space available to process theories of mentation is examining how much computational power people use to accomplish cogntive tasks. Feldman (Feldman & Ballard, 1981) has used constraints derived from estimates of the available computational capacity of human brains to generate theories of vision and other cognitive abilities whose computational requirements do not exceed the capacities available to humans. This is the kind of useful constraint that can help direct theory formation.

Notice that the usefulness of the estimate of available computational capacity depends crucially on the plausibility of using it to provide an *upper bound* on the amount of computation that a process theory may use. One can eliminate theories that require vastly more than human computational capacities to do human-like cognitive tasks. For example, a popular naive theory of category recognition and expectation generation attaches probabilities from each perceptable feature (and each independent combination of features) to each category in memory (cue validity in the psychological literature) and from each category to perceptable features (category validity). Such a theory is extremely space hungry, using an amount of storage exponential in the number of features and categories (double exponential, counting feature combinations). Given reasonable estimates of the number of features that people can and do use in recognizing categories or generating expectation and of the number of categories people can distinguish would indicate such a theory of memory would take immense amounts of memory "component capacity." A reasonable estimate of component capacity of humans would probably eliminate such a naive theory by providing a constraint on the number of memory elements available.

If Landauer had been able to provide a new upper bound on the number of memory components available to humans, his contribution would have been significant. An upper bound on component capacity necessary for human-like performance would be a useful constraint on theories of memory, and might provide incentive for building computers with such capacities to act as sufficiently powerful testbeds for such theories. Unfortunately, in this case, upper bounds are much harder to estimate than lower bounds. Evaluating the computational complexity of brain hardware has been one approach. Landauer's guess of 10^{12}–10^{14} synapses each storing 2–10 bits yields an upper bound of 10^{15} or so memory elements. This estimate is sufficient for excluding theories that are very computationally inefficient, for example, the one described in the previous paragraph. On the other hand, 10^{15} bits is so much memory that it does not provide very specific constraints on any current theory of memory. Certainly, Landauer's estimate does not provide a plausible new upper bound of the bits available to implement a human-like memory.

Other approaches for estimating underlying computational capacities are possible. Moravec (personal communication, March 1986) has made estimates of human computational abilities by extrapolating from the computational density of retinal tissue, the only neural tissue whose functioning has been clearly elucidated. Another approach might be to estimate the information-carrying capacity of input and output channels using psychological methodologies. It might be possible to estimate the bit rates of sensory surfaces and neuromuscular junctions. Unfortunately, relating such measurements to memory requirements might be difficult because of the complex relationship between prior experience and current behavior. The behaviors effected by a previous experience are orders of magnitude richer than mere recognition of an identical stimulus layout at a later date. Genuinely cognitive memory is more than information preservation; information must be transformed, stored, and recalled in such a way that the goals the organism is pursuing are achieved more often or at lower cost. The actions in which a memory of an experience might be in some way manifest are very difficult to identify precisely, and it seems likely that a significant experience would influence a very large number of future actions. This fundamental fact makes estimates based on measuring "information transferred from input to output" extraordinarily difficult, thereby reducing the utility of any attempt like Landauer's. Aside from estimates based directly on human "hardware," it seems that any reasonable estimate of the number of bits of storage necessary to support human-like memory will have to wait for a plausible theory of how such a memory might function, or a least a more complete description of what precisely it is capable of.

In short, Landauer's estimates of memory capacity are flawed by his failure to appreciate the versatility and power of human memory in his measurements, and by his failure to understand the relationship of bit counting to theory building in cognitive science. Although cognitive scientists such as Feldman and his fellow connectionists have shown that it is possible to take brain capacity constraints on cognitive theories seriously, Landauer shows that it is also possible to muddy the already clouded waters of cognitive theory further by trying to do so.

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