MICROSCOPE Vol 52:3/4, 135-144 (2004)

Are Cells Ingenious?

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KEYWORDS

Molecular, biology, microscopy, cells

INTRODUCTION

These ideas have emerged from the 'Evening with Brian' talks in Chicago in 1998 and 2003, and more recently in the opening lecture for the new program of Cambridge Society for the Application of Research at Churchill College, Cambridge University, UK, on October 11, 2004. The topic will be extended in a talk scheduled for June 9, 2005, at the Linnean Society, Burlington House, London, UK, and July 6, 2005, at the University of Surrey, Guildford, UK.

ABSTRACT

Modern models of life are based on molecular biology. This is a micromechanical view of nature, and – to scientists – it is almost the ultimate in reductionism. Microscopists, however, look differently at life. We are aware how cells behave, respond, and react. And I'd like to show how our holistic sense of familiarity with the living cell can fault some of the most widespread views of the modern world of biology. Rather than looking at the living cell as a puzzle on the point of solution, I shall show it as an enduring mystery still beyond the reach of human understanding, and capable – within its own frame of reference – of surprising ingenuity.

MODELING THE CELL: TRIUMPHS AND BLIND SPOTS

Current concepts model life through molecular biology. I'm a great admirer of the astonishing progress that this crucial branch of science has made. Yet in unraveling some of the key pathways we have lost sight of the intricate and self-regulating mechanisms of living cells. Molecular biologists see life as a set of coded reactions. But we know its unfathomable complexity, its ability to respond and self-renew. This paper will show the astonishing abilities that lie within the compass of the single cell.

The structure of the DNA molecule may be simple to understand, but the reality of what it does is far more complicated than we have been told. In consequence, practical results that benefit us all are proving elusive.

Molecular biologists have failed to address some of the basics. For instance, nobody has finally cracked photosynthesis. There is a curiously named compound, rubippy, and this human-made substance is the closest we've come to imitating chlorophyll. The magnesium ion that lies at the heart of chlorophyll is replaced by ruthenium in rubippy, and a pyridine ring is attached in rubippy in place of the porphyrin found in chlorophyll (Figure 1). Rubippy has been claimed to show some photosynthetic properties, but it is costly, unstable, and inefficient. Even a tiny weed growing in the sidewalk can perform a reaction on which all life depends, and which science cannot imitate.

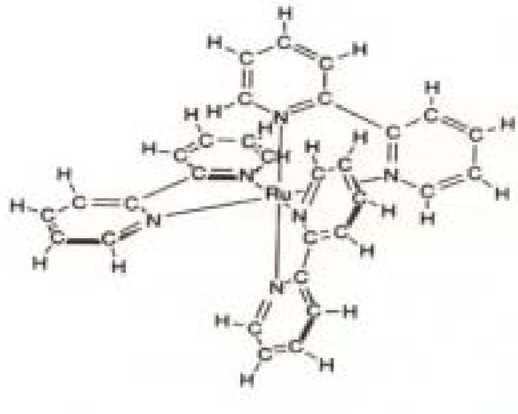

Figure 1. The rubippy molecule has been claimed to mimic the photosynthetic properties of chlorophyll. It is inefficient, expensive and short-lived, and reminds us of the efficiency of natural green plants in harnessing solar power. Each chlorophyte cell achieves energy-capture in a way science cannot imitate.

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Nitrogen-fixation is another enduring problem. We still have not managed to transfer genes coding for nitrogen fixation into non-leguminous crops. This should have been one of the first topics to tackle, but remains beyond our reach.

Even the successes are often less than they seem. There has been much excitement about 'golden rice', for example, which had been genetically modified to contain genes coding for the synthesis of vitamin A. Since a lack of vitamin A causes blindness, this harnessing of genetic engineering could potentially help solve a serious threat to human health. There are key problems, though; there are over 100,000 strains of rice in use around the tropics and subtropical areas, and each would need to be genetically modified. Not only are there regulatory and safety issues to be addressed, but there will be consumer resistance to the new product (which has an unnatural yellow coloration).

It remains true that the most far-reaching innovations in agriculture are due to accident or to traditional cross-breeding, and not to molecular genetics. If you read about a male-sterile wheat, a giant loganberry, super-apples or extra-tasty peppers then the chances are they've been produced by chance or by plant breeders, not by implanting genes through molecular engineering.

This is equally true in medicine. The new genetics has allowed us to identify spermatozoa or a blastula that carries the genetic determinant of disease in later life, but this is a preventive measure, and not a cure. Time and again the headlines have assured us that, with the genome decoded, we could begin to introduce widespread changes in medical practice that could banish cancer, conquer leukemia, eradicate diseases by genetic engineering, and take us quickly to the sunny uplands out of reach of our present-day burdens of ill-health. This hasn't happened. The secret of a disease is usually found in the living cell, and concentrating on our success as analysts has led us to ignore the fact.

