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Constructing the Enchanted Loom

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Zusammenfassung

Der grosse englische Neurophysiologe Sir Charles Sherrington nannte das Gehirn einen «verzauberten Webstuhl», der Gedankenmuster webt. Er versuchte die Frage zu beantworten, wie das Gehirn funktioniert, aber auf diese Frage gibt es bis heute keine Antwort. Wir versuchen gegenwärtig, die damit eng verbundene Frage zu beantworten, wie das Gehirn sich selbst konstruiert, um funktionieren zu können. Schon vor der Geburt muss das Nervensystem aller Tiere zu einem hohen Grad funktionsfähig sein, um die Verhaltensweisen zu organisieren, mit denen das Tier überleben und aufwachsen kann. Wir wissen noch nicht, wie dies genau geschieht. Aber es ist bereits klar, dass der Prozess, mit dem ein biologischer Organismus sich selbst konstruiert, sehr verschieden von dem ist, den wir und andere Tiere benutzen, um gebräuchliche Artefakte, wie Werkzeuge, Maschinen und Wohnungen, zu konstruieren. Dieser Artikel beschreibt, worin sich diese Konstruktionsmethoden unterscheiden.

Summary

Sir Charles Sherrington, the great English neurophysiologist, described the brain as the «enchanted loom» that wove patterns of thought. His quest was to answer the question, «How does the brain work?» but to this deep question there is as yet no answer. The closely related question that we are currently trying to answer is, «How does the brain construct itself so that it can work?» Even before birth the nervous system of all animals has to function to such a high degree that it can organise the behaviours that will allow the animal to survive and develop into an adult. How exactly this happens we don't yet know. But already it is clear that the process by which the biological organism constructs itself is a very different one to the process we and other animals use in constructing the artefacts we use, like tools, machines, and our habitation. This essay describes how these construction methods differ.

Introduction

If a stranger came up to you and said he knew the whereabouts on earth of a machine that could construct itself, calibrate itself, and whose power needs were no more than 30 watts, you would wonder what they were talking about. If they went on to tell you that this extraordinary machine could teach itself – and others like it – to perform complex tasks that no other machine on earth could, you would probably think they were pulling your leg. But if they went on to tell you with great conviction that the machine they were talking about had created every other technology on earth, then you would be certain that you were talking to a lunatic. Yet such a machine does exist. Our relationship to this machine is very intimate – in a real sense we are it, it is us.

Natural and Artificial Machines

It is a feature of our modern existence that most of us never actually construct a machine. Thus, although we all use machines, we are largely ignorant of their inner workings. Yet we use the technologies – machines – with confidence because we sincerely believe that the machine does what its manufacturers claim it does, that there is someone on earth who really does know how the machine works, and perhaps yet others who really do know how to build and to repair them. Indeed, we are absolutely sure that these technologies were built according to the original blueprints designed and drawn by another human. 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 technologies or machines we encounter in nature, although we use many of 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

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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 17th-century English writer Thomas Browne (1645) 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.

Springtime is traditionally the time of new life, but even when we see it arriving, we give little thought to the singular ability of biological systems to self-replicate and self-assemble and survive and evolve without the intervention of a designer. We ignore this awkward fact of our own existence: that each of us only breathes earth's air as an autonomous agent after a lengthy process of dependent development during which – unbelievably – our parents were not asked to add one mark to our blueprint or add one letter to the manual required for our construction. Our nervous system is one essential part of that development program; yet quite unbeknown to our parents were the divisions of the neurons between 7 and 17 weeks of our gestation that created all the neurons – 15'000 million – we will ever possess. Similarly, our parents knew nothing of the nomadic travels taken by these neurons through our developing brain and nothing of their intended destinations, where our neurons began to differentiate into their recognizable adult forms. And who was the chaperone that introduced each neuron to their multiple life-partners, who told them how firmly they were to clasp those partners? This process, silent, invisible, yet immaculate in conception, is seemingly magically carried out by the micro machinery embedded in the organism itself. When we look, we see no visible scaffolding, no architect, and no master builder. How can we really believe that each child knows how to build itself in a way that it resembles all other children ever born, yet has never ever seen?

