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The brain is wider than the sky

Rodney Douglas and Kevan Martin direct the Institute of Neuroinformatics, which is a joint Institute of the ETH Zurich and the University of Zurich. Their common interest is in discovering the physical basis of thought. One of their approaches to this goal is to define the circuits of the neocortex and to provide a predictive model that accounts for its formidable performance. Such models would also provide the knowledge-base necessary to construct artificial brain-like machines, which is a major goal of research and development work in the Institute of Neuroinformatics.

For those of you who see members of the Institute of Neuroinformatics (INI) studying the principles by which brains work, and then applying those principle to the construction of brain-like machines, our work seems quite typical of scientists and engineers. Although quite strange 'neuromachines' might emerge from the INI, our neuromachines are unlikely to attract particular attention even if they are 'brain-like.' This lack of attraction not because brains and neuromachines are uninteresting, but rather because it is a feature of our existence that we have not the faintest clue of the mechanisms and inner workings most of the instruments and machines that we use, whether or not they are natural or artificial. So, the exquisite neuromachines that the INI produces simply add to the huge heap of machines whose inner workings most people accept as incomprehensible. We use all these artificial machines with confidence because we sincerely believe that the machine does what it claims to do, and that there is someone on earth who really does know how the machine works and others who really do know how to build or repair them. Indeed, there may even be still in existence the human designers who drew the original blueprints. Our faith in the constancy of the inanimate compared to the animate, is indeed touching.

We spend even less time worrying about the inner workings of the instruments and machines we encounter in nature, although we too use them throughout our lives. These natural machines, which are found through all of biology, exploit the working of devices whose dimensions may be as small as a macromolecule or as large as an elephant. If we were to think of natural systems in the same way as we do artificial systems - cars, telephones, power stations and the like, then we would include in our thoughts a Designer who sits at the drawing board (or in modern studios, at CAD – Computer Aided Design – systems) and who imposes the same constraints on the natural machines as we humans do when we design an artificial machine. This is an awkward thought for a secular science and even the few who believe, as the poet Robert Browning did, that 'all things are artificial, for nature is the art of God', are unlikely to wait for divine intervention to explain the inner workings of cells, organs or organisms.

When we wander out into the garden in early spring and admire the bulbs thrusting their tumescent stalks through the soil, seeking the sun and warmth, we give little thought to the singular ability of biological systems to self-replicate and self-assemble and evolve without the intervention of the designer. This awkward fact of our own existence, that each of us only gasps earth's air as an autonomous agent after a lengthy process of dependent development during which, curiously, our parents were not asked to add one mark to our blueprint or add one instruction to the manual required for our construction. Quite unbeknown to our parents were the cell divisions that created all the neurons we will ever possess between 7 and 17 weeks of our gestation. Unbeknown to our parents were the nomadic travels taken by these neurons through the developing brain before they reach their final stations and began to differentiate into their recognizable adult forms. And who was the chaperon who introduced each neuron to each of their many life-partners, who told them how firm their handshake with each partner was to be? This process, silent, invisible, yet immaculate in conception, seems to have been carried out by the micromachinery embedded in the organism itself, for we see no visible scaffolding, no architect, no master builder. But can we really believe that the child knows how to build itself in a way that it resembles all other children ever born, yet has never ever seen?

A design without designer, seems to violate basic principles of making anything. Yet this paradox of evolution has produced not simply the breathtaking magic that is the single cell, but has produced something as astonishingly wonderful as the the network of the brain, imagined by the English neurophysiologist Charles Sherrington as, 'an enchanted loom, where millions of flashing spindles weave a dissolving pattern'. What is it about these biological processes that allow such unbelievable competence at do-it-yourself (DIY) construction? The answer probably lies in the interaction of two processes: one that grows complexity and the other that uses Darwinian selection to prune away branches that have grown in ways that are ill-adapted to the prevailing environment.

It is here that we begin to discern more clearly the difference between the constructivist method and DIY. Those wonderful pieces of equipment that we use daily – the refrigerator, tram, and telephone, are inherently fragile and depend on a vast infrastructure to permit them to operate. As objects they are difficult to construct to the tolerances necessary to make them functional, and they are easily broken. The earliest artificial machines were very individual in their design and construction, probably being built entirely by one individual. But as our production methods have become more sophisticated and automated, our machines have become more modular and hierarchical in design and construction. These methods produce Swiss watches, Smart cars and even Space Shuttles (of course not all 'Made in Switzerland'), but it is all to clear that in all these cases, that the principles involved are not those that are easily applied to natural engineering. Human intelligence in each case, has to provide the key ingredient that makes these artificial machines work and be useful.