Science has worshipped too heartily at the altar of molecular biology, and has ignored the astonishing complexity of single cells. They do not function like mere robots, but reveal themselves – within their own small compass – as sentient and responsive entities. Shall we take a stomatal cell as a single example? These stomata look so much like microscopic mouths, and in many ways they open and close like lips, admitting atmospheric air and releasing interstitial gases on a controlled basis. Stomata respond to touch, to vibration, to light levels and to chemical stimuli. Note those carefully, for they echo the fundamental senses associated with humans.

MICROBES IN NATURE

Single-celled microorganisms can be seen to perform all sorts of unexpected tasks. *Vorticella*, for example, is probably the most important single microbe that affects human beings. We owe our lives to organisms like *Vorticella*. This organism is a single-celled protozoan, each cell less than a tenth of a millimeter across. It develops as a bell-shaped body on a spiral stalk. This stalk can suddenly contract, and then slowly unravel. It does that when it has exhausted all the food in that particular compartment of water – the cell jerks in, and then re-emerges in a different direction – and the response is also used to escape from danger. If some blundering water-flea comes near the stalk, it suddenly contracts, and the water-flea, with any luck, is denied its meal. *Vorticella* features a ring of cilia around the bell, and these circulate a current of water into the mouth of the cell and out again. Any unwanted particles (small sand-grains or dust particles) are ignored by the cell; but anything alive that the cell wishes to consume, like a bacterium, is taken in by *Vorticella* and devoured. The chosen food passes down the gullet, and into the cytoplasm. Any residues are subsequently ejected when digestion is complete.

Vorticella is the organism that gives us pure water. If you look at a mountain stream you can see how the water runs down through peat and gravel. There may be a dead cow around the corner, whilst down at your

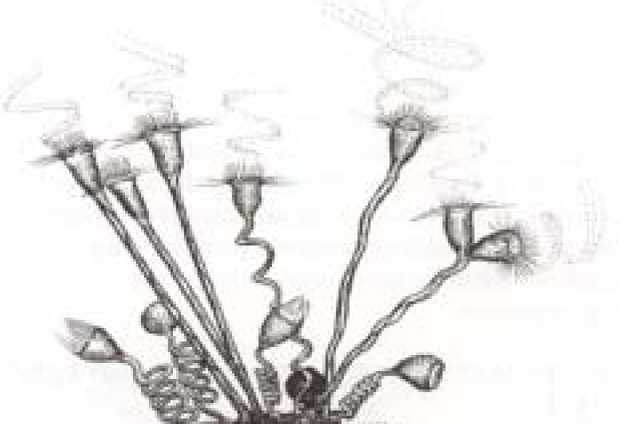


Figure 2. Colonies of vorticellid protists serve to purify water and remove bacterial growths through ciliary action. Though not widely taught, these complex sessile organisms are crucial to human survival. The contractile stalks of Vorticella show an ability to respond to potential predation and the cells make fine distinctions between food and non-food particulates.

camp-site (which you selected as suitable before you knew there was a dead animal upstream) the stream is pure, and clear, and wholesome. Take some of the rocks from the bottom of the stream, over which the water has been trickling, and you will find them covered with similar vorticellid colonies; they are consuming the bacteria in that water as it flows down.

Much of the world's water has traditionally been purified by passage through slow sand filter bends, and it is taught that the sand mechanically filters out the unwanted components of the water. This cannot be correct, for the interstices between sand grains are large fractions of a millimeter, many hundreds of microns, across. Bacteria are orders of magnitude smaller than the gaps between sand-grains, and sand cannot act as a mere mechanical filter. The water that passes through a slow sand filter is not passed into the mains until the filter has begun to develop what the Germans call a *Schmutzdecke*, a 'slime layer', in the top 1 ft (the first 30 cm or so) of the filter-bed, which forms through a process of maturation that takes several days. This layer has always been believed to be the slime, the germs, and the rubbish in the water that the sand held back. But when I first looked at that under the microscope in my teens I found extensive colonies of the vorticellids, and the slime is in fact these protozoan organisms which colonize the sand. The lesson was plain. These are the microbes that clarify and purify the water – they are not mere sludge trapped between the gains of sand.

