for a perfect crystal. This proves that for the best regions of this sample, the number of (995) crystal planes that remain in perfect registry is ~10^7.

As well as its low photoelectric absorption there are several other advantages to using diamond over silicon for X-ray optics. The reflectivity of any atomic plane is impaired if atoms are not at their ideal crystal positions, so any thermal vibrations will reduce the crystal reflectivity. The diamond Debye temperature of ~2,200 K is several times higher than that of silicon, and the combined effect of lower absorption and smaller thermal displacements (through the Debye–Waller factor) leads to the greater than 90% reflectivity in diamond, and to less than 20% reflectivity for comparable reflections in silicon (ref. 5). Although materials research into other low-atomic-number, high-Debye-temperature materials such as BeO, SiC and Al₂O₃ may ultimately lead to competitive high-resolution X-ray monochromator crystals, right now diamond outshines them all. For the goal of achieving the ultimate X-ray laser, hopefully the results of Shvyd’ko et al. will motivate continued efforts towards producing perfect crystals of diamond.

Stephen M. Durbin and Roberto Colella are in the Department of Physics, Purdue University, West Lafayette, Indiana 47907, USA. e-mail: durbin@physics.purdue.edu; colella@purdue.edu

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NONLINEAR DYNAMICS

Spontaneous synchrony breaking

Research on synchronization of coupled oscillators has helped explain how uniform behaviour emerges in populations of non-uniform systems. But explaining how uniform populations engage in ‘chimera states’ — states of sustainable non-uniform synchronization — may prove to be just as fascinating.

Adilson E. Motter

Synchronization phenomena continue to inform and surprise. In classical and quantum physics, the harmonic oscillator is a paradigmatic model both because it describes periodic behaviour found in a wide variety of systems and because it provides insights into more general behaviour. Similarly, the study of networks of coupled oscillatory dynamical entities has a lot to offer for the understanding of emergent behaviour in complex systems. The strongest form of such collective behaviour is spontaneous synchronization, in which the oscillators coordinate their dynamics in a decentralized way. Spontaneous synchronization occurs in diverse contexts, from communities of chirping crickets to arrays of pulsing lasers. Its study has helped explain how heterogeneous entities, such as the cricket populations, can adjust their ‘rhythms’ exclusively as a result of their interactions. Writing in Physical Review Letters, Erik Martens, Carlo Laing and Steven Strogatz now address the reciprocal to this question: they investigate the surprising scenario in which identical oscillators with identical coupling patterns self-organize into subpopulations with different synchronous behaviour.

In a similar way as other forms of collective behaviour, synchronization depends on the properties of the oscillators and on the structure of the network of interactions. But it also depends on the initial state of each oscillator. The latter is at the heart of the study of Martens et al.¹. They consider certain initial conditions that lead to the coexistence of a synchronized and a desynchronized region in arrays of oscillators: a chimera state².

Chimera states are spatiotemporal patterns in which mutually synchronized oscillators — characterized by having identical frequency and hence constant phase differences — coexist with desynchronized ones, which run at different (and not necessarily constant) frequencies. Such states were first reported to exist eight years ago by Kuramoto and Battogtokh³. They are generally observed in systems with finite-range non-local coupling. That is, the oscillators are neither coupled to all the others nor only to first neighbours. Also, all oscillators have the exact same frequency if uncoupled and the coupling is identical for all of them; potential differences owing to boundary effects can be eliminated by considering periodic boundary conditions, in which the oscillators are organized on a circle or on a torus. Given the symmetry of the setting it is not at all intuitive that the oscillators could do anything other than to evolve with statistically equivalent oscillatory patterns or provide support for stationary waves. Yet, stable chimeras can exist even when the state of complete synchronization is stable.

The discovery of chimera states has fundamental implications as it shows that structured dynamical patterns can emerge from otherwise structureless networks. As noted by Abrams et al.⁴, analogous symmetry breaking is observed in dolphins and other animals that have evolved to sleep with only half of their brain at a time⁵. Neurons exhibit synchronized activity in the sleeping hemisphere and desynchronized activity in the hemisphere that is awake. Moreover, because synchronization is believed to play a central part in information processing (and abnormal synchronization may lead to epilepsy), the extent to which local synchronization is determined by the properties of the underlying network is important for the study of neuronal networks in general.

