Analogical Reasoning, Analog Computation and the Computational Hypothesis of Cognitive Science

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"Any kind of working model of a process is, in a sense, an analogy" (Craik 1943)

"… analogy is like a modeling relation except that it relates two natural systems, rather than a natural system and a formal one" (Rosen 1991)

"But it can be misleading to call analogies 'models', because verbal models are not straightforward small scale versions of a larger object" (Johanssen 1993)

There is a very strong tendency for scientific models—or explanations—of new phenomena to be analogical. For if we seek to explain the unfamiliar in terms of the familiar, what is this but analogy? To quote Popper (1972, p. 358):

> From Descartes … to Maxwell, most physicists tried to explain all newly discovered relations by *mechanical models*; that is, they tried to reduce them to laws of push or pressure, with which we are acquainted from handling everyday physical things.

This is only natural. Models are abstract simplifications of a complex reality: The more concrete ('mechanical') the abstraction, the simpler the model, the more likely we are to accept it according to Occam's principle of parsimony—always provided it passes the test of satisfactorily explaining the observations. Yet analogical reasoning is far from a sound or secure route to scientific knowledge (Knorr 1981). Its appeal seems to transcend scientific theorizing and to reflect a strong operational principle of human thought itself. This is the essential argument of Craik (1943) who writes [pp. 120–1]: "I have outlined a symbolic theory of thought, in which the nervous system is viewed as a calculating machine capable of modelling or paralleling external events, and have suggested that this process of parallelling is a basic feature of thought and explanation".

These considerations raise the question of the exact relation between a model, a theory and an analogy. We will not pursue this in detail here, other than to point out that the question is vexed. For instance, Leatherdale (1974, p. 41) writes: "… the literature on models displays a bewildering lack of agreement on what exactly is meant by the word 'model' in relation to science". (See also Nagel 1961, Moor 1978 and Wartofsky 1979.) Our main purpose is different.

If analogy is, as we have argued above, a strong operational principle of human thought, is there something to be gained by considering the brain as a machine for making analogies—an *analog* computer? This is effectively the thesis of Craik, and it is salutory to reflect that his book predates by some years the equally seminal paper of Turing (1950) which so firmly established the *digital* computer as the accepted metaphor/model of brain in the fields of artificial intelligence (AI) and cognitive science. While Turing readily conceded that "Everything really moves continuously" still he argued "there are many kinds of machines that can profitably be thought of as being discrete-state machines." Turing's typically bold assertions led the way for other thinkers to develop (often in equally assertive fashion) *computationalism*—"the hypothesis that cognition is the computation of functions" (Dietrich 1990, p. 135). Influential work in this tradition, post-Turing, includes Newell (1980), Pylyshyn (1984), Pagels (1988) and Dietrich (1990). Only relatively rarely has this foundational assumption been questioned by, e.g., Searle (1980, 1990), Johnson-Laird (1983), Rubel (1985), McGinn (1989) and Penrose (1989).

Some workers in symbolic AI have championed analogical reasoning as a practical approach (Mitchell and Hofstadter 1990; Hofstader and the Fluid Analogies Research Group 1995). Also, in the machine learning community, analogy (under the various guises of 'lazy' learning, memory-based reasoning, case-based reasoning, similarity-based reasoning etc.) has been well formalized and frequently applied—most often to problems of natural language processing (Stanfill and Waltz 1986; Stanfill 1988; Skousen 1989; Jones 1996; Aha 1997; Daelemans, van den Bosch, and Zavrel 1999; Pirrelli and Yvon 1999). It is probably not the case, however, that these workers actually see the brain itself as an analog computer. For as Rubel (1989) points out, the digital computer is a universal simulation device and is routinely used to simulate real-world (analog) phenomena.

If computationalism is to be useful, capable of illuminating questions about brains and cognition, it is vital that the notions of *computer* and *computation* are closely and carefully defined. Apart from a short heyday in the late 1950's and early 1960's when practical applications of analog computation were briefly popular (see Korn and Korn 1964 and Wilkins 1970 for state of the art surveys towards the end of this period), digital computation has always been the more advanced of the two paradigms, both in theory and in practice. Hence, AI has always focused strongly on digital computation as its fundamental metaphor, to the virtual exclusion of analog computation. This preoccupation directly mirrors the situation in computer science in general, where the classic texts and reviews (Minsky 1967; Hopcroft and Ullman 1979; Lewis and Papadimitriou 1981; Hey 1999) are virtually silent on the topic of analog computation. Almost certainly, this reflects the availability of a formal, discrete-state model of computation—the universal Turing machine (Turing 1936; Herken 1988)—which apparently makes the notion concrete.

By contrast, in the realm of analog computation, it can even be hard to determine precisely what 'analog' is supposed to mean, and exactly how it differs from 'digital' (see Lewis 1971, Moor 1978 and Pylyshyn 1984, Chap. 7). Hence, we have long had to content ourselves with such nebulous 'definitions' as (Korn and Korn 1964, p. 3):

> "An analog computer is any physical system which establishes definite prescribed relations between continuously variable physical quantities."

The problem with this is that it makes *everything* computation! Without a tighter definition, I can claim that the weeds in my garden are computers for they are solving the energetics equations of photosynthesis. Admittedly, the situation is starting to change with increased interest in formal models of analog computation (see, e.g., Siegelmann 1999, Chap. 11 for review material) yet still it remains a cinderella relative to its digital counterpart.

In this paper, I will argue that the Turing machine is an *abstract*, theoretical device which should not be confused with a practical, digital computer. To do so is tantamount to confusing a scientific theory with reality. This exceedingly common error is encouraged by use of the same word ('computation') for the operation of both the abstract Turing machine as well as a practical computer. As Turing well knew, and every electronic engineer knows today, a 'digital' computer is physically an analog machine—designed to hide its fundamental analog nature from its users. For in the real world, everything is analog. So why should this not be true of the brain too? The previous points emphasize the importance of semantic interpretation in computation. This is what makes an analog machine into a 'digital computer': the eye of the beholder, which assigns discrete states to continuous physical variables. But there can be no computation—digital or analogue—without semantic interpretation by an external observer. This surely distinguishes computation from cognition, at least if we are to avoid the worst excesses of homuncular 'explanations'. As Harnad (1994) reminds us—"Computation is just interpretable symbol manipulation: cognition isn't".

[1024 words]

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