# Learning from failure

Catastrophes of all sorts — social, biological, environmental — stir-up feelings of unease from which the human mind naturally recoils. What seemed stable and dependable — a community or a financial market, an organ or a portion of the Earth's crust — suddenly seems charged with invisible menace. As Friedrich Nietzsche noted long ago, longing for that feeling of safety is a prime force behind the human weakness for fabricating comforting, if illusory, explanations: "To trace something unknown back to what is known is alleviating, soothing, gratifying and gives moreover a feeling of power. Danger, disquiet, anxiety attend the unknown — the first instinct is to eliminate these distressing states. First principle: any explanation is better than none."

But catastrophic failures also alarm us because they seem to violate our intuitions about cause and effect, striking with no prior warning: a tissue that has functioned perfectly for 50 years suddenly becomes cancerous; or tectonic plates locked in place for centuries shift abruptly, releasing devastating energy in a matter of seconds. The trigger for the event, in other words, is by no means evident on the scale of its consequences, or the natural level of its description.

Indeed, this is more than perception, and reflects a real phenomenon — the intimate linking of processes across many scales of space and time — that makes the science of such catastrophic failures so rich. In the fracture of any brittle material, for example, including the Earth's crust, the causal dynamics depends on events ranging from the atomic scale all the way up to the size of the system. Glass shatters by cracks propagating at close to the speed of sound, which can be initiated by the breaking of a few atomic or molecular bonds.

The science of such failures is, of course, extremely old. As Markus Buehler and Sinan Keten describe in a review of this area (*Rev. Mod. Phys.* in the press), Leonardo da Vinci even conducted experiments on the breaking of metal wires of different lengths, concluding that a wire's strength decreases in linear proportion to its length (because, as we now know, greater length increases the likelihood of weak points introduced by defects). But this science is also very new, and is perhaps now entering a golden age owing to advanced means for studying structures and processes at the atomic level, and also because of the rapid confluence of engineering and materials science with biology.

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What Buehler and Keten make clear is that the dynamics of failure in earthquakes or other brittle fractures, or in disordered biological materials such as bone or muscle tissue, show both deep similarities and enormous differences. There seem to be certain patterns lending unity to the science of catastrophic failures, yet also surprises and unique phenomena, especially in biological systems, which may have important applications.

Hints of universal behaviour, for example, emerge out of studies showing strikingly similar phenomena in very different settings. For example, in 1999 geophysicists first observed a phenomenon known as intersonic propagation in an earthquake in Kocaeli, Turkey. The earthquake started near Kocaeli and spread along a weak plane in the Earth's crust. The rupture grew subsonically for a short period of time, but then burst out into a new behaviour of intersonic propagation — the rupture travelling faster than the normal speed of shear waves in the crust — with speeds exceeding several kilometres per second. Such propagation, which was initially predicted on theoretical grounds in the 1970s, can create shock fronts involving extremely violent displacements of the crust and capable of causing immense structural damage.

Curiously, similar dynamics has been documented in 'laboratory earthquake' experiments conducted on a scale some 10,000 times smaller, using polymer slabs which have been weakened to simulate a fault line. These experiments replicate the transition from subsonic to intersonic rupture propagation, along with the generation of shock fronts. Most impressively, similar processes have also been noted on the atomic scale in molecular-dynamics simulations of rupture in a weak layer between two dissimilar materials. Some basic features of rupture dynamics — and even subtle features — can be observed at multiple scales ranging from tens of kilometres down to the atomic scale.

But things are very different in biological materials. A key feature that gives these materials remarkable properties, as Buehler and Keten point out, is their hierarchical construction — small molecules binding into proteins, which link into filaments, which in turn organize into mesoscale structures, and so on. These hierarchies seem to have a crucial role in determining a material's properties, and especially its propensity for abrupt failure. Take bone, which is a remarkably tough, lightweight material composed of assemblies of tropocollagen molecules and tiny hydroxyapatite mineral crystals. Its toughness reflects its possession of numerous mechanisms for the dissipation of energy — such as elastic biomolecules, which can uncoil — which take up energy that would otherwise cause material rupture.

As a result, such materials have their own unique modes of failure, involving distinct energy-dissipation mechanisms that come into play as stress cascades down through different scales. Recent research suggests that this hierarchical organization is probably the key to explaining some of the most remarkable properties of biomaterials.

What is perhaps most surprising is that, in the biological context, the role of defects in weakening materials sometimes gets reversed. For example, one study has shown how cracks in such materials can actually improve their ability to withstand stress. In the context of alpha-helical protein networks (which make up filaments that provide mechanical and structural components within cells), it has been shown that typical geometries include flaws ranging widely in size, which give the material a wide spectrum of energy-dissipation mechanisms operating on different space and time scales. These underlie an extreme stretchiness, as the filaments can stretch up to three or four times their initial length without breaking.

It seems that biology, in hierarchical organization, has found a way to improve durability through the deliberate placement of defects at controlled locations and scales. This goes against anything that might have been guessed on the basis of traditional materials science, and offers some ideas for making artificial materials using similar tricks. Ultimately, it's hard to think of any topic with more far-reaching implications for engineering. ❐

MARK BUCHANAN

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## Correction

In the Thesis article 'Learning from failure' (*Nature Physics* **5,** 705; 2009), the name of Markus Buehler was originally spelled incorrectly. This has been corrected after print in the HTML and PDF versions: 28 October 2009.