Pleats are in fashion

I once heard an economist present a novel explanation for the failure of economics to match the predictive certainty of the physical sciences. The reason, he asserted, is that whereas the subject matter of physical science — that is, nature — emerges out of more or less fixed principles, human invention and creativity mean that the nature of economic life is always changing. Every era invents new ideas, goals and products, which often transform the world dramatically; hence, the project to understand economics must perpetually begin anew.

To me, this idea at first seemed convincing, but now I don't think it really makes sense. Not because human innovation doesn't make economics subject to perpetual change, but because it also has the same effect in the physical sciences. To take one example, superconductivity seemed completely understood half a century ago, with the BCS theory standing as a crowning achievement. But the very success of this theory gave theorists new ideas about other possible types of superconductivity. Inevitably, the human mind found its way to the synthesis of new high-temperature superconductors, materials that had never before existed in the Universe, and which present puzzles that remain unsolved today.

Knowledge gives physicists the ability to create novel materials or conditions, and thereby new physics, so that every scientific success creates new problems even as it clears up old ones. An intriguing example, likely to have technological repercussions very soon, comes from the mixing of modern materials science with age-old human thinking about folds, pleats and other features of fabrics.

We all know, of course, that hexagons will easily tile a flat two-dimensional plane completely and perfectly, leaving no gaps. Curve the surface, however, and things become more interesting. How things change, as William Irvine, Vincenzo Vitelli and Paul Chaikin recently described (*Nature* **468,** 947–951; 2010), can best be understood by thinking in terms of crystal defects — flaws induced into the perfect hexagonal tiling to account for the curvature.

Of course, the study of atomic arrangements in two-dimensional solids has a long history. Early in the twentieth century physicists understood that the ideal perfect hexagonal order is broken in real solids by dislocations and other defects, and many

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suspected that the movement of such defects might underlie the plastic deformation of materials. Powerful visual evidence confirming the plausibility of this idea came in 1947, when physicists William Bragg and John Nye first showed how the details of such defects and their dynamics could be explored conveniently using soap bubbles.

Blow many bubbles of the same size onto the surface of a flat soapy film, and they will naturally assemble into a hexagonal array that mimics the hexagonal crystal pattern of atoms in two-dimensional layers. Bragg and Nye showed that applying stress to these 'bubble rafts' would lead to their bulk deformation through the movement of bubble-scale dislocations (see F. Stellacci & A. Mortensen, *Nature* **468,** 906–907; 2010).

These early experiments looked at flat geometries. Deform the surface by curving it, and a perfect hexagonal arrangement of bubbles or atoms also has to give way. Many experiments, for example, have shown that the bubbles, if placed on the surface of a sphere, respond by forming 'scarred' regions where the perfect order breaks down. A curved surface can be more easily tiled if some of the hexagons deform into pentagons or heptagons.

Irvine and colleagues have now taken the characterization of curved two-dimensional crystals much further. In their experiments, they haven't used bubbles, but colloidal crystals formed by small self-repelling plastic particles on a liquid surface. First forming cylindrical capillary bridges between two cover slips, they then stretched them out to produce an increasingly curved surface. In the process, they observed a rich sequence of transitions in which the crystal with initially perfect hexagonal order gives way through the gradual formation of isolated dislocations, which subsequently proliferate and organize together into linear pleats — lines of dislocations that play the same role as fabric pleats in reducing the energy of stress. Finally, with further change in curvature, complex scars and isolated heptagons appear.

These kinds of experiment open up a new world of curved-crystal physics. As Irvine and colleague argue, they offer the opportunity to develop the theory linking curvature and defects, as well as many possible technological applications in the self-assembly of complex materials. In this, they also share the spirit of other recent work exploring folds and pleats in other solids, particularly graphene.

Graphene— formed as a two-dimensional sheet with the structure of graphite — is among the most interesting of modern materials because of its remarkable electronic properties. As Kwanpyo Kim and colleagues have shown in experiments, a single graphene sheet can be folded twice in sequence along distinct, parallel axes, much as one might fold a piece of fabric (arXiv:1012.5426). The result is a triple-thickness region between the two fold axes with highly curved folding edges embedded within the monolayer sheet (they call this a 'regular pleat fold', using the language of the textile industry).

These structures seem to form naturally during the cooling of graphene sheets created by chemical vapour deposition. Kim and colleagues have explored such folded structures in both suspended and supported graphene samples. For example, microscopy shows that the thickness rises abruptly by a factor of three, as it should, on entering the folded zone. Electron diffraction data indicate that the crystal structure also shows three distinct hexagonal lattices in the folded zone.

Importantly, this double-folding modifies the electronic band structure of the graphene sample, creating localized electronic states in the folded regions. Kim and colleagues have also shown how precise control of graphene synthesis should enable the creation of superstructures with desired properties, including "single or periodic hems, pleats, creases, ripples and ruffles". The possibilities are endless for further variation, especially if one imagines the intercalation of specific atoms within the folds to alter local mechanical, chemical, optical or electronic properties.

Again, as in the experiments of Irvine *et al.*, we see a higher world of possibilities never anticipated by the initial science and engineering of two-dimensional graphene sheets. Human innovation creates scientific challenges anew, never an ending, but always a new beginning. ❐

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