The Ghost in the Machine

This essay was written by **Ed Hulme** and was first published in the 1998 *Mill Hill Essays*.

The biggest puzzles are often right in front of our eyes, so commonplace that everyone takes them for granted. In fact, one of the great mysteries of the universe is located right behind the eyes, and between the ears of every normal human being: the origin of our own consciousness. How does it come about that a particular transient organisation of atoms, as I am and all of you are, is aware of its own existence, and of its surroundings? Why does it have a mind? Why is it a self? In fact, why is it me?

Most of the time, we take our selfhood for granted. We get on with our lives just like other organisms, using our minds to make the best of our individual prospects. In strictly evolutionary terms, that is what we would expect our minds to be for. But, unlike all other creatures, our minds have enabled humans to transcend their immediate physical environment. The most important things in our personal ecological niches have become other people: Other minds. This allows us an incredible variety of specialised roles. Nowhere amongst non-human species will you find individuals who can find the wherewithal to fulfil their biological imperatives by behaving as say a rock star, or a neuroscientist!

The relationships between the mind, the emotions, and the body have preoccupied thinkers for millennia. The pre-scientific view was that the mind and temperament are ruled by four "humours", mystical fluids associated with different visceral organs. Even now, we "take heart!" , or "lack the stomach for a fight".

Although we still refer to ourselves as being good, or bad-humoured, we are now sure of the seat of the mind-body problem: The brain. Some of you may remember an educational toy called the Visible Man. The Visible Man, like the pre-scientific medieval savants, focused on the visceral organs, the gut, the liver, the kidneys etc. The brain was obviously there, like a walnut in the shell of the skull, but what was missing (and would have been impossible to show in a plastic model) were the billions of nerves in the brain, receiving signals of temperature, pain, touch, vibration, stretch, distension, smell, taste, sound, light … from all parts of the body, and sending signals to control all the forms of behaviour; posture, motion, eye movement, speech, facial expression, secretion, ingestion, excretion, heart rate, erection …. If one were to remove all other tissues, the body would still remain outlined as if by a spectral mist of sense organs, and fibre-like nerves. It is through these that the brain, and the self which it generates, communicates with the rest of the universe.

The ultimate aim of neurobiology is to understand the mechanisms through which the brain unites and processes all of these inputs and outputs to produce behaviour. In the course of this, we hope to solve the much harder problem of why we ourselves know *what it is like to be* the organism whose brain is performing these operations. This is, in a nutshell, the central problem, the hard problem, of consciousness.

In a very perceptive article, the neurophilosopher David Chalmers proposed two psychophysical principles. The first is that there is *coherence between the structure of consciousness, and the structure of awareness.* The form of our awareness, and therefore of our consciousness, is determined by the structure of our sensory machinery, and the associated processing mechanisms in the brain. We can be conscious of the three primary colours, red, blue and green because, in the retina of the eye, there are sensory cells which contain three closely-related but distinct forms of a light-sensing protein molecule. Each gives maximum output at a different wavelength of visible light. People with red-green colour blindness have a tiny genetically-determined change, a mutation, in these molecules which abolishes their ability to discriminate these colours. Colour blind people live in a slightly different perceptual world from "normals". Even normal humans however have no direct consciousness of ultraviolet radiation, unlike bees, or magnetic fields, unlike some birds, because we lack the organs to sense them.

The second principle is that *any two systems with the same detailed functional organisation will have qualitatively identical experiences.* Thus, if I could model the entire structure and function of my brain and its connections, inputs and outputs in a supercomputer, the simulated brain would have the same conscious experiences as the brain inside my skull. I am sure that my co-workers are grateful that this is not yet a practical proposition, although, of course, they could always turn me off……..

For neuroscientists, the message is clear. We need to study the structure and function of the nervous system, particularly the brain, at all levels, from molecules through cells to the whole system, not neglecting the development of new theories, with all the tools at our disposal.

The elementary unit of life on earth is the cell. The fundamental feature of all cells is that they are surrounded by a continuous barrier, the cell membrane. Like the skin of a balloon, this separates their contents from the surrounding environment. All of the chemical process which are needed to keep the cell functioning, go on, cosily, inside this barrier. In this respect each cell is a self-sufficient individual. All that the simplest cells need to stay alive is a source of nutrients, and a way of getting rid of waste products.

The brain is composed of basically two types of cells, nerve cells known as neurons, and support cells . That the brain is composed of neurons, connected together to form pathways, was a major discovery of the nineteenth century. There are about one thousand billion neurons in a human brain.

Neurons are cells which are specialised for communication. Unlike most other cells, which have simple compact shapes, neurons have many long branches, which are used for talking to other neurons, or to executive cells, such as muscle cells or gland cells. Neurons generally have a number of short branches, which receive input. These look rather like the branches of a tree. They project out from the cell body of the neuron, which contains all the internal machinery needed to keep it and its branches alive and active. The cell body is typically about one fiftieth of a millimetre in diameter. It usually gives rise to a long tap-root-like branch, which can be up to one metre long, which carries its information output.

