of how photoperiodic flowering is controlled by the coincidence of light with circadian timing [the so-called external coincidence model (*1*)].

By analyzing the phenotype of plants with mutations in *FKF1* and *GI*, Sawa *et al*. determined that GI function in photoperiodic flowering does not completely depend on FKF1. Thus, GI may regulate the activity of other ZTL-FKF1-LKP2 family members or that of additional proteins controlling circadian clock functions. The demonstration of such a possibility comes from a complementary study by Kim *et al*. (*3*) describing the relationship between GI and ZTL. Kim *et al*. show that GI interacts with ZTL in plants and that ZTL-GI complex formation is, as in the case of FKF1, triggered by blue light. Interaction between GI and ZTL cooperatively stabilized both proteins, thereby increasing their accumulation. This increase consequently amplified and sharpened the rhythmic expression profile of the clock protein TOC1, thus providing the clock oscillator with the robustness necessary to maintain proper circadian rhythms.

Both Sawa *et al*. and Kim *et al*. provide mechanistic views on how day-night cycles shape circadian clock oscillations and how light is integrated into the clock to precisely regulate expression of a gene (*CO*) that controls flowering. The studies raise many questions: What factors control ZTL, FKF1, and GI stability? What role(s) do other light receptors (phytochromes and cryptochromes) play in controlling light signaling to the clock? Are there more targets for the GI-containing complexes? These insights will help us to better understand why plants see changes in seasons by standing on the shoulders of GIGANTEA.

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MATERIALS SCIENCE

Crackling Wires

Wires bend through a series of tiny avalanches as defects move through the material.

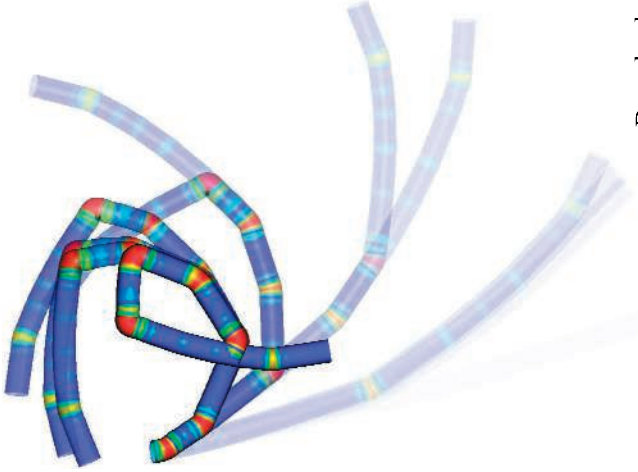
James P. Sethna

Take a paper clip, and pull one of the ends sideways. If you pull gently and release, it will elastically rebound to its original shape like a spring. If you pull harder, it deforms permanently into a new shape, a process called yielding. On page 251 of this issue, Csikor *et al.* (*1*) provide convincing theoretical evidence that, rather than a smooth process, yielding is like a phase transition that consists of a series of small avalanches. These avalanches not only provide the microscopic underpinnings we need to build theories of how ordinary-sized objects bend, but Csikor *et al.* further argue that the avalanches become crucial problems for controlling bending on micrometer and nanometer scales (see the figure).

Phase transitions are either abrupt or continuous. For example, the melting transition (solid to liquid) and the boiling transition (liquid to gas) are usually abrupt; water is water until at 0°C it turns to ice. Brittle materials respond to external stress in a similarly abrupt fashion; a piece of glass will bend elastically until abruptly it breaks in two. In contrast, magnets gradually reduce their magnetization as they are heated, with the magnetization smoothly going to zero at the critical temperature. Superconductors, superfluids, and some liquid crystals also change phases in a continuous fashion. Near continuous phase transitions there are dramatic fluctuations; the material doesn't know which phase to choose, so it wanders in space and time among its options.

In the past few decades, physicists found that the characteristic features of continuous thermodynamic (temperature-driven) phase transitions are also found at so-called depinning (force-driven) transitions—continuous transitions between a stuck ("pinned") and moving phase as an external force is increased. Depinning has been studied in many systems (*2*, *3*): charge-density waves in electric fields, fluids invading porous media (milk being poured into breakfast cereal), tearing of paper, superconductors with large currents, and domain walls in magnets. Here the fluctuations near the transition take the form of avalanche-like motions, resulting in crackling noise (*4*). A good example is provided by the response of the Earth's crust to the motion of the tectonic plates—earthquakes are avalanches driven by the forces across fault lines. If you speed up the seismic recordings of earthquakes from 1 year to occupy a single second, they sound like crackling noise (*5*). The characteristic power-law distribution of earthquakes, with many small ones and few large ones, has analogs in all of these other depinning systems.

What about paper clips? The yielding of crystals can be viewed as the depinning of tangles of dislocation lines (flaws in the crystalline lattice structure). But rather than concentrating on deformation of materials, physicists have focused on relatively obscure cases



Miniature avalanches. Csikor *et al.* predict that bending a 0.1-μm-wide aluminum wire will be an irregular, jerky process, dominated by a few large dislocation avalanches that span the width of the wire. The different images show the progression of bending. The color scale shows the local amount of deformation (blue is low, red is high). Note that the red regions are introduced one by one (individual avalanches).

CREDIT: IMAGE BY BRYAN DANIELS/CORNELL UNIVERSITY, BASED ON DATA FROM CSIKOR *ET AL.* (*1*)

The author is in the Laboratory of Atomic and Solid State Physics, Cornell University, Ithaca, NY 14853, USA. E-mail: sethna@lassp.cornell.edu like magnetic vortex motion in superconductors and sliding of charge-density waves. Why is this? Surely the deformation of metals would rank just below earthquakes in the list of important depinning problems to study.