Biological processes differ from those of artificially engineered systems in many ways, perhaps most obviously in being adaptive. They do not fail catastrophically, instead they show a graceful degradation as individual components are damaged or destroyed. They can compensate for losses by increasing production of components elsewhere and when that is not possible, other strategies of problem-solving are tried.

The nervous systems of animals are a case in point. They seem to contain belts and braces and a few other redundancies to yet to be discovered, which allow the nervous system to avoid embarrassment when challenged with new situations. Does this imply that biology has discovered a more flexible organization for construction than the sequential, modular, hierarchical design and construction methods we have developed for artificial systems? When it comes to it, how do we specify in engineering terms what it means to be 'adaptive'? If one engine fails on an aircraft, who adapts to the changed circumstances, the aircraft or the pilot? We have designed our machines to be extensions of ourselves and while we try to make some of them 'fail-safe', we have generally neglected to make them intelligent or adaptive, because those are the ingredients we supply, usually unconsciously. It is why we refer to human actions that seem involuntary or repetitive, as 'machine-like', i.e. without intelligence or adaptability. It is the human operators who find the work-arounds when machines go wrong, not the machine. It is the reason why humans, not robots, drive cars, fly aircraft and build space stations.

Humans stand out from all other animals for two particular qualities. One is their use of language and the other is their use of tools. That other animals, including other primates, can communicate, is well accepted. But it is clear also that this communication cannot really be called language. Even performances of communication by other species look rudimentary in comparison to the richness of human language, where an infinite number of unique utterances are possible and where the torrent of new words never ceases. Language shares with biological systems the properties of being adaptable and self constructing, which is not necessarily true of animal communication. Bees, while famous for their energetic dances, use their dances to communicate only limited information: where, what, and how much? Their communication is simply that, communication, not a language. Similarly, while it is clear that animals other than humans do make and use tools, their tools are rudimentary, usually consisting of just one element. For example, amongst birds, the crow family excel in tool use, but the tools they construct are simple, consisting typically of one part (e.g. a bent wire), and are usually a means to acquiring or preparing food, as indeed were the early hominim stone tools.

We generally define machines as consisting of a number of interacting parts. Our ancestor, Homo habilis ('Handy man') first started making tools in the Olduvai Gorge 2.6 million years ago, but it is only relatively recently – perhaps in the last 100 000 years that hominims have constructed multipart machines. Clearly, even species with high intelligence have difficulty in constructing machines. Biology by contrast, constructs machines with ease and at multiple scales, from the nanoscale machines like ion gates and pumps embedded in membranes to huge organisms like the Blue Whale. What indeed, as Sydney Brenner has asked, is the 'grammar' of biological systems that allows such sophisticated designs to be achieved through self-construction? The Spanish neuroanatomist Ramon y Cajal wondered much the same when he saw down his microscope the myriad connections formed by millions of nerve cells: 'What mysterious forces precede the appearances of these [neural] processes? Promote their growth and ramification? And finally establish those protoplasmic kisses which seem to constitute the final ecstasy of an epic love story?'

As if this self-assembly were not remarkable enough, the result of these processes produce the state we call consciousness. Can we ever hope to understand how it is that the assemblage of atoms we call humans come to have this astonishing quality? This question of the relation of spirit, or mind, to the physical matter of the universe has occupied philosophers for centuries and any serious answer we could contrive in a few lines would be hopelessly inadequate: it is one of the most demanding questions facing neuroscientists in the 21st Century. One particularly controversial point is whethe assemblages of molecules can ever be responsible for 'mind'?

Interestingly, this question of the origin of consciousness bears a close resemblance to another question, 'what is life ?' which was asked by the physicist Erwin Schrödinger in 1944. Part of Schrödinger's question was answered in 1953 by Francis Crick and Jim Watson, whose theory of the structure of DNA revealed that the secret of life was that there were 'just' molecules. i.e. There was no 'vital force', no mysterious non-physical spirit, but simply the interactions of complex molecules governed by the laws of physics. The half of century of molecular biology that has followed their discovery (perhaps one of the most significant for humankind) has not changed this view. Instead it has revealed more and more of the extraordinary abilities of the molecules that make up the living world.

Molecules are formed by atoms that bond together because they are attracted to each other by forces far stronger than the pull of gravity. The history of 20th century physics has largely been concerned with the discovery of the forces that bind together our universe, such as nuclear forces, weak Van de Waal's forces and gravitational forces. Mysterious until our own lifetime, physicists' theories and experiments have now provided us with an extraordinarily rich picture of the particles and forces that make up the fabric of our universe. Molecules are not exempt from laws of physics, even when they are as large and complex as biological molecules such as DNA, which codes our genetic information and generates the sequences necessary to build all our proteins. Proteins are particularly beautiful molecules. They are built from linear strings of amino acids, which then fold into the intricate three-dimensional shapes that are essential for their correct function.

