Comparing Properties of Brains and Computers*

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The criterion that pure natural science can only investigate objective phenomena which can be observed by independent observers sets certain limits to pure natural scientific understanding of brain functions. It excludes consciousness and feelings since these are only subjectively accessible and alternatives cannot be decided objectively. The limitations of brain research are discussed by comparing the properties of brains and computers. At least for the time being we do not know of any natural scientific – i.e. physical or chemical – method which allows the objective measurement of consciousness, sensations, and emotions.

In addition it is discussed how and in how far our brain understands its surrounding nature.

Foreword

Brain research is a field that goes beyond the limits of natural science**. Brain research and computer science intensely stimulate each other. A number of important questions concern both fields.

Here I want to compare the properties of brains and computers. I want to discuss the epistemological limitations of scientific brain research by asking the question whether the observable capabilities of brains and computers are fundamentally different. This subject is dealt with more thoroughly in Stieve (1995).

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** In this article I use the word "scientific" strictly in the sense of naturwissenschaftlich" i.e. "pertaining to the natural sciences", not just "wissenschaftlich" conforming to the rules of academic discourse. Moreover when I use the word physics, it is meant to include chemistry and all the so-called exact natural sciences as well. Psychology, however, is not a pure natural science, it applies methods both of natural science and of humanities.

Introduction

There are two different aspects of human brain activity:

1. The brain can be described as an information processing organ which controls bodily functions. These brain functions can be observed and measured using the methods of physics (so-called third person perspective).
2. We know the human brain to be the "seat" of the mind (including such phenomena as psychical experiences, consciousness, sensations, emotions, etc.; see Guttenplan, 1994) which – at least for the time being – can *not* be measured by the methods of physics (first person perspective), they can only be observed from within.

Do the same aspects exist for computers?

Computers can be described as information processing devices, which may control artificial organisms, like robots or the functions of machines. These computer functions can be described using the methods of physics.

Can there be properties of computers comparable to the mind, to mental processes (Buschlinger *et al.,* 1998)? And if so, can they be investigated? Again, the first person aspect of computers is certainly not accessible to the methods of physics.

Natural Science

Natural science operates by applying a number of strict game rules by which it arrives at its statements about the world. The most essential of these

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rules is that a phenomenon is only regarded as *objective* if it can be observed by several *independent observers*. Natural science can only observe *properties* and it can subsume combinations of properties in its concepts. Implicitly or explicitly all terms of natural science are defined by procedures of measurement (which include counting and all kinds of observable, measurable tests). But we also know of phenomena inaccessible to natural science, our feelings and emotions, our primary, subjective, private experiences.

Part of the strength of natural science stems from its limitation to what it has access to. Science has specific game rules and within them it is powerful. If a scientist oversteps this area, then his conclusions lose their strength. In science's inductive method of verification a statement becomes more and more probable with the accumulation of evidence and is finally regarded as good as certain, because it has invariably been confirmed in many tests. The progression to a secured statement is very gradual. Unlike the deductive proofs of mathematics which proceed logically and cogently from unprovable axioms, scientific proofs are inductive, they have no sharply defined line beyond which they can be regarded as certain.

What Does Biology Know of the Nature of Living Beings?

Biology is the natural science of living beings. It does not deal with all aspects of living beings; it is only concerned with those properties that can be observed objectively, i.e. quantified, counted, mediated intersubjectively, and verified. This is also true for ethology. Of course one can deal with biological objects in different ways. Psychology, sociology and anthropology do so with a variety of scholarly methods, some strictly scientific, some not. I may even be convinced that I understand the feelings of my dog; but that is not natural science.