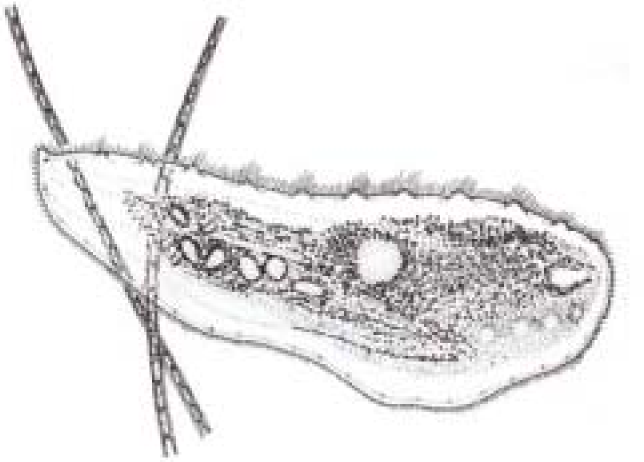


Figure 3. Delicate, thin cells of Loxophyllum and found in the aquatic environment. These ciliates browse on selected microorganisms, and – like Vorticella – they occasionally cease grazing to undergo conjugation and sexual reproduction. The decision-making and recognition mechanisms they utilize are refined and have been little studied.

Another protist that exists in the aquatic environment is the ciliated protist *Loxophyllum*, and I have pictured here as it crosses a couple of algal filaments that emphasize the fact that it is both flat and tenuous. It has the appearance of a floating flame, less than a tenth of a millimeter from end to end. *Loxophyllum* is transparent; it is more than translucent. It is exceedingly thin, like nothing more than a floating piece of cytoplasmic membrane. It exhibits food vacuoles and a highly complex nuclear structure. Once in a while *Loxophyllum* will cease to feed and seek out another of the same species. The two approach each other with the oral side of the cells, and – after mutual inspection – they may join together as a pair, fuse and exchange nuclei in a microbial embrace.

It is impossible that micro-organisms do not 'enjoy' this sexual phase. If they did not, then they would not indulge. Consider: they are browsing around, feeding. They select what they wish to consume, and the more food they eat the faster they keep growing and undergoing mitosis. To stop feeding and search out a mate is an interruption of that vital process. So, at a cellular level, organisms like these ciliated protozoa must 'prefer' courtship to mere feeding. There are clear resonances here in our own behavior, which reflects the propensities of the cells of which we are composed.

Look now at an extraordinary microorganism, *Epidinium*, a rumen microbe of cattle. It is a remarkably complex protist. The organism is a single cell, though structurally it seems to reveal features that are analogous to those of multicellular organisms. It possesses something with the appearance of a brain. This is the motorium, and in electronmicrographs it shows itself to have something in common with neuronal organi-

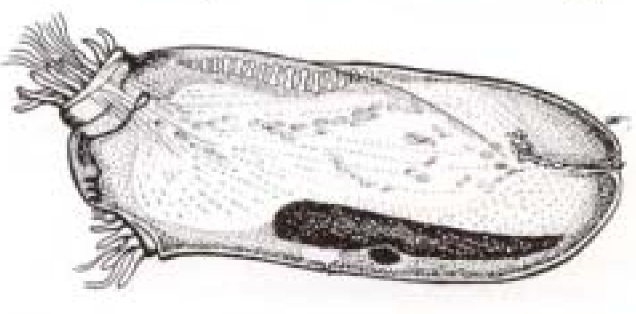


Figure 4. The bovine rumen ciliate Epidinium is one of the most structurally complex protists. The motorium can be seen encircling the mouth-like stoma, and the segmented body – reminiscent of a vertebral colum – is also apparent. Not seen here are the fine skeletal plates, almost invisible in the living organism, that serve to maintain its morphology. Multicellular specialization harnessed many of these structural conventions as evolution proceeded.

zation. The motorium features a small loop which encircles the mouth-like stoma through which food particles are ingested. The organism also has a defined anal pore. And there is even a clearly visible segmented structure containing food storage materials such as glycogen, that to the educated eye might remind one of a vertebral column. This single-celled organism has developed a complex and specialized structure that is beginning to embody some of the characteristics multicellular forms of life.

Within this process of development I perceive the single strand of an important principle. Multicellular organisms are rich in such resonances of how single cells behave. It is not correct to think of the human body as being subdivided into cells. Quite the converse: the human body is a coordinated system of cells living in a choreographed community for mutual benefit. We are nothing more than cell colonies, and we can only carry out tasks to which single cells point the way.