Neural diseases such as Jacob-Creutzfeldt disease are thought to be primarily due to incorrect folding of the prion proteins, which results in defective functioning. Proteins often work as molecular-scale machines, working in breathtakingly rapid movements in an enormous variety of tasks, such as enzymes, channels, switches and molecular motors. The shapes of molecules and their movements are dictated by the bonds between their atoms and their interactions with the other molecules and ions that surround them. They are controlled by the forces of nature, not the forces of the supernatural. Although they are individually relatively large, biological molecules do not act alone, but in networks that show highly coordinated and organized behaviours. The products of long evolution, biological molecules are the acme of nanotechnology, yet they do seem, well, so *purposeful*. The important discovery of molecular biologists, like Crick and Watson, was that this coordinated behaviour is not due to someone or something telling the molecules where to be and what to do, but instead each individual atom, each individual molecule, acts under the constraints determined by the laws of physics. They exist like members of an ant colony, where each individual does only what they are able without orders from some dictator, yet the sum of their activities is more like a single purposeful, intelligent organism.

Nonetheless, when we look at the almost unbelievable micromachinery of even a single cell, like a bacterium, we have to wonder how it can 'know' how to do what it does. It is easy to imagine that there must be some unknown external intelligent force, operating outside the laws of physics, that controls all the intricate machinery within the cell. But the truth is, there is no external intelligence. All the bacterium has