Consciousness

My consciousness is my primary subjective mental experience, my feelings, my emotions and my thoughts. But I know that solely from self-observation and because of this I cannot prove whether other beings have a consciousness or not. It seems reasonable to assume that other humans have the same or similar conscious experiences, and we are supported in this assumption by the fact that we can communicate by language about them. However, we never know for sure if other people's descriptions of experience are true, false or simply fake. With regard to animals we can only guess, and our guesses become more and more speculative the more distantly we are related to them. That chimpanzees and gorillas experience sensations in some kind of consciousness appears fairly certain to us. When it comes to the housefly, the mosquito, and the slug, any guess – be it positive or negative – is pure speculation. Experiments involving their own mirror image indicate it is likely that chimpanzees experience a consciousness; however, the negative results of similar tests with other animals such as dogs cannot exclude the possibility of them having a consciousness. Epistemology does not provide a criterion as to whether or not a beetle has a consciousness (however, c.p. Buschlinger *et al.* (1998), this issue, pp. 455–479) Therefore the statement that bees have no feelings is as unsure as that to the contrary. Some biologists, uncritical in their application of the scientific method, tend to disregard these limitations of natural science. I can conceive of no natural scientific way to measure subjective mental experiences, consciousness, and emotions objectively. However, we can fairly accurately quantify our own subjective sensations as evoked by various stimuli in psycho-physical experiments (Campenhausen, 1993). By observations of behavior and reports of other people's self-observations, we are able to extrapolate general statements about human conscious experiences, e.g. that consciousness is linked to attention and short term memory (Crick and Koch, 1990; 1992). We do not doubt that other people have quite similar feelings when they speak of identical conscious experiences. Again, this principle fails with regard to the bee.

We know only very little about the *development* of our consciousness in our individual life, since our memory of our early days is very poor. We feel justified to assume that consciousness develops during the early phase of our ontogeny, but we cannot positively decide when it starts.

Proceeding from the scientific finding that in the course of *evolution* organisms evolved from more primitive forms to higher, more differentiated ones, one may ask the question if there have been earlier stages of consciousness in the evolutionary forbears of humans. Furthermore, are there less differentiated stages of consciousness in contemporary animals? Even though natural science is unable to make statements on consciousness, the multi-disciplinary answer to both questions is probably yes (Delbrück, 1986). It seems plausible to us to assume that in higher animals with their (in comparison to humans) less highly evolved brains, there possibly exist earlier stages, less differentiated forms of consciousness. Apes, for example, are able to identify themselves in a mirror, so it is probable that – unlike monkeys – they already have an individual consciousness (a self awareness).

The Hypothesis of Psycho-Physical Identity

In my subjective experience, physiological processes in my body, i.e. processes that can be physically measured, are closely linked to events in my consciousness. If I get burned on a hot stove, I feel pain. We know – e.g. from psycho-physical research during brain surgery under local anesthetics – that the activity of the human brain is accompanied by certain reported psychic experiences, sensations or emotions. Certain patterns of excitation in the brain then correspond to certain feelings. Reports by humans about their feelings and sensations when specific areas of their brain are subjected to focused stimuli, and of deficits experienced due to brain injuries allow us to identify a relation between measurable brain activities and certain – reported or even self-experienced – conscious experiences. We can relate localized brain activity that we measure physico-chemically to sensations human subjects report. Such investigations have shown that conscious experience is linked to activities of neurons in restricted areas of the cortex, the primary sensory fields, and not to activities in the many other fields. We can identify the activity of certain groups of neurons when test subjects report certain hallucinations. The reports of hallucinations (phosphens e.g.) can even be used to identify the circuitry in the brain (Ermentrout and Cowan, 1979; Cowan, 1986).

These findings lead us to the *multi-disciplinary* postulate: Consciousness, feeling, and thinking are functions of the brain. However, none of these important experimental observations can give natural science a direct access to consciousness and feelings. This is a border area of science: In ethology different observers observe the same behavior of a subject in a given situation; a classical scientific experiment. In psychology we can have reports by different subjects on their mental experiences as observed individually under similar experimental conditions. This latter case meets several – but not all – criteria of science. The two cases are different insofar as the primary mental experience can only be observed by the person concerned (not several independent observers) and that the reports are "translations" which may be (possibly even systematically) adulterated. Of course, one can conjecture and successfully study how consciousness is linked to physical processes, but that is pure natural science no longer, rather a promising, very interesting multi-disciplinary type of scholarly research. Such an approach to acquire knowledge of consciousness by combining neural and psychological data from experiments on humans and animals with subjective reports from humans is termed "triangulation" (Churchland, 1986; Dennett, 1991; Flanagan, 1992). It is important to be aware of the difference in the applied methods because they have consequences for the reliability of the conclusions.