Design without a Designer?

A design without a designer violates the basic principles of making any artefact. This is the teleological argument for the existence of God made by William Paley (1802), amongst others. For Paley, Nature was a mechanism far more complicated than that of a watch, so why, he thought, should we suppose that nature is any different to the watch and does not also require a Designer? Charles Darwin countered Paley's argument in the following way: «The old argument of design in nature, as given by Paley, which formerly seemed to me so conclusive, fails, now that the law of natural selection has been discovered. We can no longer argue that, for instance, the beautiful hinge of a bivalve shell must have been made by an intelligent being, like the hinge of a door by man. There seems to be no more design in the variability of organic beings and in the action of natural selection, than in the course, which the wind blows. Everything in nature is the result of fixed laws.» (Darwin, 1958). Yet this paradox enacted through evolution has produced not simply the spellbinding complexity of a single cell, but also something as astonishing as the neural networks of the brain.

The English neurophysiologist Charles Sherrington (1940) imagined the brain as, «an enchanted loom, where millions of flashing spindles weave a dissolving pattern» (see Figure 1). What is it about these biological processes that allow such stupendous skills at do-it-yourself (DIY) construction to be performed? 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 not well-adapted to the prevailing environment.

Tools and Machines

We generally define a machine 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 multipart 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 (1938) wondered much the same when he saw down his light 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?» (See Figure 1). We ourselves continue to ask these questions, using a combination of experiment and computer simulation (e.g. Zubler and Douglas, 2009).