inside it are molecules, dynamically going about their work as predicted by the laws of physics. It is fortunate it is so, because unlike engineers, the processes of evolution have provided cells and organisms with incredibly robust mechanisms. These biological structures often can continue to function in the face of extensive damage. They show the property of graceful degradation, where the remaining functionality is in proportion to the extent of the damge, rather than the catastrophic failure that your personal computer suffers when one bit goes astray. Biological systems frequently have belts, braces, air bags, parachutes, and may other fail-safe devices to ensure that life still goes on even if one part of the system is incapacitated. This flexibility of use and plasticity of the system is what allows us endlessly to survive accidents, to adapt to new circumstances, and indeed, to learn throughout our lives.

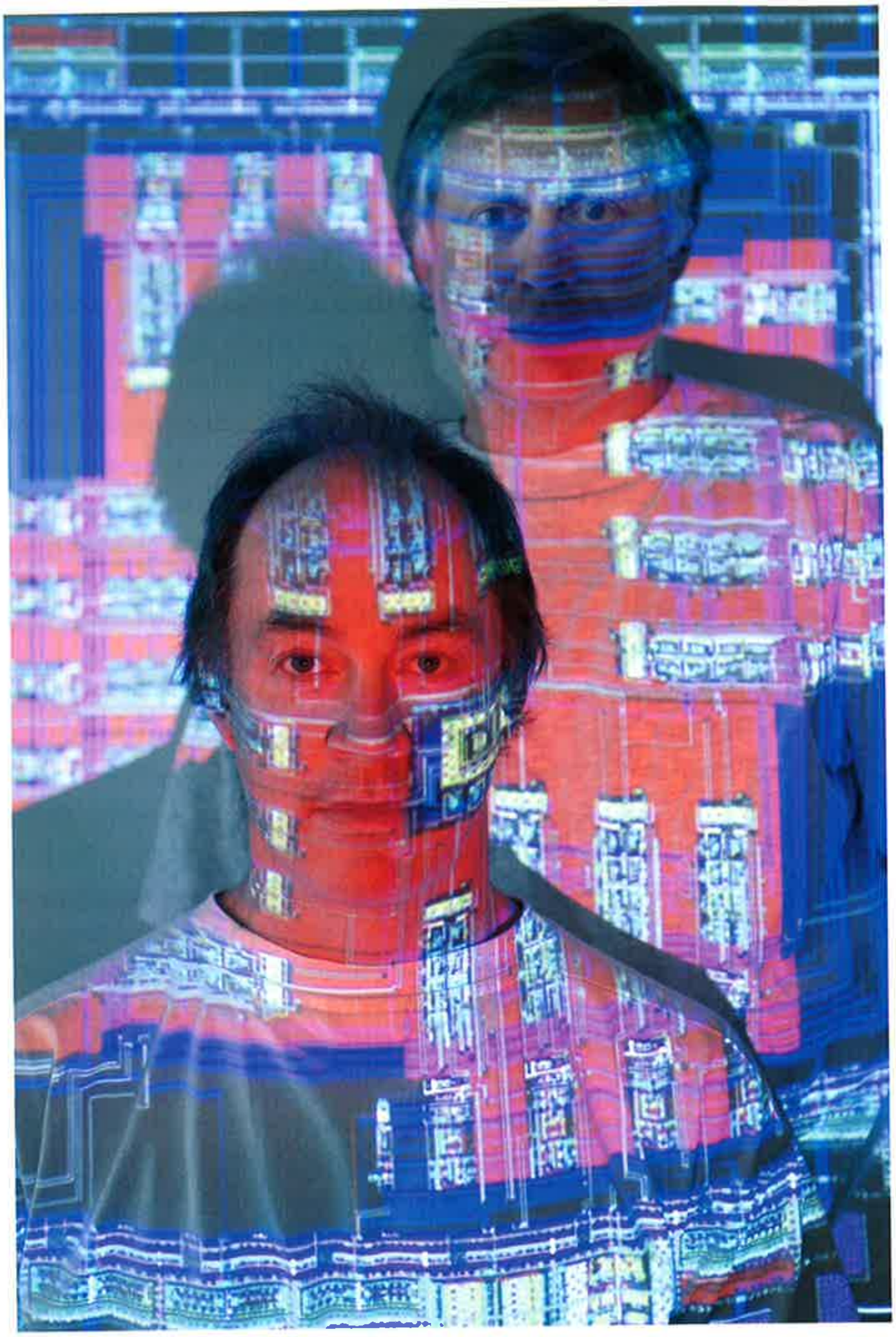
Francis Crick, co-discoverer of the structure of DNA and the genetic code, who sadly died last year, was one of the greatest scientists of the twentieth century. He was the key figure in driving the application of physics to biology, which led to a whole new field now called molecular biology. Francis Crick once wrote, if you cannot making headway understanding the function of a complex system, then study its structure and knowledge of its function will follow automatically. When he burst into the Eagle Pub in Cambridge England on 28th February 1953 and announced to the bemused customers that he and Jim Watson had discovered the secret of life, he was perhaps the first to really see how the DNA molecule could copy itself and also provide the code for making the proteins that determine what sort of organism – bacterium, flower, or human – is to be built.