LESSONS FROM AMOEBAE

The common amoeba *Amoeba proteus* was known in the Victorian textbooks as *Chaos chaos*, a memorable name that is somewhat more evocative than the modern equivalent. These amoebae are taught to us as ineffably simple, and the specific epithet *proteus* is an allusion to the implied lowliness and simplicity of amoeboid microorganisms. In familiar terms, an amoeba represents the "simplest form of life known to science". It is also any shape you wish. People say that all one needs to do is drawn a wavy line and add a dot for the nucleus . . . yet none of this is true. *Amoeba proteus* is actually distinguishable from other amoebae because of something about the dimensions, the shape, the outline and orientation of the patterns of its pseudopodia. Its shape is actually diagnostic. Although no amoeba is ever exactly the same shape twice, we can distinguish one from another because of the morphology. Amoebae are recognizable, and many of the species truly do have a characteristic configuration.

Our understanding of amoebae remains founded firmly on the notion of simplicity. This is a misleading illusion. In terms of metabolism and activity, sensation and excretion, feeding and motility, amoebae have so much in common with us. But an amoeba can also carry out a number of actions which humans cannot do; such as exactly regulating its rate of reproduction to the available food supply, and building a protective capsule around itself so that – when the environment which it needs to sustain life disappears – the amoeba can survive until conditions improve.

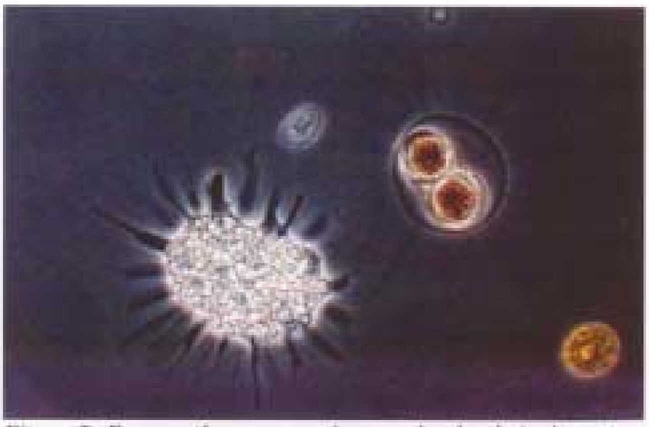


Figure 5. Frequently we recognize amoebae by their characteristic morphology. This micrograph of Asterocoelium, *taken by my distinguished colleague Ms. Hilda Canter-Lund, clearly shows the ovoid cell body and the hyaline pseudopodia. The components of the amoeboid cell are predominately water-soluble, and the mechanisms enabling these cells to carry out coordinated tasks remain beyond the understanding of modern biology.*

The way in which humans move and walk is simple to model with two sticks of wood and an elastic band. Yet when an amoeba heads off in its chosen direction, it does so without the benefit of limbs, without any supporting skeleton, and without the benefit of organized musculature. An amoeba is predominately composed of water-soluble constituents, yet does not dissolve away into the surrounding water. And we do not have to search far to find amoeboid cells; our bodies rely upon incalculable armies of leucocytes to protect us from infection, and each is a self-propelled amoeba.

HOW INGENIOUS IS THE LIVING CELL?

The activities of multi-cellular organisms, like humans, are resonances of what single cells can perform. As I advance this view I can imagine your response: "What about, say, the Great Wall of China?" It is a fair and proper challenge. If humans are communities of cells, and if – as I here suggest – we are making the best of what single cells can do, then single cells must be able to make comparable constructions of their own. Of course, they can.

Building constructions from inert materials, building-blocks, is indeed found in the microbial world. Consider a thecate amoeba such as *Difflugia*. Here we have an amoeba with longer, narrower and less granular pseudopodia than is the case for *A. proteus*. It lives in pond water, and finds small sand-grains which it picks up and cements together to form a microscopic home. That is a considerable accomplishment for a 'shapeless protozoan'. Humans discovered how to build with stones a few millennia ago, and we regard ourselves as advanced to have discovered the principles of cementing separate items together to make a protective wall. Yet amoebae can do this too. Many species confine the raw materials for home-building to specific components – centric diatom frustules, for example. These amoebae embody mechanisms for seeking out the correct frustules, identifying them, and cementing them together as the shell is constructed.

These amoebae have a range of senses and can adapt their behavior to the exigencies of the moment. The organizational complexity involved in the varied

Figure 6. Slender and non-granular pseudopodia are characteristic of the testate amoeba Difflugia. These organisms select grains of siliceous sand and cement them together to produce a recognizable flask-like shell. The actions of recognizing, retrieving and coordinating the construction of these microscopic particles mirror the propensities of multicellular organisms. Little is known of the mechanisms involved.

Figure 7. Centric diatom frustules have been used by this tintinnid ciliate to construct a protective shell. This micrograph by Hilda Canter-Lund reveals the ability of the protist cell to make discriminations between suitable raw materials for its project. A moment's reflection on the intricacy and precision of the task remind us of our failure to comprehend the functional complexity of single cells.

tasks of locating, sensing, identifying, selecting and ordering minute mineral fragments into a delicately constructed, purpose-built shell is a complex task. It is not one that science can model, nor anything that molecular biologists have begun to comprehend. This is an intricate and ingenious process, performed by a single cell that science dismisses as simple.

