View from the top

It's time to turn the reductionist idea about cause and effect on its head, argues physicist **George Ellis**

PROFILE
George Ellis is a cosmologist at the University of Cape Town, South Africa, focusing on general relativity and the structure of the universe. He co-authored the seminal 1973 book *The Large Scale Structure of Space-Time* with Stephen Hawking

LOOK at the complex world around you. There's a basic assumption that the things you see – be it humans, computers or trees – can ultimately be boiled down to the behaviour of the particles they are composed of. Biology is determined by chemistry, which is in turn governed by the underlying physics. Much of modern science is rooted in this bottom-up, reductionist view of cause and effect, which has been an excellent way of explaining many phenomena. But can all things be understood just by looking at their constituent parts?

Consider a computer. You want to type a document, so you press the keys to give the sequence of letters "I love this machine because it is so obedient". Electrons in the transistors in the central processing unit obligingly flow in such a way as to make these letters appear on the screen. The underlying physics – governed by the Schrödinger equation for electrons and Maxwell's equations for the electromagnetic field – doesn't control what happens. On the contrary, the physics obligingly does your bidding by making electrons flow to the screen in precisely the right way to achieve your desired outcome. That's top-down causation from your brain to the fingers that press the keys, then down to the level of electrons flowing in the processor and onwards to the screen.

And what about the way that social influences act on the brain? If you are brought up in an English-language environment, for example, society shapes your neural connections in such a way as to let you think in English. This is the result of top-down causation from the social environment to the synaptic connections in your brain.

Physicists don't usually think in terms of top-down causation, as they tend to assume that everything flows from micro to macro scales, but neuroscientists must in order to make sense of brain processes such as vision. As Chris Frith explains in his book *Making Up the Mind*, what we see is determined by what our brains predict we ought to see, rather than simply by the signals reaching our brain from the retina.

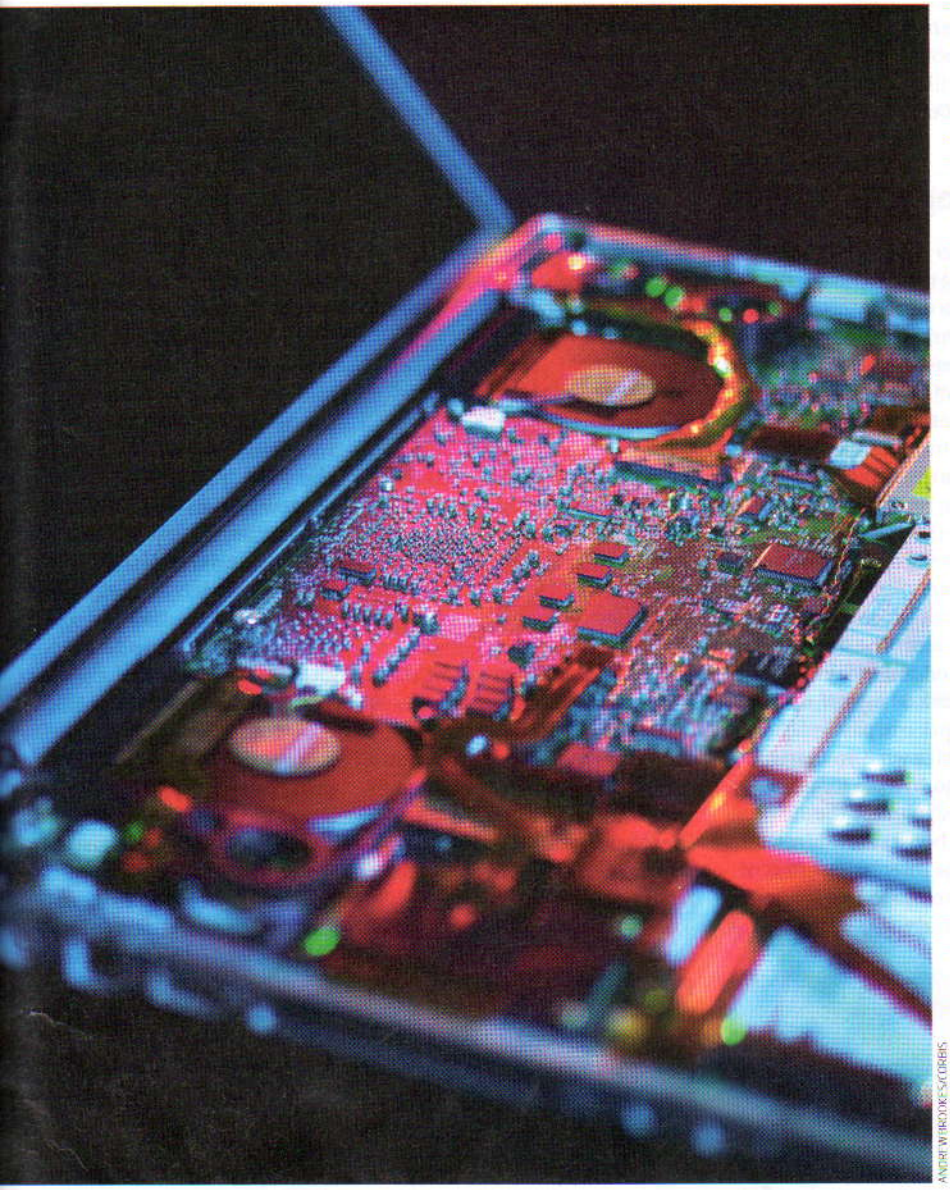
Indeed, this kind of causation is all around when you look for it. For example, it's a central feature of Darwinian evolution. The brown bear, *Ursus arctos*, is brown because it lives in Canadian forests. The specific sequences in its genes have been selected through evolution so that brown fur will be the outcome of developmental processes. Its polar cousin *Ursus maritimus* has different sequences in its genes that give it white fur, which is better for survival in the Arctic. The environment is a key feature influencing genetic structure. It obviously makes sense to label this a top-down effect. The gene sequence didn't make the polar environment white – the flow of causation went the other way.