After his revolutionary discoveries in molecular biology, Crick turned his attention to the brain, and this led him to propose his 'astonishing hypothesis', which he explained in a book of the same name. His astonishing hypothesis is that our minds can be explained by the interactions of nerve cells and the other cells and molecules associated with them. Thus, the unique, conscious, 'I' that each of us is, arises from complex physical structures, like brains and muscles, skin and bone, that are made up of billions of molecules. Crick called his hypothesis 'astonishing' because people are still so reluctant to accept that a complex system like a brain can be explained by the properties of the parts and their interactions. Yet the revolution in molecular biology that Crick helped bring about, happened precisely because the replication and inheritance of genes could be understood and explained by the very structures and functions of biological molecules themselves. Crick's point is that our bodies are not simply machines that are controlled, puppet-like, by some separate, non-physical, 'mind', but that our minds arise from the very physical substance of our bodies and brains, which, in turn, arise from the atoms and molecules that are the basis of everything in the universe.

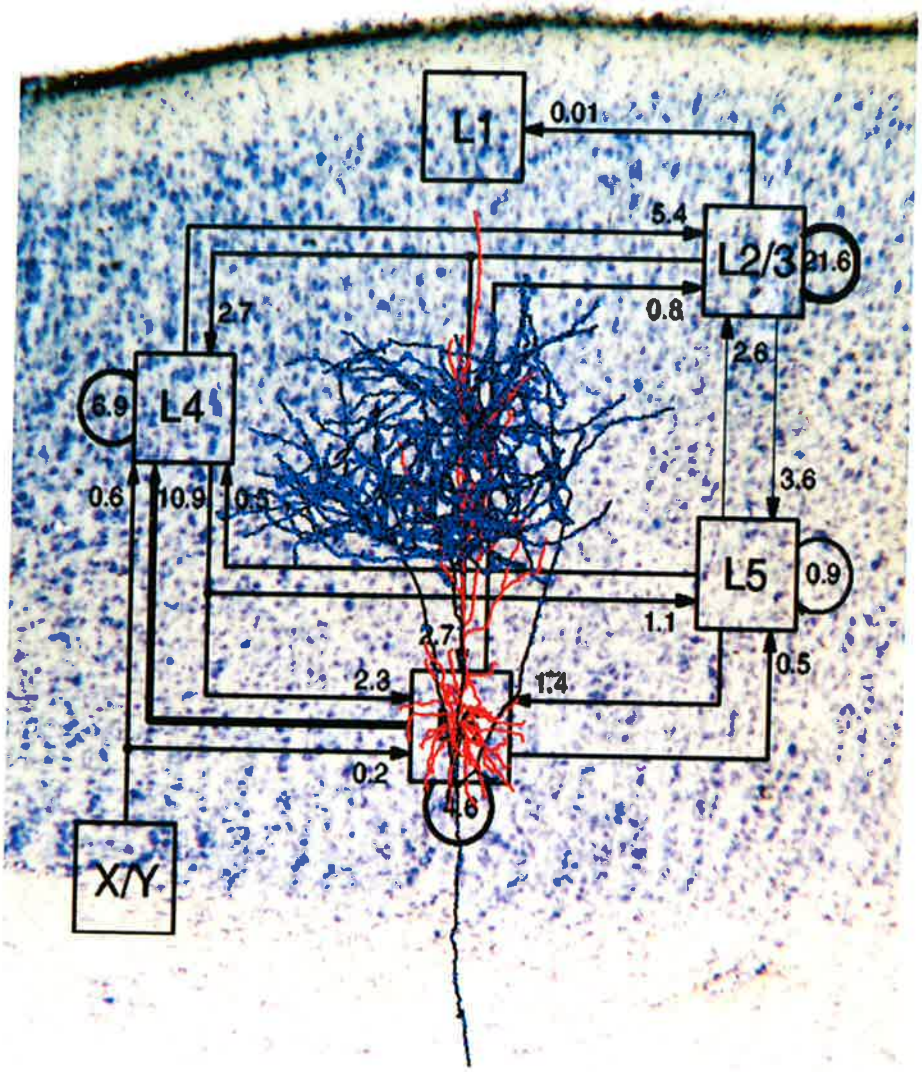
This seems a long and roundabout way of considering the question, 'what is consciousness? Surprisingly, what is emerging, however, is that the modern scientific quest for the origins of consciousness has begun to connect many practitioners of meditation and religion who seek a 'psychophysical unity', which is a shorthand way of saying that mind and body are one. How the one merges or emerges from the other is the challenge that faces scientists, philosophers and artists. Emily Dickinson found in her imagination one possible solution:

> The Brain is just the weight of God -
> For - Heft them - Pound for Pound -
> And they will differ - if they do -
> As Syllable from Sound -

For brain scientists, a rather more earthbound, but no less imaginative group of people, Crick's astonishing hypothesis seems to be the best hypothesis in town and testing it is keeping them very busy.



The Institute of Neuroinformatics (INI) is a joint institute of ETH and Uni Zurich. It was established in 1995, under the directorship of Profs. Rodney Douglas (above) and Kevan Martin, the authors of this article. The mission of INI is to identify the principles by which brains perform computation and to apply that knowledge for neurological health, as well as the development of new computational technologies.



A particular focus of our work in INI is the architecture of the neocortex. Here detailed computer-assisted 3D reconstructions of the various types of neurons and their connections in the neocortex are made. Analysis of these data enable us to derive the basic circuits that support computation, and so to model how the cortex works.

The neurons of cortex behave as individuals, ever changing their interactions with one another, forming transient patterns of activity that represent the world.