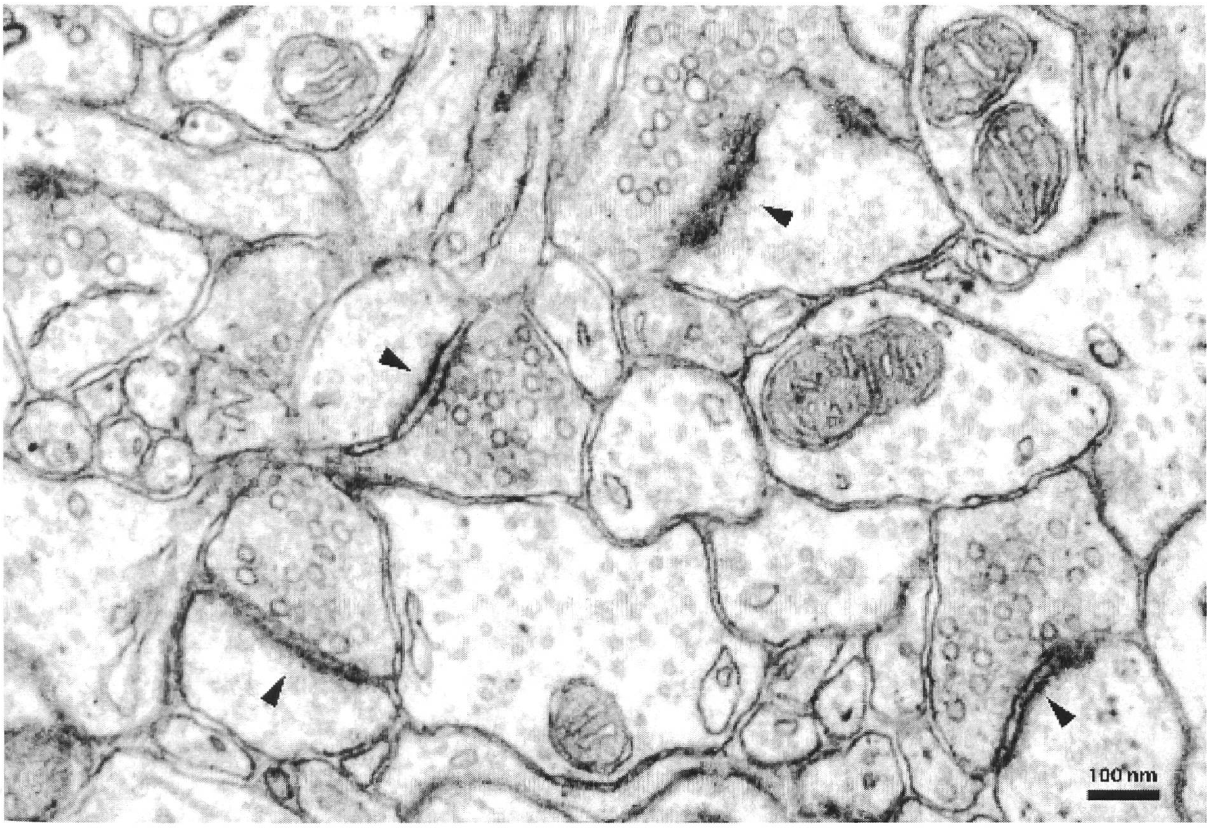

Figure 1. A tiny piece of Sherrington's «enchanted loom» – seen at very high magnification. This is an ultrathin section of the neocortex of a mouse viewed under the electron microscope. Most of the structures in view are cross-sections of the «threads» of Sherrington's loom, which conduct the nerve impulses. There are 4 km of «thread» in every cubic mm. of the neocortex. The structures indicated by the arrowheads are the points of transmission of the nerve impulses from one neuron to another, which Sherrington named «synapses» after the Greek word meaning «to clasp». Ramon y Cajal imagined that during brain self-construction these threads extend and ramify, and finally, as if in «the final ecstasy of an epic love story», establish these «protoplasmic kisses» (synapses). At the peak of our own brain construction we have to make 2 million synapses per second and all these synapses have to be in the correct place and at the correct strength if the brain is to function properly. Discovering how we do this by self-construction is our great challenge. (Electron micrograph made in the Institute of Neuroinformatics by Rita Bopp and Nuno da Costa).

It is here that we begin to discern more clearly another essential difference between the constructivist method, in which the designer intends to make a particular tool or machine for a particular function, and the DIY of biology. Those wonderful pieces of equipment that we use daily – the refrigerator, bicycle, and cell phone, are inherently fragile. 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, often being built entirely by one individual, much as animals build their tools today – the chimpanzee uses a stick to fish termites out of a nest, elephants use a branch to scratch themselves, and the sea otter uses a rock to crack open a shellfish. Most of the artefacts we would consider to be tools used by animals are rudimentary, usually consisting of just one element. For example, amongst birds, the New Caledonian Crows excel in tool use, but the tools they construct are simple, consisting typically of one part (e.g. a stick or a bent wire if they are urban), and are usually a means to acquiring or preparing food, as indeed were the early hominim stone tools. These are not what we would call «machines». (Unless, at a stretch, you consider the nests that various animals build are, «machines for living in» - the polemic description of the Swiss architect «Le Corbusier» for the houses he designed). By contrast, as human production methods have become more sophisticated and automated, our machines have become more modular and hierarchical in design and construction and usually involve many builders. 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.

Adaptive Systems

Biological processes differ from those of artificially engineered systems in many ways, perhaps most obviously in being adaptive. They do not fail catastrophically, they show a graceful degradation as individual components are damaged or destroyed. They can compensate for losses by increasing production of components elsewhere. When that is not possible, the animal tries other strategies of problem solving. The nervous systems of animals 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 so while we try to make some of them «fail-safe», we have generally not been able to make them intelligent or adaptive, and those are the ingredients we supply. 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, not the machines themselves, who find the work-around when machines go wrong, it is the reason why humans, not robots, drive cars, fly aircraft and build space stations.

Self-assembling nanomachines

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 der Waals 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 contains the sequence of bases necessary to build all our proteins. Proteins are particularly large and 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 of this nanomachine.

Proteins are employed 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. That is why DNA forms a double helix and proteins coil and form sheets in the way they do. 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 micro-machinery 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, the harder we look, the less we find the need for an 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 damage, 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.