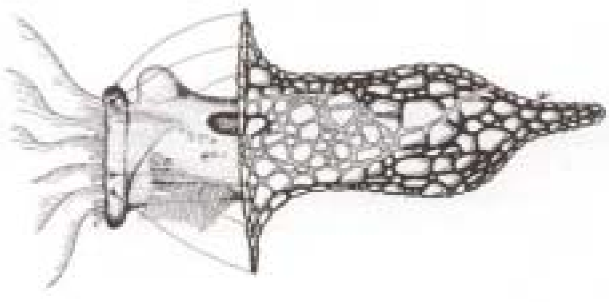


Figure 8. Many such ciliates are marine. Tintinnopsis *constructs a close-fitting shell from sand grains. Reflect on the fact that a human covering a vase with mosaic fragments is congratulated on their skill; here we have a single-celled microorganism that embodies a comparable facility. Dismissing these cells as 'lowly' and modeling their functions as robotic in nature is to ignore crucial mechanisms that we now need to study.*

In sea-water we find *Tintinnopsis*, another ciliated microorganism like those we have considered earlier. It uses its cilia to swim – think of it as being a little like a bell-shaped *Loxophyllum* – but *Tintinnopsis* gathers fragments of rock, and tiny particles of quartz, and cements those together to make a protective chamber that is shaped like a bell (hence the generic name of the organism). It emerges from its home, holding itself secure with fine, translucent, contractile fibrils. Then, when danger comes along it jerks back inside the refuge which it so perfectly fits. If you wish to see resonances between these single-celled forms of life and higher organisms, then whether it is caddis-fly larvae or hermit crabs, you would not have to look very far.

HOW MICROBES MODEL THE BRAIN

I have exemplified ways in which protists can make selective decisions about where they are going to go, whom they are going to mate with, what they are going to eat, which direction they are going to take. Single celled organisms can clearly communicate with each other, especially when conjugation is in the wind, yet their decision-making propensities are ordinarily self-regulated. Single cells perform complex and unfathomable manipulative tasks.

Figure 9. Neurons within the human brain are arguably the most highly developed cells of all. These Golgi-stained neurons are conventionally modeled as functioning in life like transistors, or as go or no-go gates. It is now postulated that, if protists can carry out complex coordinated tasks of discrimination and construction, then it must surely be that neurons carry on intracellular data-processing.

This brings me to a crucial lesson. We are marveling here about the extraordinary complexity of single-celled organisms slipping through the slime at the edge of a pond. Yet what about our own cells? The leucocytes on which we all rely have much in common with amoebae. At this moment there are probably polymorphonuclear granulocytes in your throats that have identified some inhaled *Streptococcus* as a threat to your health. These single cells will have recognized the foe by themselves, will have very likely communicated the fact to their fellows, and between them they will – as a rule – extirpate the enemy and preserve the health of the whole community of cells that is each of you.

When we rightly marvel at the achievements of surgeons, we should not neglect the principle component of the healing process – the reorganization, specialization and regeneration of tissues that is controlled by each cell in cooperation with its neighbors.

Within minutes of accidentally cutting yourself, the hemostatic flow has probably been brought to rest as erythrocytes attach themselves to fibrin threads. Within days, the cut itself has been bridged as fibrocytes proliferate and lay down new connective tissue. And a week later there is new skin, new strata have formed within the epithelium, and the cut itself is healed. This is a process of meticulous and self-motivated coordination and is something we have rarely admitted into our discussions. Comparable mechanisms exist in vascular plants, which can shed components (even substantial branches) and initiate a sequential healing process that restores the plant's structural integrity. There are subtle, powerful forces at work here and they are testimony to the regulatory mechanisms on which all life depends.

PUTTING THE BRAIN IN CONTEXT

How is this controlled? There is a widespread view that all the great brain books repeat – that every such aspect of the functioning of the body is ultimately controlled by that vast computer we know as the brain. The implications are that the relationship may be tenuous, it may even be indirect, but in the final analysis it is always present. This universally expressed belief is flawed. The cells in the body may sometimes come under central control; they may often heed impulses and signals received from other cells. But they are essentially self-regulated, and are not controlled by the brain.

If leucocytes misidentify their target of attack, then you may find conditions like the autoimmune diseases. If the sense that controls reproductive timing is lost, then you may find a malignancy. Now, were the cells of the body controlled by the brain, then within the brain would you find the cure for such diseases. We don't find any such thing.