Chimera states need not be frozen — they can propagate as rotating spiral waves. Propagating waves are common in reaction–diffusion systems and have been widely studied in the so-called Belousov–Zhabotinsky reaction systems. There too, the pattern will depend on the initial conditions. But there is something that is unique to the states considered by Martens et al.¹: they are chimea, and therefore have not only synchronized but also desynchronized regions. Simulations in two-dimensional arrays of oscillators have shown that the system can self-organize into a desynchronous core surrounded by a spiral wave of synchronized oscillators⁶. Along the arms of the spiral the oscillators have the same phase — they are phase-locked. In
their study, Martens and colleagues\(^1\) provide the first analytical description that predicts the existence of such spiral-wave chimeras. Therefore, as unusual as these spirals may seem, they cannot be attributed to artefacts of the numerical simulations. Admittedly, Martens et al. obtained their results for a relatively simple system under analytically treatable conditions. This is, on the other hand, also a reason why they are important: they reveal what may well be just the tip of the iceberg.

Open problems abound. The characterization of the basins of attraction associated with chimera states — and, for that matter, the possible attractors — remains widely untouched. For instance, how can one determine whether a given set of initial conditions corresponds to a uniform as opposed to a chimera state? The characterization of the stability of these states as functions of the system parameters also remains fairly under-explored. It is possible that for some parameter choices several coherent formations will coexist or new forms of non-stationary chimeras will emerge. Also, experimental observation of such states in natural systems, neuronal or not, would be particularly informative. Indeed, although chimera states do not need extra structure to exist, they are not destroyed by small disorder either\(^7\). This strengthens the prospects for observing them in real systems. More importantly, additional structure can lead to a myriad of other possible behaviours, including quasi-periodic chimeras\(^8\) and chimeras that ‘breathe’, in the sense that coherence in the desynchronized population cycles up and down\(^7\).

Future research might benefit from two other surprising recent discoveries. First, for several systems of infinitely many non-identical phase oscillators, it has been shown that a wide class of solutions can be reduced not approximately, but exactly to a system described by just a handful of degrees of freedom\(^9\). This has already inspired recent research on chimera states for non-identical oscillators\(^2\). Second, in complex networks of identical oscillators, it has been demonstrated that the stability of globally synchronous states depends sensitively on the structure of the network\(^10\). It is therefore natural to ask about the nature of (partially synchronous) chimera states in such complex networks. If previous experience is anything to go by, one can expect that this research will lead to incongruous yet fascinating new surprises about the dynamics of complex systems.

Adilson E. Motter is in the Department of Physics and Astronomy and at the Northwestern Institute on Complex Systems, Northwestern University, Evanston, Illinois 60208, USA.

e-mail: motter@northwestern.edu

References

GRAPHENE

Switched on

Despite its amazing electrical properties, the fact that graphene is a semimetal — there is no energy gap between its conduction and valence bands — can be a bit of a handicap. The small bandgap in semiconductors such as silicon (small relative to insulators that is) is essential for the operation of transistors and diodes. Jingwei Bai and co-workers have now shown that shaping a graphene layer into a mesh can open up a bandgap large enough for electrical switching (Nature Nanotech. 5, 190–194; 2010).

A bandgap has previously been created in graphene by tearing it into ribbons of less than 10 nm in width. The problem with this approach is that it is not easily scalable to produce arrays of devices. Bai et al. constructed their devices using techniques borrowed from, and therefore compatible with, large-scale semiconductor fabrication. A layer of graphene was coated with protective silica upon which lay a polystyrene film with a hexagonal array of cylindrical pores. Bombarding this with reactive ions transferred the pattern into the silica. A mesh was then created by placing the sample into an oxygen plasma to copy the pattern to the graphene.

The team constructed a transistor by placing the graphene mesh onto a silicon substrate and attaching two electrical contacts. A small current flowed through the device when a voltage was applied across the contacts. However, applying a voltage to the substrate ‘turned on’ the device and enabled a much larger flow, just like in a switch.

The space between the holes in the graphene mesh was crucial to the behaviour of this transistor. Research on graphene ribbons has shown that the bandgap increases with decreasing ribbon width. A similar trend would be expected in the mesh structure, which can be thought of as many ribbons in parallel. This is exactly what the team discovered: the ratio of the on-current to the off-current was 6 in the case of 15-nm-wide channels, but increased to 100 in a device in which the space was just 7 nm.

There are a number of effects that could open a bandgap in this way: localization of the electrons at the newly created edges open a bandgap in this way: localization of the electrons at the newly created edges of the material, for example, or the small bandgap for future work.

DAVID GEVAUX