Genes and Brains

Francis Crick, co-discoverer with Rosalind Franklin, Maurice Wilkins, and James Watson of the structure of DNA and the genetic code was a key figure in driving the application of physics to biology, which led to a whole new field now called molecular biology. Crick once said, «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 see really 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 – will be constructed. The insight was that the gene provided information, and this information was not in the form of a blueprint of how to construct a virus, bacterium, or a human, but in the form of a linear combination of chemical bases - guanine and cytosine, adenine and thymine. These 4 bases form the triplet code that defined the linear sequence of amino acid molecules that could be used to make a protein. The proteins assemble themselves into the constituent parts of a cell, which in turn assemble themselves with other cells to form the organism that – seemingly miraculously – interacts intelligently with the world. The amount of information in the gene is insufficient to create a detailed blueprint, let alone the construction and operating and trouble-shooting manual and this is why biology, uniquely, has evolved the means for self-construction.

Self-construction is the method by which organisms (and brains) construct themselves. It depends on a collection rules that are encoded in the genome of the first cell that will give rise to the target organism. Then, by successive replication and specialization of this first cell, various families of construction elements are formed. The replicated cells are frequently motile and move to particular locations with respect to their neighbours. When they arrive at their final destination they differentiate into their adult form and carry out the function for which they are specialized. In concert with other differentiated cells they contribute to ability of the whole animal to perform some competent behaviour that allows them to survive in the world.

In conventional construction we need an external explicit blueprint that can be read by an external constructor who then performs an external and predominantly forward fabrication process. By contrast, biology installs exactly the same inactive and implicit instruction code (its genome) in each cell of the target organism (animal or vegetable). Then, under cell replication and message-passing between cells, which activates some ever-shifting subset of their available instruction code, these cells multiply, differentiate, and self-organize. Through this developmental process the whole organism is finally constructed. Note that the actual blueprint of the organism is nowhere to be found (see Zubler and Douglas, 2009). Each cell knows nothing of the form or function of the final organ or organism. The information as to what the final outcome should be is only implicit in the instruction code of each cell. This is a completely different way of construction to any that humans or animals have devised and there is no machine we have built that can yet emulate biological self-construction, although already before the discovery of the coding properties of DNA, John von Neumann (1966) developed a seminal theory of self-replicating automata, which allows self-replication and guarantees the possibility of the open-ended growth of complexity we observe in biological organisms. While his theory shows that a self-replicating machine is logically possible, however, his theory does not show how it is possible in practice. Biology provides the only existence proof that such machines are indeed possible.

Consciousness

The effectiveness and efficiency of these principles of biological self-construction are especially impressive in the development of nervous systems, where in our case the organization of the final structure – our brain – must promote the complex abstract information processing that will enable us to learn and adapt useful behaviours. It is easy to see how relevant it would be if we could discover how to apply this biological style of construction to building a new generation of computers, but would such a self-constructed brain-like machine also exhibit consciousness?

After his revolutionary discoveries in molecular biology, Francis Crick turned his attention to the brain and proposed his «astonishing hypothesis», which he explained in a book of the same name (Crick, 1994). 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.

Can this remarkable self-construction really produce the state we call consciousness? Can we ever hope to understand how the assemblage of ever-changing 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 answer we could contrive in these few lines would be hopelessly inadequate: it is one of the most demanding questions facing neuroscientists in the 21st Century. At the moment it is an open question of whether assemblages of molecules are solely responsible for «mind» for we lack a scientific theory of what physical requirements are essential for the construction of a machine that is conscious.

However, it is perhaps worth noting that 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 (Schrödinger, 1992). Part of Schrödinger's question was answered in 1953 by Francis Crick and James Watson, whose model 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.

This seems a long and roundabout way of posing the question, «Can a conscious machine be constructed by humans?» To begin to answer this question, however, we have to develop a new theoretical foundation, for at present we have no idea what physical property of brains it is that allows them to be conscious, let alone how we might build it. Surprisingly however, what is emerging 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 to understand how the one merges or emerges from the other is the challenge that faces scientists, philosophers, and artists. Emily Dickinson (1976) is one artist who found in her imagination this metaphor:

> *«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, finding out how the brain constructs itself is proving to be one of the great voyages of discovery of 21st-century biology.

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