I first became aware of top-down causation through the work of Dennis Sciama, a key figure in modern cosmology, who outlined how cosmology influences local physical laws. My ideas developed through conversations with biochemists and philosophers, and since then it has become clear to me how ubiquitous and important top-down causation is. It is also a counter to strong reductionist ideas, which I believe misrepresent the way causation works in the real world. As scientists focus more on the emergence of complexity, taking this into account will become increasingly important.

Top-down causation provides a foundation for genuine emergence, where complex systems with new kinds of behaviour emerge from combinations of simple ones. It also underlies how entities such as computers and brains can have causal power in their own right, despite being made up of transistors or neurons, themselves made of molecules comprised of protons, neutrons and electrons. When my muscles do what I want them to do, it is because signals from my brain have genuine causal powers: they coordinate the way electrons move in my muscles.

However, many reductionists say that in the end, this is nothing but disguised bottom-up effects, because the physics at the bottom is causally closed: there is nothing but interactions between particles such as protons and electrons at that level, leaving no room for any other causal effect and no causal slack to allow top-down effects to take place.

This is mistaken. Firstly, it omits the crucial way in which a higher-level structure channels lower-level interactions. Paradoxically, when the wiring in a computer constrains the motion of electrons, this creates new possibilities that do not exist when the



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It is impossible to fully understand a computer by only studying its components

"Entities such as computers and brains can have causal power in their own right"

electron flow is unconstrained, as in a charged plasma. Such constraints underlie emergence of higher-level computational capacities. What then occurs depends on what software is loaded into the computer. The physics makes things happen, but the context determines what will happen.

Secondly, such critics are thinking in terms of the billiard-ball model that was so successful in the kinetic theory of gases: unchanging lower-level entities with fixed behaviour interact with each other through deterministic laws, and so determine higher-level behaviour. The pressure of the gas results from the motion of molecules, for instance. But that's not what happens in biology, or in quantum physics. The lower-level entities are not unchanging: context affects their nature and shapes how they behave. A neutron decays in about 15 minutes when free, but lasts for billions of years when bound in a nucleus.

But things are even more radical than this. Sometimes the lower-level entities only exist because of the nature of the higher-level structures. This is the case for all symbiotic relationships, where the partners are unable to survive when separated. They can only exist in the context of the interacting whole. An example from physics is the Cooper pairs that underlie superconductors. These are pairs of electrons that would normally repel each other. But the lattice structure of the metal gets distorted by the electron charges in such a way that it modifies the interaction, and the electrons form bound pairs. So the existence of the entities that enable superconductivity (Cooper pairs) is due to the nature of the context (the metallic lattice). This is why it is impossible to deduce superconductivity in a purely bottom-up way, as emphatically pointed out by physicist Robert Laughlin in his 1998 Nobel prize lecture.

Also, during the process of evolution, adaptive selection deletes lower-level elements, leaving behind only those better suited to higher-level purposes – genes coding for greater strength, for example. This deletion of unsuitable entities is the way order arises from disorder. It is central to biology but it also occurs in physics, for instance when optical filters cut out unwanted polarised light.

The case for top-down causation seems to me to be pretty conclusive, but not everyone agrees. Even today many scientists concur with the bottom-up, reductionist view strongly expressed by the late Nobel prize-winning biochemist Francis Crick in his book *The Astonishing Hypothesis*: "You, your joys and your sorrows, your memories and your ambitions, your sense of personal identity and free will, are in fact no more than the behaviour of a vast assembly of nerve cells and their associated molecules."

However, hard-line reductionists would question why Crick assigned causal powers to nerve cells when their behaviour is no more than that of the electrons that convey neural signals. If you really believe in bottom-up causation, you can't assign causal powers to an intermediate level like this – it's the electrons that are doing the real work, or perhaps not even electrons but superstrings, fundamental building blocks of matter predicted by string theory. The higher levels like electrons and neurons are mere passengers carried along by this underlying causation.

But neuroscientists believe that neurons do indeed do real work. This is only possible if they act to channel and control the flow of electrons in neural axons – that is, if top-down causation takes place from the neuron to the electron level. And if that is so, the case for top-down causation is vindicated. ■