And here is perhaps the most intriguing lesson of all. We have seen how free-living protists can undertake tasks of unimaginable intricacy, and yet we are led to believe that a neuron in the brain is little more than a go or no-go gate. I do not believe that a highly specialized cell like a neuron merely switches 'on' or 'off'. I study recordings of the sequential code of impulses that are sent out by neurons at around 40 Hertz and I sometimes wonder how intriguing it might be to play them back at a different speed, or modulated in a different way, because these signals have the makings of a language. This is not mere signalling that neurons

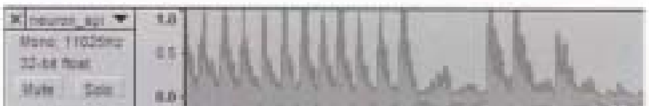
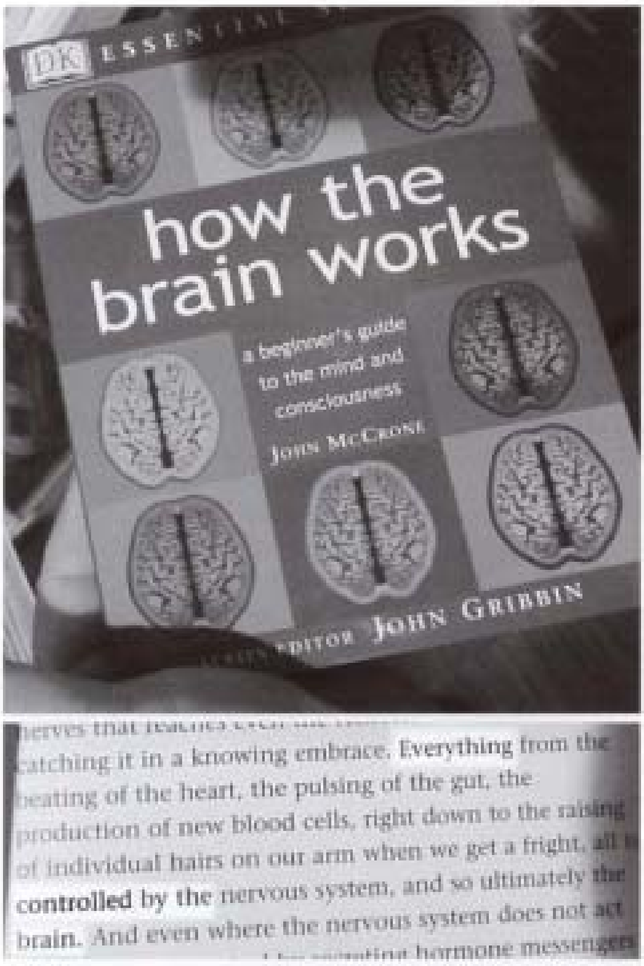


Figure 10. Traces from living neurons are categorized, from the appearance of the wave-form, as 'spikes'. Here the original recording has been temporally modified to resolve the structure within each of the 'spikes' and modulation is apparent. If the mean frequency is adjusted to approximately 400 Hz, approximating to sounds that the human ear is accustomed to hear, we can listen to the results and appreciate their complexity. The sounds, in this form, are reminiscent of sea-birds communicating with each other. This is the language of the neuron.

are somehow 'on' or 'off'. They are no binary switches. This is surely neurons signaling complex and refined output to each other; here we have the language of the mind. Each brain cell is no mere transistor or gate: it is, in my view, more like an entire 'computer'.

Current models of the brain are complex enough. We calculate that there are 1×10^{15} synaptic connections, and are taught that signals sent through combinations of these provide the phenomenon of thought. And what a phenomenally large number this is – more than the number of stars in the universe, greater even than the number of seconds that have elapsed since the era of the dinosaurs. No wonder the brain's complexity is so great. However, this model of complexity depends upon us imagining that the brain's operations are carried out as though the neurons were transistors in a cranial computer. I am postulating something else – namely, that the processing is not interneuronal, but is essentially intraneuronal in nature. This view holds that, mirroring and extending the propensities of ingenious amoebae and clever ciliates, the neuron carries out its work within itself, as much as between its neighbors. We know that the processing of vision is initiated within the receptors of the retina, before signals are ever sent to the brain. Why should these cells uniquely embody intracellular processing? In my view, the functioning of the entire brain depends upon intraneuronal activity



atching it in a knowing embrace. Everything from the
eating of the heart, the pulsing of the gut, the
production of new blood cells, right down to the raising
of individual hairs on our arm when we get a fright, all is
controlled by the nervous system, and so ultimately the
brain. And even where the nervous system does not act
hormone messengers

Figure 11. Top) Of the brain books one could cite, one with 'McCrone' as the author is singularly appropriate for this journal. The topic is one of the most popular for book titles. Currently there are 8906 search results for this term on the British Library site, and 7163 on Amazon. Bottom) Descriptions of the relationship between brain and body are exemplified by this quote from the McCrone book. The brain is currently viewed as fundamentally 'controlling' every aspect of the body's function. However, it is clear that most of the activity of cells is regulated without reference to this form of mediation.