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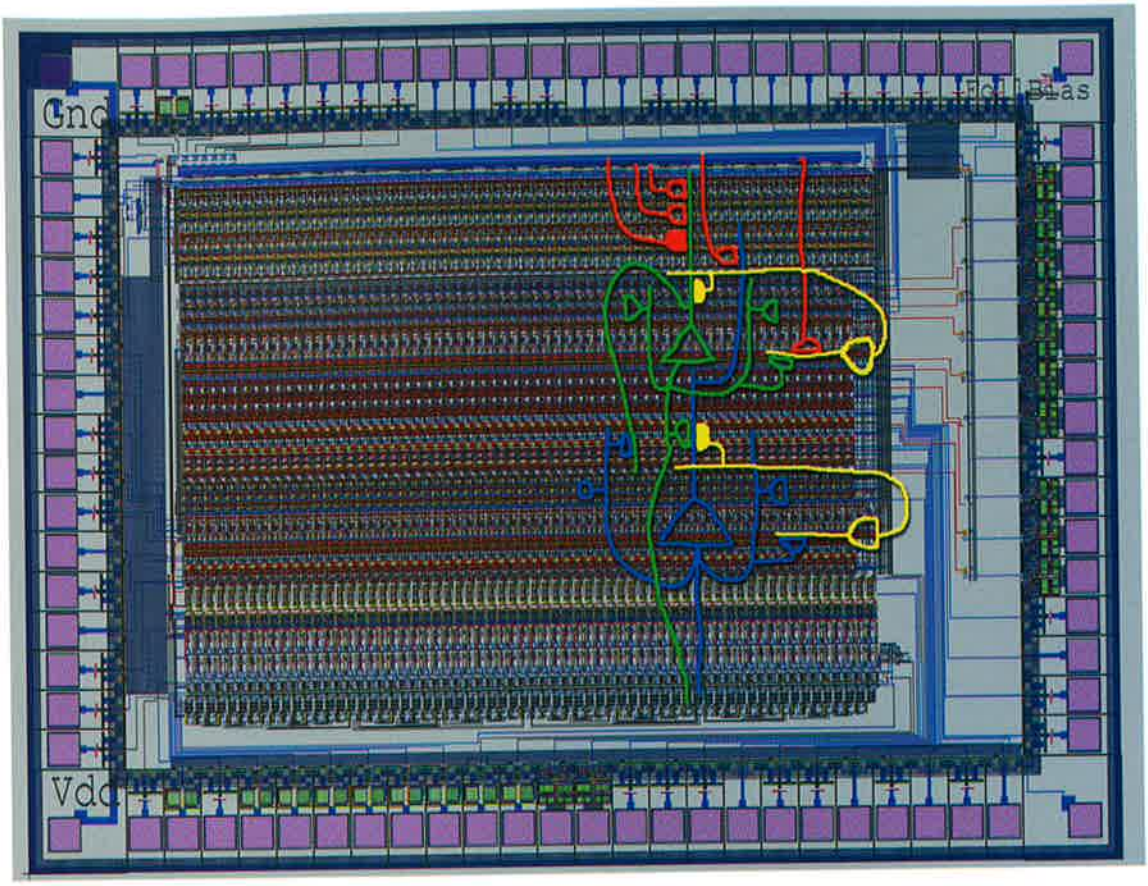