An Apparent Paradox: The Mind-Body Problem

In my conscious life I experience, or rather it appears to me, that my will is the cause of my actions. As stated above, although my primary subjective experiences, mental experiences cannot be an object of natural science since they cannot be observed by independent observers. Natural science however, proceeds from the postulate of causality. It always requires causes that can be registered with its specific, i.e. physical or chemical, methods. Consequently a mental process, e.g. *will*, may not be given as a scientific cause for an action (see also Bieri (1992)). Science demands uninterrupted causal chains and will cannot be an element of such a chain; it cannot substitute but only be associated with a physical cause (i.e. an action is caused by a certain activity pattern of the brain and this activity pattern may be correlated with the mental experienced will). This principle of the "causal closure of the physical" has been confirmed so far in every investigated example. In cases where biology neglected this principle, progress in scientific understanding was not promoted.

A similar argument holds for *free will*. A free will decision is subjectively intentional and neither predetermined nor random. Again, there is no scientific method which allows us to decide whether a certain decision has been made on free will or not. We cannot even safely decide whether free will decisions exist at all. Nevertheless it seems most comforting to believe that we have a free will.

Scientific brain research is constrained by the dictates of its method and is unable to make statements about certain feats of the brain. A philosophical no-man's land stretches between the areas in which brain researchers can reliably operate and the area of "body, mind, soul, and consciousness". I do not know of any methodically stringent solution to the so-called Mind-Body Problem from pure science. Science sees the physical and chemical processes within an organism as logical, consistent, and unbroken causal chains in themselves. There is no room for consciousness, emotions, or will to intervene in the organism's physical machinery. On the other hand, our actual primary experience is the exact reverse, namely that our will causes our action. We move because we want to. It seems we are dealing with two different aspects of the same system, of which science can only see one.

This situation can be compared metaphorically to a projection of a three-dimensional object onto two dimensions, of course a poor comparison, but it may help to illustrate the problem. Consciousness and will may be connected to something behind the physical performance of the brain.

The Four Levels of Brain Research

Our brain is a parallel processor of information encoded by pulse frequency modulation. The algorithms which are used by the working brain when solving problems seem to be different from the ones which we consciously experience when we introspectively analyze our human thinking (Creutzfeld, 1986).

Brain research is conducted on four levels. The investigation of all four levels is necessary for the understanding of the brain. Each separate level represents a sort of a closed area of description, complete unto itself. However, the knowledge of the properties of the elements alone may not be sufficient (and does not even have to be complete) to explain the properties (and their possible changes and development) of the system. The properties of the system are determined both by the properties of its elements and their functional linkages. On the higher level only the input-output dependencies of the sub-systems are important, not the manner of their actual realizations.

1. *Molecular-biological level.* An increasing number of key reactions in the brain are analysed on the molecular level. For example, many transmitter receptor molecules, which by changing their conformation act as switches and some associative or convergence-detecting molecules, which play a key role in memory formation, are well characterized (Kandel and Hawkins, 1992).
2. *Cellular level.* Processing information means the performing of mathematical operations, algorithmic transforming, and combining of sets of data. This task is performed by the neurons in the brain.

   Neurons are interconnected, sophisticated processing elements. Their performance, i.e. their admittance and amplification factor is variable:
   a) It can be modified (adjusted) according to use (experience), i.e. it can adapt.
   b) It depends on the state of activity of neighboring elements, taking into account neighboring activity patterns (cooperativity of local nerve nets).
   c) It can be modified by other systems of the brain which regulate sleep, alertness, and attention or represent emotional states.