This revisionary postulation confers far greater complexity on our notions of the workings of the brain. The cutting-edge findings of the molecular biologists are not eclipsed by this proposal, but are more clearly set in a humbler context. Just look at some of the implications of what I am saying. It makes a nonsense of the notions of artificial intelligence (A.I.). There can be no doubting the magnificence of modern computers, and the machines we have in our offices sometimes seem to have minds of their own. But the proponents of A.I. hold that their best machines now rival some creatures. Some say they have the power of a rat's brain. I say not. Even the best of computers is put to shame by the functioning of a single cell. Yes, our machines can digest enormous amounts of data and sort them, rapidly but unintelligently, into a form we find amenable. But cells are sensate. Cells are working things out for themselves. Cells remain a mystery to us all.

CONCLUSIONS

From this informal survey, there are several lessons I think we should learn.

* First, the brain does a lot less to control the body than science currently accepts. The tragedy of a patient in a persistent vegetative state proves the point. The brain, even the brain-stem, are no longer functioning. For the individual, cognition is ended. But – as long as the lungs are ventilated – the cells of the body still regulate its workings, reproduce as they should, control the dynamic flow of blood and lymph . . . the patient may look like a near-dead person, but the essential functions of a living body are still evident. The cell community still carries on without that central control. Hair grows. The liver lives.

a

b

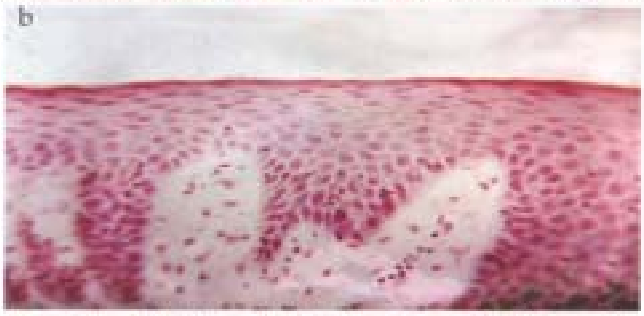


Figure 12. a) Studies on the histology of wound healing mechanisms for Mr. John Bunyan in 1963 first revealed the abilities of cells within the buccal mucosa to repair trauma. It is the self-regulated propensities of cells that restore structural integrity to tissues after surgery. b) Similar self-regulation is observed in vascular plants. Cells within the tissues of the parasite Cuscuta, *seen here in a transverse section of host stem, are able to identify the nature of tissues within the host. Vascular elements grow to tap directly into the vascular system of the host plant. Refined systems of recognition and response at the cellular level are an essential component of such relationships.*

* A second lesson is that A.I. is an over-stated dream by its adherents whose machines are as wonderful as their understanding of life is limited. The living cell far transcends anything we can make in a factory, and we would do well to respect the complexity of the single cells that we rely on for survival and of which we are comprised. We even hear talk of technicians manufacturing nano-robots, programmed to enter living cells and carry out engineering work. The already-existing entities of retroviruses, phages and other viruses exemplify how nature has long since created such miracles; and – unlike ours – these far more complex natural structures are self-powered and do not require external mediation.

* Much new insight can be gleaned from a study of the resonances between single cells and the multi-cellular entities that comprise them. Just to take an example, there has been long controversy of the origin of the eye in its various forms. The most recent findings suggest that both mammalian and arthropod eye structures have their evolutionary roots in the light receptors of the ragworm *Nereis*. This is only a half-way house explanation. Science should go back to the

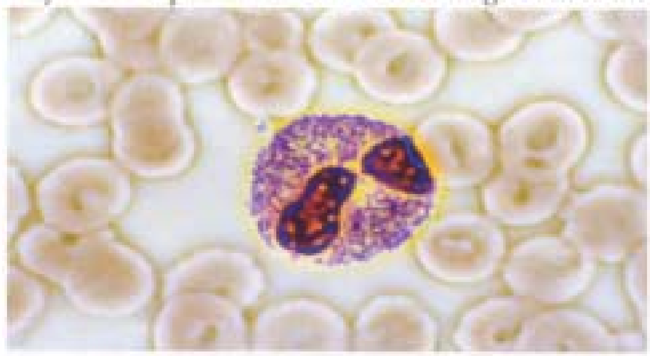


Figure 13. Leukocyte populations ward against pathogens and mediate immunity. This eosinophil granulocyte, imaged by the leading British microscopist Mr 'Spike' Walker, reminds us of the independent role such cells perform. Although there may be central control of some population levels and the cells are attracted by chemokines, the action of granulocytes and others in identifying and responding to immunological challenge and invasion by pathogens is self-regulated. These cells feature refined levels of diagnostic and response capability which can, if compromised, cause long-term deleterious effects on the whole body. These mechanisms are beyond the regulation of the brain.