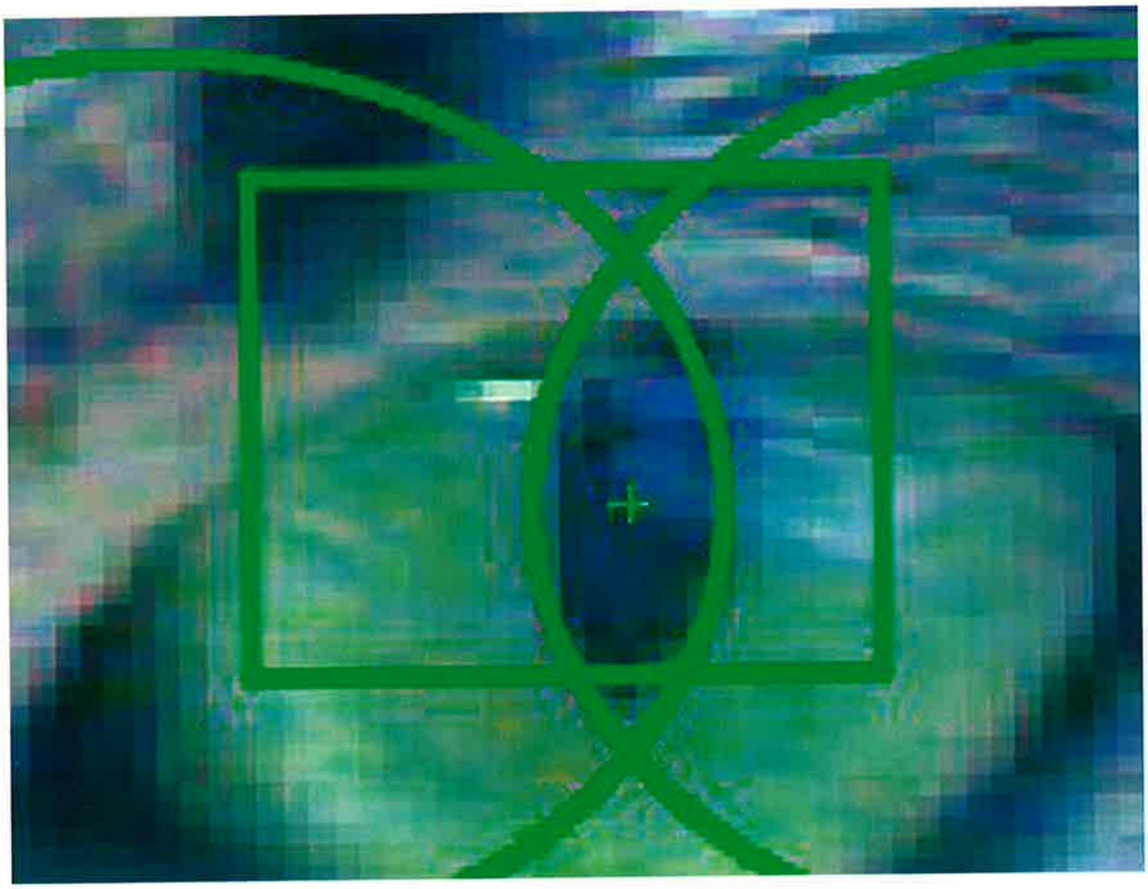
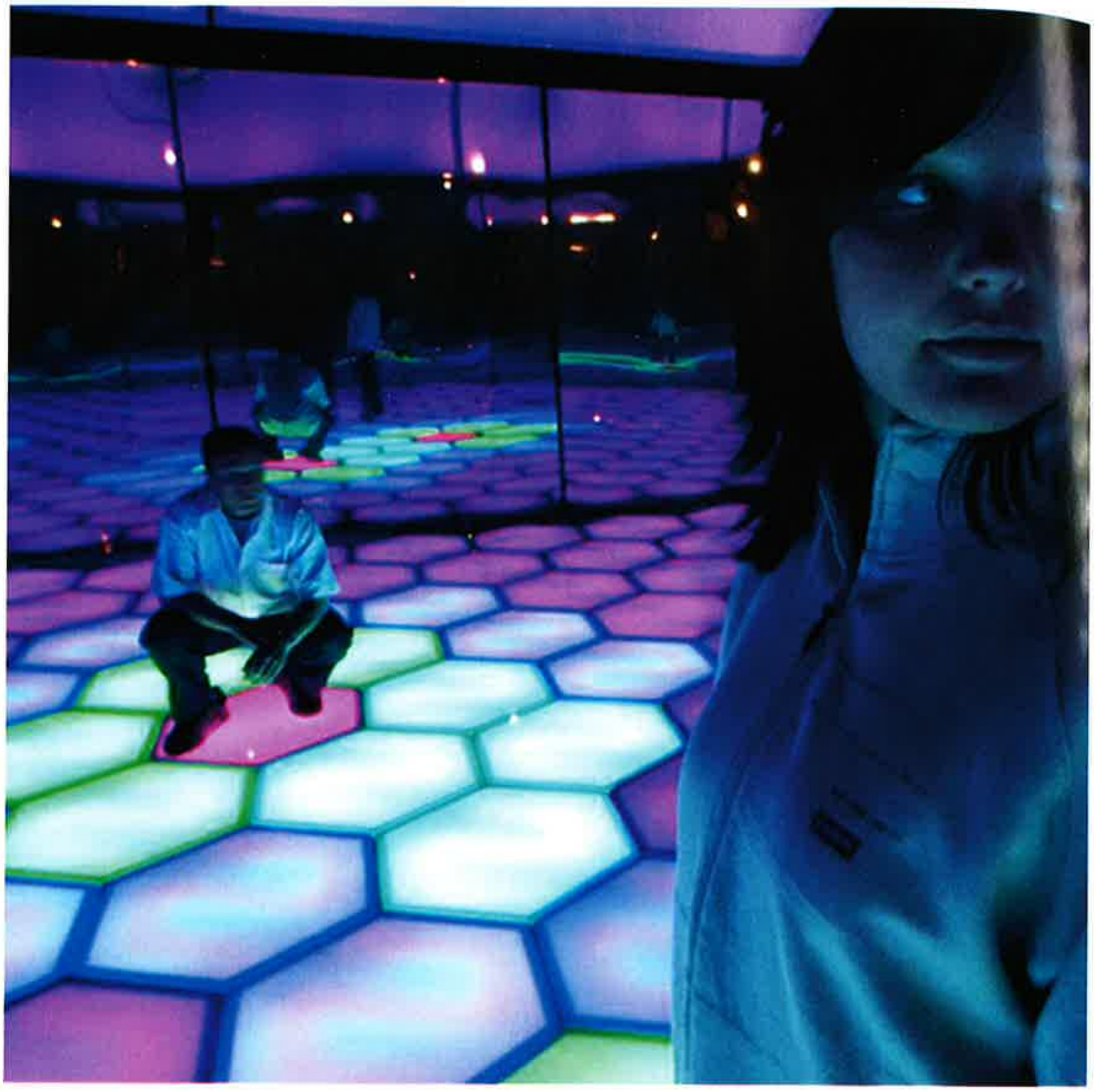