   Synapses are the calculating elements of the neurons. The kind of synaptic influence (excitatory or inhibitory) on the activity of the neuron and its degree depends on the morphological and the biochemical characteristics of the synapse concerned. In addition, the performance of synapses can be modified by neuro-hormons (chemical modulators). Using their specific combinations of synapses neurons are able to add, subtract, multiply, divide, differentiate, integrate, detect coincidences, etc., and to perform all kinds of logical operations (Nicholls *et al.*, 1992; Shepherd, 1993).
3. *Connected groups of neurons.* At this level, the investigation of specific brain regions has re-

sulted in the detailed description of functional linkages between groups of neurons, e.g. reflex arcs, feed-back loops, neural circuitries and pathways etc.

A much-used model to describe such functional linkages is Hebb's concept of cell assemblies (Hebb, 1949); according to which neural brain function is based on patterns of coordinated activities of many cooperating neurons. In such a cell assembly excitation can circulate for a while and form a reverberatory circuit, thus providing reinforcement as a prerequisite for learning. Repeated coincident activity of two converging neurons strengthens the concerned synapse.

4. *In the domain of systems analysis* the neurophysiological base of the behavior and learning achievements of entire organisms become visible. So far, this has most successfully been done with a number of species of invertebrates (Reichardt, 1982; 1986; 1987) but becomes increasingly successful also in vertebrates. One example is motion detection and flight control in flies. The "wiring diagram" of the neurons from the retina of the fly has been mapped in detail (Strausfeld and Nässel, 1981); its connections within the brain and much of its functional significance is now understood (Hausen, 1993). The search for the algorithm for detection of motion started from a detailed behavioral analysis of the optomotor response of insects. This led to a correlation model and further step by step, alternating with experimental verifications, to a quantitative description of a control system capable of accounting for the main features of fixation, tracking, and chasing in flies. The equations can predict in a satisfactory way the trajectory of one fly chasing another (Hassenstein and Reichardt, 1956; Poggio and Reichardt, 1976; Reichardt and Poggio, 1976; Egelhaaf *et al.,* 1988; Egelhaaf and Borst, 1993).

Uses of Brain/Computer Analogies

Whereas brains have developed in the course of evolution without clearly defined requirements and parameters for their performance and were tested by an immense number of trials, computers are designed for certain purposes and optimized under a tight budget and schedule. On the other hand computer development has been greatly stimulated by brain research; it has used several concepts of brain functions (such as Hebb's learning rules, parallel processing of information, and neural networks).

During the last twenty years, computer developers increasingly borrowed from certain properties of nervous systems, which substantially advanced computer technology and led to unexpectedly successful simulations of brain properties. Progress in computer development can be expected from applying new concepts, new algorithms, e.g. for pattern recognition, some of which can be adopted from those found in the brain. Moreover, learning could be exploited much more. A human brain needs many years of intensive individual learning in order to reach a high performance. No computer has been trained yet by a comparable amount of experience. But still the construction of computers depends strongly upon the properties of the technical components and upon the purpose for which they are designed. Perhaps we can learn as much from brains for building computers as we learned from birds' flight for the construction of airplanes?

Brains and computers differ fundamentally in their structural components. Computers are made of electronic elements, whereas the brain is of "flesh and blood". And yet, the functional principles of both systems can be compared and exploited for brain research and computer development. After having characterized a brain function experimentally it can be tested whether the resulting principle works in *computer simulation* which may even lead to the construction of robots (Franceschini *et al.,* 1992; Martin and Franceschini, 1994).

Computers and robots are now being designed to have something similar to *motivation*, i.e. they are programmed to pursue a more general aim (like finding and rescuing a trapped person in an emergency), but the actual way of achieving this aim may be chosen by the computer depending upon the on-site conditions. Here again, motivation is used in a strictly natural scientific sense, no implication is made about consciousness and feelings of the computer.

On the other hand, conceptual models and computer development have contributed significantly to advance our understanding of brains. Information theory and cybernetics have supplied conceptual tools. An example is the figure-ground discrimination. Flies can detect spatial discontinuities of speed within the retinal images and thereby distinguish figure from ground on the basis of relative motion. The interplay of experiments and theory led to a model for the algorithm used by the fly's visual system, which discriminates a figure from its visual context by laterally inhibiting non-linear interactions between motion detectors (Reichardt *et al.,*1983; Reichardt, 1986). This principle, discovered in insects, is now established as a general principle for the processing of visual information in a variety of species including man.