The transmission of signals through neurons is by electrochemical impulses. Rather as in a transatlantic cable, an electrical pulse is sent from point A onwards to point B, where it is picked up by a relay station which amplifies it, and then sends it further to point C. Eventually the signal reaches the end of the neuron. Here, the neuron terminal forms fine branches, which make a network of close contacts, called synapses, with other neurons. Synapses are specialised to transmit signals from one neuron to another, crossing the impermeable membranes which otherwise insulate them from one another, and the short synaptic gap.

The transmission of signals across synaptic contacts is, essentially, pheromonal, rather as if people could only communicate by spraying and sniffing scents. The arrival of the electrochemical impulse releases a “puff” of a specific chemical transmitter from the synaptic terminal into the synapse. This chemical, the neurotransmitter, crosses the tiny gap between the upstream and the downstream neuron, and it binds, like a key sliding into a lock, to specific protein molecules on the downstream neuron, called receptors. The array of receptor molecules provides an information channel between the outside world and the inside of the neuron. Each receptor is like a key-operated molecular switch in the insulating membrane of the cell. In the absence of the neurotransmitter, the switch is off; in its presence it is turned on. If enough receptors are switched on, at enough synapses, so that all their effects add up, the downstream neuron is triggered. It starts a new electrochemical pulse, which is passed on, in its turn, to its own particular targets.

In the brain, the connections between neurons spread widely, a given neuron can contact and excite hundreds of synapses on other neurons. They also converge strongly, a given neuron receives hundreds or thousands of synapses from other neurons, both near, and distant. Thus the brain contains hundreds of thousands of billions of circuits of neurons. Also, the neurotransmitters and their specific receptors exist in dozens of different chemical forms. One particular combination can excite the target neuron. Another can damp it down. Receptors can signal fast, or slowly. The effectiveness, or strength of the synaptic connections between nerve cells is altered by activity. New synapses are formed, and old synapses disappear. This is essential for memory.

Thus, there is enormous scope for complexity in the brain. Biological microprocessors, made up of hundreds or thousands of inter-communicating neurons work on incoming sensory information, transforming it, adding to it and sending it on to other parts of the brain, for further processing, or out to the periphery to drive specific behaviours. Circuits involving fast neurotransmitters are ideal for the fast computations needed to interpret highly

detailed input, for instance, from the eyes. As we have seen, this starts when photons of light, focused onto the retina, collide with molecules of a protein called rhodopsin. Rhodopsin is actually a modified neurotransmitter receptor. Smell and taste also use arrays of similarly modified neurotransmitter receptors.

The processing of information through the sensory pathways is highly parallel, and hierarchical. It proceeds to higher and higher levels, until, in the visual system, one can even find neurons which respond to entire complex objects, such as a complete face. The extraordinarily detailed , and effortless nature of these computations can be appreciated by anyone who, looking at a tree, is aware of being able to see every leaf on it. These complex recognition processes require experience and training, which is why a rich environment is essential in child development.

Slow neurotransmitters alter the sensitivity of the fast circuits. They are particularly important in deciding between various outcomes, selecting responses, such as movements, or routing important parts of the incoming information to be remembered. In particular, slow transmitters are the controllers of mood, and arousal in the human brain.

Many of the properties of the molecular switches, the receptors, which underlie neurotransmission are beginning to be understood. Their structures are determined by the information encrypted in the precise sequences of the four-letter genetic code in the DNA making up our genes, and hundreds of them are now known. Some particularly important questions that can now be addressed are these: How much do receptors vary between different individuals? What will this mean for differences between the perceptual worlds of different human beings? What are the implications for mental disorders, and their treatment? Are some of these a sort of colour-blindness of signalling pathways in the brain? If defects can be identified, can new specific drugs, or genetic technology correct them?

There is nothing unique about the brain’s signalling molecules, in themselves. The signalling pathways have been very highly conserved in evolution. Even single-celled organisms need to “smell” their food. This is the evolutionary precursor of mammalian neurotransmission. For instance, there is an amoeba which can “smell” opiates in a culture dish; it moves towards them, and eats them. But evolution has found a new use for opiate receptors and opiates in regulating pain pathways in the mammalian brain.

Neurotransmitter receptors are extremely important sites of drug action. Three out of every four prescription drugs modify the actions of slow neurotransmitters. These include such well-known drugs as beta-blockers for blood pressure control, the opiates for pain and diarrhoea relief, the anti-psychotics for schizophrenia treatment, the selective serotonin re-uptake inhibitors, such as the anti-depressant Prozac, and the new class of cognition-enhancing "smart" drugs. Tranquillisers and anaesthetics boost the action of fast inhibitory synapses, and so damp down the activity of brain circuits, going so far as to cause unconsciousness. Drugs of this kind, such as barbiturates, have brought about a revolution in medical practice. Because of their central role in mood and perception, neurotransmitter receptors are also the targets for recreational drugs. These include nicotine, alcohol, and, notoriously, substances such as LSD, amphetamines, cannabis, cocaine and opiates.