Schematic of the layout of an electronic circuit designed at INI. This circuit emulates in realtime the computational operations and communications performed by neuronal circuits in the neocortex. This chip is fabricated using hybrid analog-digital CMOS VLSI technology. A cartoon diagram of the neocortical circuit being emulated is superimposed on the silcon circuit.

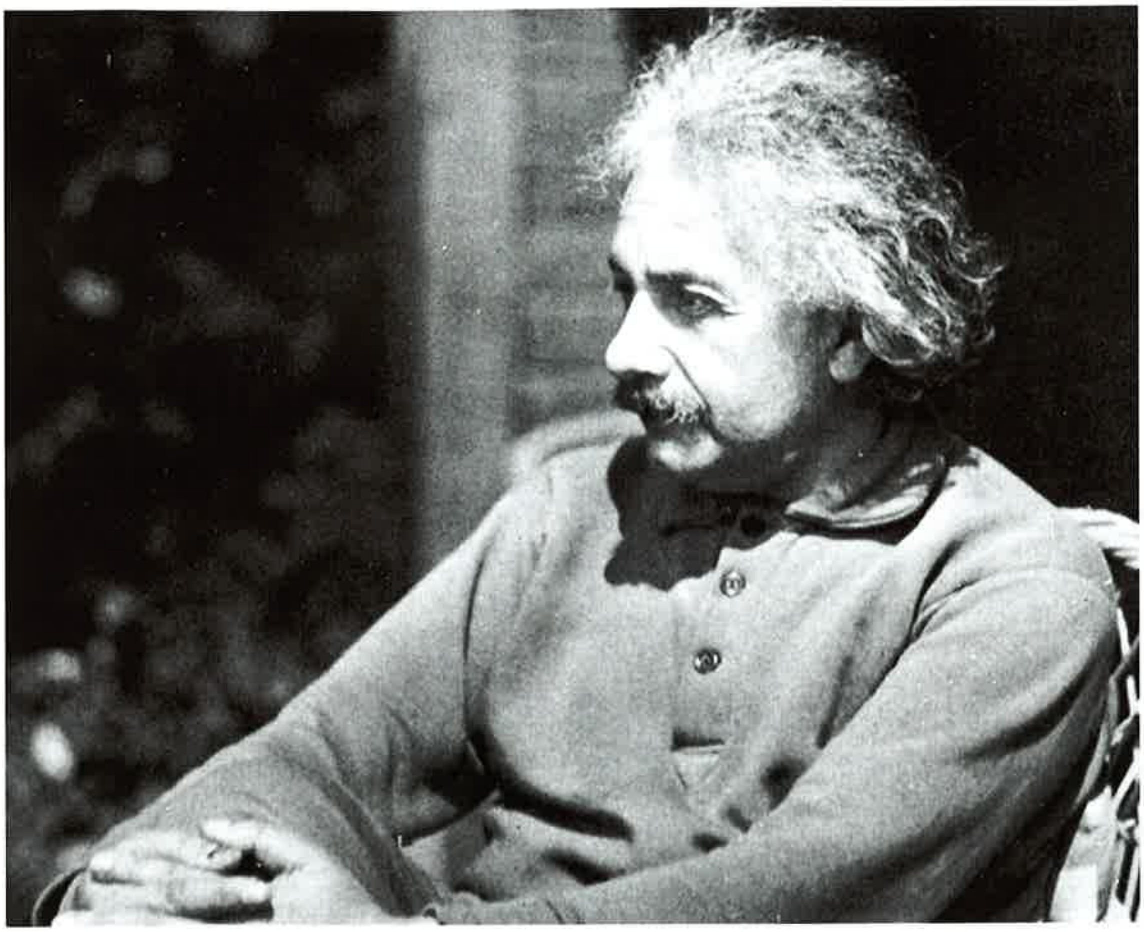
A platoon of Braitenberg Vehicles constructed by doctoral students at INI stand ready to teach school children the basics of neurorobotics.



A computerised camera tracks the location of a cat's pupil, and so records how the cat actively interrogates its visual world.



Students at INI preparing 'Ada: Intelligent Space' for the Swiss Expo.02. Ada was an artificial 'being' who had a reactive 'skin', and visual and auditory perception systems that enabled her to interact playfully with humans. Over half a million people met Ada and played with her during Expo.



The magic and wonder of human thought and consciousness is captured in Einstein's view of himself, written only 5 years before his 'annus mirabilis': "If I were to have the good fortune to pass my examinations, I would go to Zurich. I would stay there for four years in order to study mathematics and physics. I imagine myself becoming a teacher in those branches of the natural sciences, choosing the theoretical part of them. Here are the reasons which lead me to this plan: my disposition for abstract and mathematical thought, and my lack of imagination and practical ability".