Going up, going down

As I discussed in a recent column, it seems we still have quite a lot to learn about how a causal influence of one thing on another might show up in empirical data. Other aspects of our thinking about causality seem more settled. The deepest and most fundamental causes in nature, we tend to think, are those described by the laws of physics — especially particle physics. Yes, there are laws and well-understood causal links in chemistry, in biology, in geophysics, but all really rest on deeper laws for particle behaviour at the micro-scale.

In other words, we generally assume causal influences work upwards; actions at lower levels causing those at higher levels, and higher-level laws reflecting the aggregated action of deeper, lower-level laws. If you believe that the behaviour of a human being comes down to ordinary biochemistry in a very complex, adaptive system, then the base causal force behind human action is again the laws of fundamental physics.

In thinking this way, however, we may be making a big mistake. At least that's the argument of physiologist Dennis Noble, who suggests that there is no preferred direction of causation in biology, and that causal influences actually run from the top down as much as they do from the bottom up. Thinking about biology correctly, he argues, requires a kind of extension of the relativity principle to biology. Much as relativity implies that there is no preferred frame of reference for the laws of physics, here the assertion is that the same is true for the level of causation in biology.

Over several decades, Noble's research has focused on building up detailed computational models of the human heart, the aim being to explain how macroscopic behaviour — patterns of blood flow and muscle contraction — emerge out of small-scale interactions. His models follow the detailed behaviour of myriad molecular pumps and ion channels in single heart cells, and let millions of these cells interact in realistic heart geometries. The approach is analogous to molecular dynamics simulations for a fluid; get all the details right, and then let the computer follow the processes to see what will emerge.

But along the way, Noble's efforts to build more realistic models led him to accept the need for top-down causal influences as well. For example, the spiral waves of muscle contraction responsible for pumping blood in an organized way arise as a result of boundary conditions that capture global constraints on the heart geometry and dynamics. Detail at the microlevel isn't enough. Indeed, what happens at the microlevel — the behaviour of individual ion channels, for example — depends strongly on global constraints.

Causal influences actually run from the top down as much as they do from the bottom up.

As Noble notes, biology offers numerous similar examples (*Interface Focus* **2,** 55–64; 2012). Perhaps closest to home, the structure of the human brain gets rewired in response to human habits and behaviour. Again, events at the macroscopic scale — what we do and think as individuals — act back down to alter the states of neurons and molecular structure. Causes flow down as much as up.

Noble argues that biologists have been seriously misled in their thinking about causality by the so-called central dogma of molecular biology, which judges an explanation as proper only if it starts from the genes and runs to RNA, then to proteins, cells, tissues, and so on. This pathway, he points out, is really only a metaphor, as genes do not in any sense lie at a level below cells; genes, proteins and cells are everywhere throughout the body. Genes do exist at a smaller physical scale, but causal influences run back to this smaller scale all the time — for example, when someone has a thought, begins running, and transcription factors act to alter patterns of gene expression.

This makes a lot of sense to me, and what Noble argues for biology is no doubt true in physics as well. Indeed, expanding on Noble's idea, astrophysicist George Ellis has recently suggested that the same reverse flow of causation from higher-level structures down to lower orders may be the key feature that makes complex physical systems especially rich and interesting (http://arxiv.org/abs/1212.2275; 2012).

We tend to think, for example, that the character of the hydrogen atom follows from the laws of particle physics (quantum electrodynamics). But a hydrogen atom in relative isolation in the interstellar medium has very different properties from one trapped in a dense liquid of hydrogen under high pressure; the 'normal' radiative spectrum of hydrogen alters radically. Which is the 'true' hydrogen? There's obviously no answer. The nature of hydrogen depends on context.

Or consider, as Ellis does, nucleosynthesis in the early Universe. The rate of cosmic expansion depends on macro-level variables such as the average cosmic energy density. This in turn determines how temperature varies with time, which then influences the rates of nuclear reactions at the micro-level. Those reactions determine large-scale outcomes, but the causal influence works backwards as well.

Start thinking this way, and you see further examples everywhere. Think of band structures in solids, where large-scale periodicities act back downwards to determine individual electronic states. Or think of wave dynamics in fluids or plasmas, where macro-scale collective patterns determine the individual motions of particles. The failure of a half-century of research to achieve viable nuclear fusion for energy production reflects this devilish richness of causal influence in plasmas.

There is really nothing new in all of this. Scientists in many fields, physics included, face this mixture of bottom-up and top-down causal influence routinely. Sometimes, as Ellis points out, high-order structures merely constrain lower-level interactions. Crystal symmetries determine the possible states of electrons. In other cases, higher levels may even change the nature of the constituent entities. Free neutrons decay in 11½ minutes, whereas those bound in a nucleus last for billions of years. In still other instances, higher levels even create lower-level entities, as when the structure of a solid material generates the possibility of phonons.

Ellis concludes — and I suspect many others will agree — that something in the nature of the reversal in causation is elemental in what we think of as a complex system. The simpler, bottom-up emergence we are used to in more elementary systems — phase transitions, for example — can only create complexity of a limited kind. The full richness of hearts, brains and ecosystems requires something more. Can we build up a real theory of complexity from this insight? That remains to be seen. ❐

MARK BUCHANAN