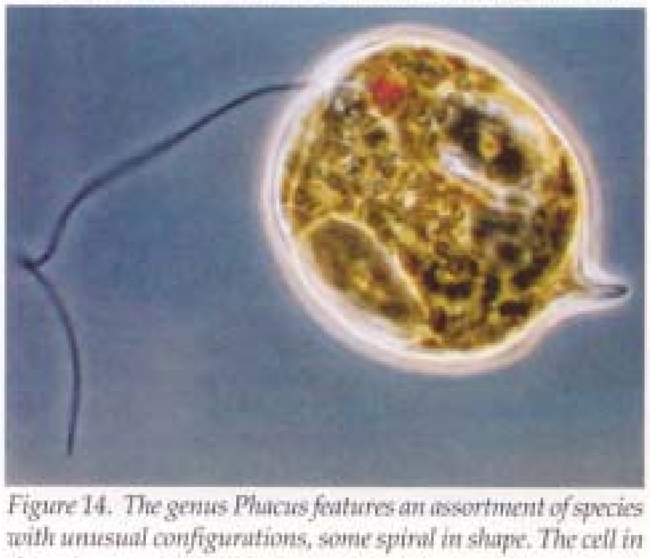


Figure 14. The genus Phacus features an assortment of species with unusual configurations, some spiral in shape. The cell in this micrograph by Hilda Canter-Lund shows a cell measuring 17 x 13 mm which contains a conspicuous red eyespot. The anatomy of eyes in more complex organisms owes much to the structure of eyespots in protists.

eye structures in single-celled organisms. It is in protists such as *Phacus* or *Chlamydomonas* that we can perceive the true origin of the eye – the devolvement of these intracellular functions into specialized cells comes later, and in my view this can only be understood through the protist route.

* The fourth is, for me, one of the most immediately important. If protists show such complex ingenuity, it cannot possibly be true that the human neuron, the most highly-developed and intrinsically specialized cell known to science, simply switches on or off. Neurons, I believe, are thinking within themselves. The implications for our view of human nature, and our understanding of its complexity, are immense.

Our familiarity with a microscopical view of life can give us a new appreciation of the intricate nature of the living cell. One recent paper published by the Institute of Biology actually began by stating that 'the cell theory is finished'. However, the converse is more the case – and as our comprehension embraces these new and startling visions, our understanding will benefit more than I can say. Perhaps cells, responding to their environment, transmit adaptive coding to ova via mitochondrial DNA. We may here find developmental mechanisms that are more substantive than the simplistic evolutionary notion of 'survival of the fittest'.

We have concentrated too much on reductionist analysis of cellular mechanisms. The great new scientific enterprises we were promised have largely failed to appear. Medicine and agriculture have not experienced the promised revolution, and there are serious consequences here both to the future of commerce and the biotech industries, and to public faith in biology. The answer will come when we move towards an understanding of the regulatory and sensate capacity of the living cell. Cells are, indeed, ingenious. They can adapt to circumstances, they are able to function in a coordinated and precise fashion, make discriminations of a refined nature, and point to sophisticated intracellular information processing. In the intricacy of the living cell, and the inconceivable complexity of the choreographed cell communities that comprise us all, we will begin to perceive the true nature of human kind.

This is what we can immediately propose:

1. Textbooks on the role of the brain need to be rewritten. We have seen that the brain clearly cannot 'control every function' of the body. Single cells predominately regulate themselves in relation to their neighbors, and the brain is unrelated to this.

2. It may well be true that our notion of the neuron is flawed. Microorganisms indicate that complicated intraneuronal activity mediates mentality and, if so, our models of the mind need modification.

3. Let us acknowledge that we should move on from the idea of the body as 'a machine'. And, while we are at it, let us admit the limits of Artificial Intelligence. The best of modern machines is a crude indicator of the majesty of living organisms, and a fresh and full study of microbes and other single cells can do so much to illuminate our thinking.

Once these matters have been considered, we can move on to new methods of modeling human behavior. This revolution, rather than mere genetics, should become an essential focus for scientific attention in the future. Microbial forms of life wreak miracles, and the lessons we can learn are needed by tomorrow's scientists.

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