The "game" of exploring computer capabilities can help to discover functional principles which later may be detected in the brain. Strategies for learning in networks of modeled neurons have been explored in computer simulation (Hinton, 1989; 1992). The competitive learning algorithm in the modifications of T. Kohonen (1982) and H. B. Barlow (1980) is able to simulate and explain certain characteristic properties of the brain as feature categorization, formation of clusters of neurons with related functions, and determination of decisions by averaging the outputs of relatively small numbers of neurons.

It is, however, important to pay attention to the usefulness of model simulations. An analogue model, e.g. a computer simulation which merely provides the same input/output relation as a certain brain function, is only of limited use, because it may not tell us how the brain does it. If, however, a simulation contains relevant elements and representations of units and processes which are actually proven to participate in the particular brain process, it may indeed help us to understand *how* the brain works. In short: a model should lead to critical experiments if it should be helpful to understand the brain.

The use of chance. The properties of chance are often advantageous for search processes. The combination of chance and selection is the basis of evolution (Monod, 1971; Mayr, 1979). It enables systems to become fit to many unforeseen challenges. In computer application chance is often used (e.g. in so-called Monte Carlo and artificial life simulations). In connectionistic computers chance is additionally used to adapt the performance to the desired tasks. It may be possible that the brain uses stochastic processes not only in development but also for certain decisions, e.g. random choices in searching behavior or trial-and-error learning. It does not seem impossible that the brain's random generators are amplified atomic processes which are determined by quantum uncertainty (Heisenberg's uncertainty principle; Gierer, 1985).

How and how far Does Our Brain Understand the world?

Our brain has the capability to understand nature. To understand nature means that we can have or make theories of the world which describe the functional relations, much of this in mental pictures that we can visualize. Is there a good reason for this capability of the brain? Konrad Lorenz (1941, 1943) and later Gerhard Vollmer (1975); (see also Quine (1968)) formulated the *"Evolutionary or Naturalistic Epistemology"*, (the theory of the evolution of cognition, Evolutionäre Erkenntnistheorie), a very plausible but not provable theory as to how our brain became world-understanding:

The structure and functions of a living being tell us something about the environment to which it is adapted. If one studies the anatomy and the bodily functions of a tree-living monkey one comes to know also some properties of the forest (e.g. the size of the hand tells something about the thickness of the tree branches which the monkey grasps, etc.) The living being is a sort of a complement of certain aspects of the environment. In a similar way our brain tells us something about the physical world. It should be possible in the future to reconstruct the stimulus situation, and by that, aspects of the physical world from the patterns of activity in the brain. Brains have models of the world and use symbols to operate in imaginative space ("Hantieren im Vorstellungsraum"; Lorenz (1941)). The theory of the evolution of cognition proposes that a brain which makes better predictions regarding relevant properties of the physical world in which the organism lives provides its owner with a better chance of survival than its competitors. A better understanding of how a rock falls may be of great advantage. The brain with the better theory of the physical world, or more specifically, of relevant properties of the possible environments of an organism, has a better chance to survive in natural selection. By this mechanism we have inherited useful theories of nature which have been tested through many generations. The models of the world of brains of higher animals include the subject in its environment. This should be a prerequisite for conscious self-awareness (which again cannot be observed objectively).

In order to interpret (to "understand") our environment the brain often uses only a few relevant clues that are characteristic – and rarely mistakable – for a certain relevant situation: a sort of a recognition code (i.e. so-called "sign stimuli", Schlüsselreize). These clues are used to initiate appropriate reactions by the organism. For this interpretation the brain needs and possesses certain expectations (pre-knowledge) about its environment. These expectations concern regularities of the physical world, probabilistic predictions about the environment including the probable behavior of other living beings etc. Part of this knowledge is learned by the individual brain during the life of the organism, but much of the understanding of the environment is innate, gained by brains in the course of the evolution by superindividual learning (Lorenz, 1978).

