

## **Manifesto of Brain Science\***

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1. We believe that there are questions of such philosophical import that they deserve being pursued without any consideration of utility. One of them refers to the nature of thought processes, or more generally, of complex behaviour.
2. We are convinced that ultimately a satisfactory explanation of thought and behaviour will be given in a language akin to that of physics, i.e. in mathematical terms.
3. The physics of living organisms, with its specialized branches of physiology and biochemistry will undoubtedly underlie such an explanation, but it will not be sufficient by itself as a theory of behaviour. In fact, when boiled down to physical fundamentals, a mouse or even a worm is not very different from man. But we are ultimately interested in thought and behaviour of people, not of worms.
4. The difference in behaviour in different species reflect different ways of coping with the environment, or with distinct niches of the environment. These different behaviours have their material counterpart in different brains. Therefore the peculiar nature of any animal brain cannot be explained from the physical components alone, the explanation necessarily involving causes residing outside the animal, i.e. information derived from the environment.
5. Concepts such as (Shannonian) information, coding, computation, are outside of physics (even if the formulas look like physics) but are

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\* This was prepared for a meeting in Brussels where the European Commission considered the future of Neurobiology in Europe.

central to brain science. They are also fundamental concepts in electronics and computer science. This is the basis for a lively discourse between certain branches of engineering and brain science. Another common aspect is that both deal with functions directed to a goal, which physics does not.

6. Our object being the discovery of computer-like operations in brains, the hypotheses we test in our experiments are really inventions of computing schemes, and are therefore necessarily more complex than hypotheses in other branches of science. Thus we are inventors of computing devices much as our colleagues in Artificial Intelligence are and we can learn from them as much as they learn from us. Some ideas in brain science (e.g. neural networks) have already turned into eminently practical applications.

7. Computation in brains is a fine-grain operation, requiring a spatial resolution of about one to ten micrometers. The functional elements are fibers and neurons, and in most cases many neurons are involved in a significant functional pattern. This requires special techniques of observation which are being developed: multiple electrode recording, optical recording by means of voltage sensitive dyes. In most cases the vast amount of information produced by these recording techniques can only be stored and digested by means of large computers. Their theoretical analysis also requires sophisticated computing techniques, and often computer simulation.

8. We believe that the distribution of electrical signals observed at a spatial resolution of  $1\ \mu\text{m}$  and a temporal resolution of about  $1\ \text{ms}$  is all we need to know as the material counterpart of behaviour. Behaviour may be modified by hormones, or by pharmaca, or by pathological unbalance of some transmitter substance, but the actual effect of these is always expressed in terms of the occurrence or not occurrence of action potentials in neurons.

A more fine-grain analysis, say at the molecular level, is relevant for the understanding of the individual cell, but probably unnecessary for the understanding of behaviour, or may even obscure the picture there.

9. Developmental neurobiology is a branch of general biology, not of brain science as defined here. "How do the fibers from the eye find

their way into the optic tectum?" The answer to this question will tell us much about how the arteries find their way into the kidney, or the roots of a tree into the earth, but very little about the problem of the analysis of visual information in the optic tectum.

10. Efficient research groups in brain science are small. Everybody is groping for experimental techniques and for conceptual models. If someone draws up a gigantic project in order to solve the problem by brute force, he is likely to have missed the complexity of the situation and is sure to produce much waste.

To illustrate my points, I want to mention some successes of modern brain science in its interaction with information engineering.

(a) The paper by McCulloch and Pitts (1943) proposed an equivalence between nets of neurons connected by synapses and propositions of Boolean logics. The terminology and the diagrams of this paper were immediately taken over by the designers of calculating machines (e.g. J. v. Neumann) and the basic ideas became the starting point for more than one theoretical development, e.g. Automata Theory and Chomskian linguistics (via the formalization proposed by Kleene, 1956).

(b) Some ideas were exchanged repeatedly to and fro between brain science and engineering. The idea of the Perceptron (Rosenblatt 1962), a randomly connected image processor, was inspired by neuroanatomy and neurophysiology. It has admirable technological consequences even today (Sejnowski 1987). It received criticism on theoretical grounds by Minsky and Selfridge, who thought that a machine equipped with preset form detectors ("Pandemonium") would be much more efficient. The Pandemonium inspired neurophysiological work by Lettvin and others which turned into the seminal paper "What the frog's eye tells the frog's brain" (1959). Parallel to it, in the same intellectual environment, work on the cat (and monkey) visual cortex in the hands of Hubel and Wiesel produced splendid, Nobel prize winning results. The Hubel and Wiesel "feature detectors" in turn gave the engineers ideas, who produced several efficient image processing devices along the same theoretical lines.

(c) Filter theory, auto- and crosscorrelation, generalized Fourier analysis are theoretical concepts developed in electronics. Reichardt (1970) described the results of his (and Hassenstein's) experiments on optomotor reactions in insects in those terms. This was the first model of animal behaviour which made detailed predictions on the neurological wiring underlying the behaviour, and the predictions were in part confirmed anatomically (Braitenberg 1977). The technological fallout was a patent for a device designed to measure the direction and velocity of a moving panorama.

(d) Associative memory was postulated by psychologists (Hebb) as a principle underlying cognition and behaviour. This idea turned into a variety of mathematical models, one of which, the neural net of the Hopfield kind, is hailed now as the cornerstone of a new age of computing technology. It was shown that the statistics of connections within the cerebral cortex (Braitenberg and Schüz 1991) can best be explained as being specialized for associative memory. The global states of activity which the Hopfield theory postulates, a sort of resonant modes or "eigen-states" of the cortex, have been shown with computer analysis of multiple electrode recordings (e.g. Aertsen and Gerstein 1991; Vaadia and Aertsen, this volume).

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