region where the system spontaneously chooses between left- or right-handed motion (Fig. 1c). This feedback effect is the key to 'Berryogenesis' — the spontaneous generation of a Berry flux.

There are two main requirements for an experimental realization of a graphene plasmonic device[8,9] such as that proposed by the authors. The first is what prevents Berryogenesis, which relies on the coherent effects of the driving on the states, from being obscured by dissipative effects. To circumvent this problem, Rudner and Song chose a frequency corresponding to an energy less than twice the Fermi energy so that direct photon absorption was prevented by Pauli blocking. The other important point for this self-Floquet effect relies on having a strong enough internal response of the material, such that it overrules the external field. The threshold driving amplitude is controlled by the plasmonic quality factor.

For the quality factors exceeding 100 that have been reported for graphene plasmonic devices[9], the authors estimated that at a driving frequency of 25 THz with a moderate intensity of about 30 W cm^{-2} on a disk of 100 nm in diameter a magnetic field of hundreds of nanotesla would be generated, which is detectable with modern techniques.

Berryogenesis marks a non-equilibrium phase transition to a situation in which a self-sustained plasmonic motion spontaneously breaks the mirror symmetry of the system. In contrast to conventional ferromagnetism, spin does not play a role in plasmonic magnetism[4]. Taking a broader view, tapping into the internal response of a material under non-equilibrium conditions might uncover a treasure trove of new physics, where long-sought-after spontaneous symmetry-breaking transitions, such as driving-induced zero resistance, could be waiting. ❐

Luis E. F. Foa Torres
Department of Physics, Faculty of Physical and Mathematical Sciences, University of Chile, Santiago, Chile.
e-mail: luis.foatorres@uchile.cl

https://doi.org/10.1038/s41567-019-0595-4

References

1. Oka, T. & Aoki, H. *Phys. Rev. B* **79**, 081406(R) (2009).
2. Lindner, N. H., Refael, G. & Galitski, V. *Nat. Phys.* **7**, 490–495 (2011).
3. Kitagawa, T. et al. *Phys. Rev. B* **84**, 235108 (2011).
4. Rudner, M. S. & Song, J. C. W. *Nat. Phys.* https://doi.org/10.1038/s41567-019-0578-5 (2019).
5. Perez-Piskunow, P. M., Usaj, G., Balseiro, C. A. & Foa Torres, L. E. F. *Phys. Rev. B* **89**, 121401(R) (2014).
6. Wang, Y. H., Steinberg, H., Jarillo-Herrero, P. & Gedik, N. *Science* **342**, 453–457 (2013).
7. McIver, J. W. et al. Preprint at https://arxiv.org/abs/1811.03522 (2018).
8. Koppens, F. H. L., Chang, D. E. & Javier García de Abajo, F. *Nano Lett.* **11**, 3370–3377 (2011).
9. Ni, G. X. et al. *Nature* **557**, 530–533 (2018).

BIOLOGICAL OSCILLATIONS

Locked body clocks

Synchronization can induce both order and disorder, betraying a multistability that is rife in living systems. Evidence now suggests that the circadian clock synchronizes with the cell cycle, and that this behaviour is common to different species.

Mathias L. Heltberg and Mogens H. Jensen

The cell cycle and the circadian clock are two of the most fundamental oscillators in biology, although they operate on quite different timescales: the circadian clock relates to daily rhythm whereas the cell cycle acts on scales ranging from minutes to hours. In spite of this difference, there is some — albeit limited — evidence to suggest that these two clocks might influence each other. Now, writing in *Nature Physics*, Colas Droin and colleagues have undertaken a thorough investigation of this interaction, reporting convincing observations of synchronization effects between the two clocks[1].

Studies of synchronization between oscillators have a long history — the coupling of clocks was one of the first nonlinear problems to be thoroughly investigated and described. The phenomenon was first observed as far back as 1665 by the Dutch physicist Christian Huygens, who was also a renowned manufacturer of pendulum clocks. During a bout of serious illness that left him confined to his bed, he observed that the numerous pendulum clocks on his wall tended to synchronize, and that even those whose frequency initially differed eventually oscillated with a mutually compromised frequency. He realized that this mysterious interaction was mediated by vibrations through the wooden walls.

In biology, there are a number of different oscillatory phenomena that should, in principle, have a similar ability to synchronize. Droin and colleagues combined mathematical modelling and precise experiments to test this idea in the context of the circadian clock and the cell cycle. They predicted and measured the phase shifts for the 1:1 and 1:2 synchronization of the two clocks, and looked at how this synchronization was influenced by the presence of noise, as well as how it might be modelled stochastically.

Interestingly, they observed that the interaction was independent of temperature, which is surprising because temperature can affect the timescales of cell divisions, implying the cell-cycle clock is temperature dependent. They also found that this entrainment between oscillations was conserved across different species, which indicates that there might be a fundamental mechanism underpinning the nature of the coupling.

Why is it that oscillators can synchronize and what are the mechanisms behind such a nonlinear interaction? Following Huygens's pioneering work, Henri Poincaré and Andrey Kolmogorov founded the mathematical theory of coupled oscillators around 1900. But the first successful explanation of the theory didn't come until much later, in the groundbreaking work of Vladimir Arnold. By considering the dynamics through a so-called Poincaré section, Arnold obtained discrete maps representing a convenient scheme to investigate the fundamental properties of the synchronization between two oscillators. This type of discrete model possesses only two parameters, the ratio of the oscillation periods in the absence of coupling and the coupling strength between the oscillators[2].