Many drugs of abuse seem to act by stimulating, directly or indirectly, the release of a particular neurotransmitter called dopamine, which produces feelings of euphoria. We are slowly beginning to appreciate the nature of the circuitry involved in this, and particularly, the role of areas of the brain which are involved in emotion, arousal and aggression.

Even primitive mammals are well-developed in these areas. A rat with a one and a half gram brain shows emotions, such as the teeth-baring response, which are recognisable by a human with a one kilogram brain. Anyone who has ever kept a dog will know how brilliantly it can interpret human emotions and vice-versa. What these animals lack is the ability to use complex concepts. The rationalist philosopher Descartes "I think therefore I am" considered them to be automata, but it is interesting to know that Darwin, the father of modern biology, attributed emotional states even to insects. Contemporary neurobiologists might consider this to be going too far, but it is notable that the legislation which regulates animal experimentation now extends to a species of octopus, an invertebrate. Implicitly, we recognise that even our distant cousins in the animal kingdom are likely to be sentient, emotional, and to have some form of consciousness.

I may enjoy the company of my dog, but still 1 don't expect to be able to teach her algebra, or expect her to appreciate a Mozart piano sonata. Why not? The difference between her brain and mine is that mine has a much larger volume of a modern, in evolutionary terms, addition to the machinery of the brain, the neo (new) cortex. Evolution is a great tinkerer. It is always fiddling with things, trying out variations, like mutant photoreceptors, or adding new things on, often by duplicating existing structures, and then allowing them to specialise. Natural selection takes care of the experiments which fail! In some ways, the neocortex is like the ever-increasing World-Wide-Web of the mammalian brain, an experiment in global integration.

The expansion of the neocortex has wrapped a layer of new, highly parallel, cerebral computing devices around the older core of the mid and hindbrain. These, particularly in the frontal areas of the brain, underpin our much greater ability to use complex concepts, and develop completely new faculties, such as spoken and written language. Language is certainly very important in my consciousness! There is a perpetual internal monologue. Animals probably have a more visceral, non-verbal, awareness, perhaps rather like the feeling that you get when, distracted, you leave a cup of tea, and something tells you that you expected one last swallow.

Where, in the end, does my consciousness come from? It certainly needs interactions between neuronal circuits in my brain, because it can be dramatically altered or completely abolished, by drugs which act on specific neurotransmitter receptors located on neurons in my brain. But the exact nature of what the cognoscenti call "the neural substrate of consciousness" is still unknown.

Fascinating clues are coming from extraordinary new imaging methods such as functional magnetic resonance imaging, and positron emission tomography, which can map the activity of the brain in conscious, behaving, human subjects. Such studies show widespread activation in many parts of the brain during complex and novel tasks which require conscious attention. This tends to fine down, and become more localised, as the performance is learned, and becomes automatic, and hence unconscious. An example of the difference between these two situations would be driving a car down an unknown, as opposed to a familiar road.

A final puzzle is this. Most of the information processing that goes on in the brain is massively parallel, but unconscious. As we have seen, evolution has continued to add new parallel processing capacity to our brains. However, the stream of consciousness is both serial, as the notion of a stream suggests, and limited in capacity. We all know that it is difficult to be actively conscious of more than one thing at a time, and how easily we can be distracted when we are trying to concentrate. Conscious thought seems to rely on a kind of active short-term memory in which items are continually being refreshed by being brought into consciousness. This form of memory seems to be able to hold no more than between five and nine pieces of information, which is why most of us have difficulty in remembering a telephone number of more than about nine digits.

One idea is that this working memory is related to large-scale oscillations at forty cycles per second, which are detected by electrical recording from the conscious brain. These oscillations represent the co-ordinated firing of whole populations of neurons. They may 'bind together' the activities of widely-separated populations of parallel cortical processors, each of which could, in itself represent a complicated concept. Each item in the active short-term memory may be encoded by a separate oscillation. Could the entrainment of the output of the parallel hierarchical series of computations which goes on in the brain in fact be the elusive neural correlate of conscious experience?

In his classic book "The Integrative Actions of the Central Nervous System", the great neurophysiologist Charles Sherrington, the discoverer of the synapse, described the brain as "An enchanted loom, perpetually weaving patterns of meaning". We are beginning to get some snapshots of the movement of the shuttle, but the sense of enchantment grows ever stronger. Scientifically, the first half of the twentieth century was the era of atomic physics and molecular chemistry. The second half was the era of molecular biology. In the new millennium, we hope to enter, fully, the age of Neurobiology. Perhaps we will, at last, come face-to-face with the elusive ghost in the machine.

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