However, there are limits to the capability of our brain. There are properties of the physical world which we can understand but cannot possibly envisage. The most popular example is perhaps the both corpuscular and wave-like properties of light. The generally accepted explanation for these brain deficiencies is that the knowledge of these properties had so far not been relevant for our evolution for which the brain was made fit. Accordingly there may be things we cannot understand and problems we cannot solve. It may well be that the brain provides no understanding of certain properties of nature, especially of those which had no direct significant impact in our evolution. But since we do not know the limits of our understanding of the world, we must attempt as much as we find possible.

Another limitation of our brain is that we appear to have no realistic conception of chance; so we almost obsessively search for a direct reason of an experienced mischief. But this is perhaps a good strategy from an utilitarian point of view. Maybe such a reductionist approach is a success strategy in most cases and therefore a "natural" brain concept which is advantageous in selection. Our brain acts as a causality engine, which compulsively searches for and even constructs causes for events.

Performance Comparison of Brains and Computers

There are certain tasks which computers can do better than brains: like velocity of storage and the processing, handling, and searching of large pools of data, and the like. Are there functional properties of the brain of such quality that they cannot be achieved by a computer – or at least not as well (Mainzer, 1994)? Let us regard the frequently chosen examples.

What is *intelligence*? – Or perhaps more pertinently, how does one recognize intelligence? – Intelligence is a fuzzily defined property. We have no viable measure for it. The so-called intelligence quotient does not fulfill this purpose (Dewdney, 1997). We can circumscribe it as the competence to extract the relevant from a mass of information, to combine the relevant data and draw logically correct conclusions. Artificial intelligence research strives to have those tasks done by computers. What we regard as intelligence depends very much on the regarded task. To date, artificial intelligence is in most examples still significantly lower than that of humans. However, in certain defined situations, e.g. in extracting relevant information from large masses of certain data, systems with artificial intelligence can already be better than the human brain.

Alan Turing devised a test to determine whether or not a machine is intelligent (Turing, 1950). In this test persons communicate indirectly, e.g. by type-written questions and answers, with a system hidden in another room, – either a computer which is made to imitate human performance, or a human. They then have to decide whether they were communicating with a human or a computer. Should they not be able to decide correctly, then, Turing suggests, we should attribute intelligence to the computer. Turing claims, there is no way to find out in such a situation whether the task is performed by a person or by a sufficiently programmed computer. Nobody has been able to disprove this. There seems to be no reason why intelligence should be a property specific only to brains.

Are there any problems that can be solved by the human brain, but not by machine intelligence? At the current state of the art, the assumption that there are none is becoming increasingly likely.

Gödel has shown that any moderately complex system of axioms yields statements that may be true but cannot be proved through those axioms (Gödel, 1931; Hofstadter, 1979; Gierer, 1985). Different consequences have been drawn from that theorem: Some claim that it implies that human thought can solve problems which cannot be solved by any computer. According to Penrose, Gödel's theorem implies that no deterministic, rule-based system – that is, neither classical physics, computer science nor neuroscience – can account for the mind's creative powers and ability to ascertain truth. He thinks that the mind must exploit non-deterministic effects (Penrose, 1994). Gierer contradicts this statement claiming that in no single, exactly described case it was possible to prove that there is a performance of the human mind that a computer could not do (Gierer, 1985).

Turing in 1936 theoretically investigated the capacity of a hypothetical computing device which masters all the operations of logic and of number theory, the "Turing machine". Any problem that can be solved by a finite succession of logical operations (i.e. algorithmically) can be solved by a Turing machine. A problem which cannot be solved by a Turing machine, cannot be solved by any kind of machine. Turing was able to show conceptually that there are problems which cannot be solved by a Turing machine (Turing, 1936).

The *Church-Turing thesis* is a hypothesis about the processing strategies which human brains use (Hofstadter, 1979). It exists in many versions and states that if a problem is human-computable it is machine-computable, or, if a problem can be solved by human reasoning (i.e. only by strictly applying logic and algorithms), then machines can ultimately be constructed to do it. This thesis has not yet been disproved.