Without any interactions, the two oscillators run completely independently of one another and do not exhibit any form of synchronization. However, as the coupling strength increases, regions

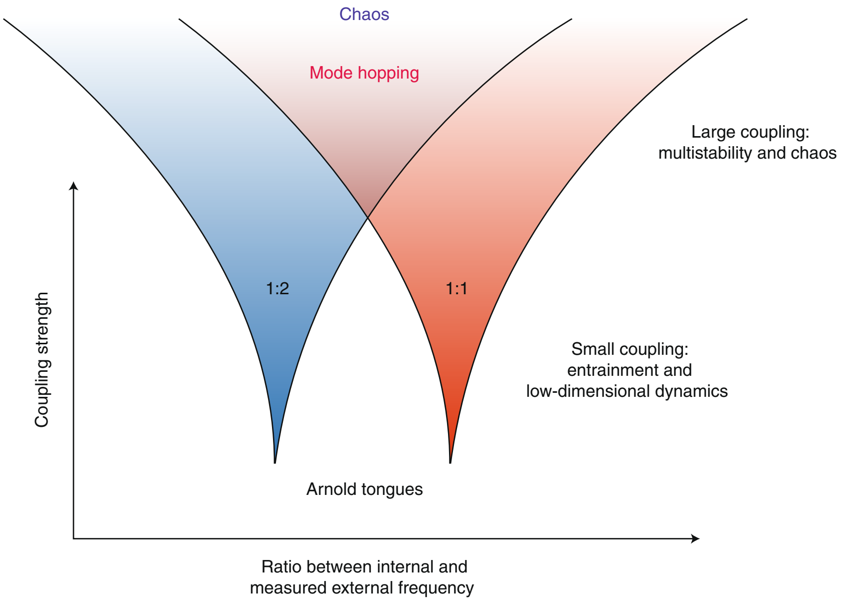

Fig. 1 | Arnold tongues represent the regions of synchronization of coupled oscillators. For small coupling strength, they describe regions of entrainment and low-dimensional dynamics, but when the interaction grows large, multistable cycles, mode hopping and chaos can occur. The 1:1 and 1:2 tongues indicate entrained states, where the numbers refer to the frequency of the external oscillator and the internal oscillator. In this way, 1:2 means that every time the external oscillator makes one rotation, the internal oscillator makes two rotations. Likewise, 1:1 means that the oscillators are synchronized in frequency.

of synchronization emerge and the ratio between the two oscillations assumes some rational number — the smaller the denominator, the larger the region of synchronization. In the parameter space spanned by the ratio of the oscillation periods and the coupling strength, these regions are known as Arnold tongues (Fig. 1). As the coupling strength between the two oscillators increases, the width of the Arnold tongue also grows. The typical set-up in a physical or biological experiment would comprise an internal oscillator (such as a wave or a variation in the protein levels in a cell) and an external oscillator controlled from outside[3,4].

The existence of these tongues in nature has been shown in numerous experiments across very different fields, from fluids to the dynamics of proteins inside cells. If the coupling strength is strong enough, the tongues can start to overlap, leading to multistable solutions and — for even stronger coupling — chaotic dynamics (Fig. 1). Synchronization thus can cause both increased order and the disappearance of order in terms of chaos, so it's natural to think that this framework might be useful for describing the complexities of living systems.

Multistable solutions have been studied in cells subjected to a cell signalling protein known as tumour necrosis factor, which induces sustained oscillations of another protein involved in the transcription of DNA into RNA. Externally affecting oscillations in the concentration of this factor results in the appearance of several overlapping Arnold tongues[3], which can induce the cell to switch between high and low production of certain genes[4]. The appearance of chaotic dynamics can similarly cause some genes to increase their production while others become silent[5].

The study carried out by Droin and colleagues demonstrates the surprising robustness of synchronization between two oscillators of very different nature. Through carefully conducted experiments, the authors have provided convincing evidence for this coupling, and by showing that the relation is conserved across different species, they have written a new chapter in the story of how nonlinear coupling mechanisms can be of fundamental importance to our understanding of living systems. ❐

Mathias L. Heltberg[1,2] and Mogens H. Jensen[1]*

[1]Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark. [2]Laboratoire de Physique Theorique, Ecole Normale Superieure, Paris, France.
**e-mail: mhjensen@nbi.ku.dk*

https://doi.org/10.1038/s41567-019-0617-2

References

1. Droin, C., Paquet, E. R. & Naef, F. *Nat. Phys.* https://doi.org/10.1038/s41567-019-0598-1 (2019).
2. Jensen, M. H., Bak, P. & Bohr, T. *Phys. Rev. A* **30**, 1960–1969 (1984).
3. Tay, S. & Kellogg, R. *Cell* **160**, 381–392 (2015).
4. Heltberg, M. L., Krishna, S., Tay, S., Kellogg, R. & Jensen, M. H. *Cell Syst.* **3**, 532–539 (2016).
5. Heltberg, M. L., Krishna, S. & Jensen, M. H. *Nat. Commun.* **10**, 71 (2019).

STRONG-INTERACTION MATTER

Fireball spectroscopy

The visible mass in the Universe emerged when hadrons — the building blocks of atomic nuclei — formed from a hot fireball made of quarks and gluons. This mechanism has now been investigated in baryon-rich matter at relatively low temperatures.

Ralf Rapp

It is fascinating that temperatures that were last present a few microseconds after the Big Bang can be recreated in the laboratory by colliding atomic nuclei at high energies[1]. In these collisions, fireballs of strongly interacting or quantum chromodynamics (QCD) matter are formed. However, they only last for a short time before disintegrating into thousands of