First, deformation of crystals seemed complicated. Yielding in solids is microscopically more complicated than in these other systems; studying avalanches of dislocation lines (each with a Burgers vector indicating the direction and magnitude of the dislocation, a slip plane, and a long-range interaction with all of the others) is daunting both analytically and numerically. Second, deformation seemed different from other phase transitions. The yield stress (the force per unit area at which the material begins to deform) depends on the deformation history. Roughly speaking, it grows to equal the previous peak stress, because the yielding leads to tighter dislocation tangles, resisting further deformation (a phenomenon called work hardening). In contrast, the freezing point for water doesn't rise as the water heats. We should have understood work hardening as an example of self-organized criticality (*6*); the dislocations moved as far as they could under the previous stress, so they start moving again (the new yield stress) at the historical stress maximum. And finally, physicists were ignorant of the fluctuations. Textbooks treat the yielding of solids as a smooth process—oozing, not crackling.

Recent experiments in ice and recent simulations in two dimensions (*7*) show clear evidence for avalanches and crackling noise during yielding—completely analogous to that seen in earthquakes, magnets, and other depinning systems, and in complete contrast to textbook discussions. But why don't we hear crackling noise every time we bend a paper clip? Is yielding in three dimensions different from that in two? Are metals different in some crucial way from ice? (Indeed, ice has a different crystal structure and different allowed dislocations than most structural metals.)

Csikor *et al.* address precisely these last questions, using a large-scale numerical simulation of the dislocation motion, designed to describe yielding in aluminum. Is aluminum different from ice? No, they find an excellent power-law distribution of avalanches; aluminum crackles just like ice. Are there enormous crackles, which should be visible in any experiment? No, they find a cutoff in their avalanche size distribution, and provide a theoretical explanation for their cutoff.

Why are there no large dislocation avalanches? The key observation of Csikor *et al.* is that the avalanches are not three-dimensional objects. They find that the avalanches have a fractal dimension of roughly two (see their figure 2); indeed, their avalanches are fractal versions of the pancake-like lamellar slip models long used by materials engineers. A two-dimensional slipped region of thickness δ extending entirely across a sample of length L can only relieve the strain in a fraction δ/L of the sample. Their theoretical explanation for the cutoff (involving work hardening and the limitations of the measuring device) gives a thickness δ that varies between one and a thousand atomic spacings. The largest avalanches in a centimeter-scale experimental sample (10^8 atomic spacings) will thus have strains of 10 parts in a million—easily ignored in textbooks.

On geological length and time scales, continental drift is smooth; the fact that the motion of South America away from Africa is mediated by earthquakes may not be crucial for theories of plate tectonics, even though it is important to those living near fault lines. Similarly, dislocation avalanches cause jerky bending fluctuations that can be ignored on the scale of automobile fenders and beer cans. But as we bend metals on the micrometer and nanometer scales (such as the wires attaching to computer chips), the irregular, jerky microscopic deformation will become a serious (and interesting) problem.

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MATERIALS SCIENCE

Printing Cells

Paul Calvert

Inkjet printing technology offers a way to create three-dimensional biological structures for studying cell interactions and artificial organs.

Materials scientists and biotechnologists are eager to build three-dimensional structures of cells held together in a tissue matrix. With such structures, researchers could study how cells interact and perhaps fabricate implantable organs. Inkjet printing—essentially the same technology used in desktop printers—is a promising method because it is simple and versatile and avoids contact with the substrate. A number of groups have recently developed inkjet printing of various cell types, so this is a good time to consider what can be done and what remains to be resolved.

There are two main types of inkjet printer. In thermal printers, a pulse of energy boils liquid at the surface of a small heater, and the expanding bubble drives a drop of ink through the nozzle. In piezoelectric printers, an applied voltage pulse causes a glass tube or a bending plate to eject the droplet from the nozzle. Inkjet printers for the low-cost consumer market can use either type of drive, whereas most high-end commercial printers are piezoelectric. A number of researchers, including my colleagues and me, have simply rebuilt consumer printers to replace the paper-feed system with a computer-driven platform to move the sample under the nozzle (*1*).

As might be expected, bacteria and yeast can be readily printed, whereas animal cells vary in their ability to survive the process. In addition to selecting the right cell type, one can use a concentrated buffer solution to shrink the cells and so reduce the possibility of damage in the nozzle. Often a more complex growth medium may be necessary to protect the cells during printing, in which case viscosity may be a limiting factor. Sterility is of course also a major concern in cell viability. Consumer cartridges probably cannot be autoclaved and must be cleaned and washed with alcohol. In addition, the printing equipment must be sterilized and used in a laminar flow hood to avoid airborne contamination.

Recently, for example, Chinese hamster ovary (CHO) cells and motor neuron cells have been printed from 3× concentrated phosphate buffer with a thermal printer (*2*). For the CHO cells, about 20% were damaged during "ink" preparation and a few percent during the printing step. In our work with

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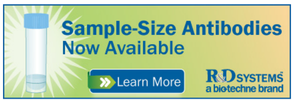
The author is in the Department of Materials and Textiles, University of Massachusetts Dartmouth, North Dartmouth, MA 02747 USA. E-mail: pcalvert@umassd.edu



Crackling Wires

James P. Sethna (October 12, 2007)

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Editor's Summary

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