Are there performances by brains that can be observed by scientific methods, but cannot be achieved by suitable computers? The brain may solve some problems not by solely applying deterministic instructions (algorithms) but by other methods, e.g. the use of lucky intuition. Are *intuition, creativity,* and *flashes of inspiration* achievements specific to living brains? If we try to describe intuition, flashes of inspiration, and creativity in a scientifically conceivable way, we arrive at a different conclusion. Scientific terms always require an observable, measurable test. By what measurable features can we recognize creativity?

Creativity can be described as inventing or designing something new, based on guessing and playfully trying of unknown relations. And what is a flash of inspiration? – The unexpected, "intuitive" presentiment of relations that have not yet been explained. Intuition could thus be described as a preference for a certain decision or procedure which cannot yet be justified by logical reasoning. It may be based on pre-knowledge and on previous experience and on (brain-) system-specific preferences. Described in this way, creativity, inspiration, and intuition can of course be simulated in computers. They might e.g. be simulated as random tests of runaway assumptions (derived in part from "wild" hypotheses) that are triggered by associations. These random associations, however, must be restrained i.e. afterwards checked by a not too strict, but well-dosed control based on experience and logic. (By the way, creativity and inspirations need not to be right.)

The question of *consciousness* and subjective experiences also remains for computers (Penrose, 1989). As stated above, natural science is unable to make statements about them since they cannot be observed by the methods of natural science. Self-observation is limited to a single human individual. In psychology, one person's subjective findings are generalized and applied solely to other humans. They can be extrapolated neither for beetles nor for computers. That is to say that no one can prove or disprove that computers can have a consciousness. Maybe consciousness has some relation to information. As outlined above, the brain uses symbols to model the reality and to operate in imaginative space. These symbols represent information. It is conceivable that consciousness is a – not objectively measurable – property of certain complex systems, a property that does not depend on the material representing that complexity, just as information is inherent in temporal and spatial patterns and is not bound to a specific form of matter or energy. Some people, inspired by chaos research, suggest that consciousness may be an emergent property of the brain's complex behavior (Crick, 1994; Horgan, 1994). Emergence, which has become a fashionable term lately, is used in a variety of meanings (Stephan (1998)). In this context it means that consciousness may be an unpredictable and irreducible phenomenon of brain function. Even so, it is not a property that can be observed by an independent observer.

Some postulate that consciousness (self awareness) is a quality peculiar only to the living brain. Can arguments be found for this hypothesis? Two cases are conceivable:

1. Consciousness is an additional property characteristic of certain brain functions. It is peculiar to the brain of humans and their relatives.
2. Consciousness is an additional property of certain data processing systems, regardless whether they are living beings or machines like complex computers.

   I do not see how this alternative can be tested empirically.

One can reverse this question and ask: Why is the performance of certain brain functions accompanied by subjective experience? Does consciousness have a biological advantage for the observable performance of an organism, that is, a bonus in evolutionary fitness (Vollmer, 1980; Barlow, 1980)? Consciousness could make satisfaction possible which may serve as a bonus or reward to approach optimal performance. However, if there were a robot which had all the objectively observable third person properties of a human, could one distinguish it from someone who has consciousness? Searle has discussed a related question in the "Chinese Room" thought experiment. He shows that such a system can give the right answers to questions without "understanding" them, just by applying proper algorithms (Searle, 1984). Natural science alone cannot supply an answer to these questions concerning the function of consciousness (Horgan, 1994). Some take it for granted that consciousness is not an additional property but by itself causes an improvement of measurable performance. The problem is that so far no one has come up with a method to prove or even to test this hypothesis.

Furthermore, the question if there are capabilities of the brain inaccessible to natural science that a computer cannot furnish, is in all probability not solvable.

Brains and computers have much in common. In principle, it is possible to compare the measurable performance of both systems with the methods of pure natural science. How far the similarities in the capabilities of future computers will lead, cannot be gauged today. It cannot be excluded that computers can have capabilities analogous to those only fuzzily defined capabilities, intelligence and creativity. Whether computers can have a "Innenperspektive", properties comparable to a mind, i.e. mental processes cannot be decided by methods of natural science. Most statements regarding this are matters of belief.

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