between temperature and ring width is dominated by the negative impact of the warmer months (May to July). This not only shows that the dynamics of wood formation, and the amount of wood produced, changes during the growing season, but also indicates that warmer temperatures can have different effects depending on the time of the year (for example, stimulating wood growth in spring, but hindering it in summer). As shown by studies monitoring wood formation[5], the ring-widening process follows a bell-shaped curve that peaks around the summer solstice. Therefore, an early start of growth will make only a minor contribution to the final annual ring width.

Two elements further complicate efforts to associate the timing of leaf development (leaf phenology) with the dynamics of tree-ring formation. First, the ability to transform the carbon captured by leaves into woody structures depends on a process called xylogenesis, which occurs in a tissue called the vascular cambium and generates wood cells for water transport, mechanical support and storage of reserves, including water and carbon. In other words, carbon acquired through photosynthesis can be converted into woody biomass only to the extent that xylogenesis allows[6]. Moreover, there is a high degree of autonomy between the carbon sinks and sources, thanks to the role of carbon reserves that accumulate in wood tissues. In addition, coarse roots and branches (which also contain large quantities of carbon) might exhibit different growth dynamics from the stem[7].

Second, at a seasonal scale, growth encompasses two distinctive processes involved in wood formation[8]: on the one hand, cell proliferation and enlargement are responsible for growth in terms of size; on the other hand, cell-wall thickening and deposition of complex organic polymers called lignins are responsible for growth in terms of weight. To add to the complexity, these two processes exhibit different dynamics and are related to different environmental factors — their seasonal maxima synchronize with the maximum length of daylight (photoperiod) in the case of growth in size, and with temperature for weight gain[5].

Dow and colleagues' study provides evidence that warmer springs have advanced the leaf emergence of temperate deciduous forests but have not substantially increased their wood production. This suggests that the extra CO_2 uptake does not contribute to sustainable carbon sequestration in the trunks of long-lived trees. The fate of this extra carbon is unknown, but another group has proposed that carbon taken up by trees might be directly emitted back into the atmosphere[9].

The results obtained by Dow *et al.* challenge our current representations of carbon allocation in trees, and contradict certain projections from dynamic global-vegetation models, which are essential tools for assessing and interpreting the responses of terrestrial ecosystems to global changes and their feedback to the climate system. These models generally assume that plant growth depends principally on the amount of sugar produced by photosynthesis (but see ref. 10, for a contrasting example). However, different climatic factors influence photosynthesis and xylogenesis — mainly sunlight intensity and CO_2 concentration for photosynthesis, and temperature and water availability for xylogenesis[11]. We think that current insights into the process of wood formation and its sensitivity to environmental factors can help efforts to reformulate vegetation models[12]. Such insights might improve the structure and outputs of these models, and enhance our knowledge about the carbon cycle and the climate system[13].

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Condensed-matter physics

Carbon's lesson from a heavy friend

Aline Ramires

Electrons in a pure-carbon material display properties that are reminiscent of those in heavy-element compounds. A model inspired by this link hints at how a single-element material can exhibit complex electronic behaviour.

Carbon is a special element: it exists as diamond, the hardest natural material, but also as graphite, which is fragile enough to slide from pencil tip to paper with minimal pressure. Graphite comprises stacks of single layers of carbon atoms, and each sheet, known as graphene, has exceptional properties[1]. When two sheets are twisted relative to each other by a 'magic' angle, a plethora of phases of matter arises[2,3]. Finding such wide-ranging phenomena in a single elemental material is surprising, because such complexity is usually reserved for systems with complicated structures and composition. Writing in *Physical Review Letters*, Song and Bernevig[4] report that a model for magic-angle twisted bilayer graphene can be mapped to a model for materials containing heavy elements, in structures that are much more complex than that of graphene.

Heavy-fermion materials (or, simply, heavy fermions) are compounds containing elements that are found near the bottom of the periodic table — most commonly, cerium, ytterbium or uranium (Fig. 1a). These elements have electrons (which are particles known as fermions) that are highly localized, meaning that they can access only a very small region around the nucleus of a given atom. The strong interactions between localized electrons, and the mixing of these electrons with the delocalized electrons of other atoms, generates hybrid electrons that behave as though they have masses that are up to 1,000 times that of an electron at rest[5]. These interactions also give rise to a range of intriguing behaviours that make heavy fermions key materials for studying phenomena such as magnetism, superconductivity (the ability of a system to conduct electricity without loss) and phase transitions[5].

By contrast, the electronic properties of graphene are dominated by delocalized electrons, suggesting that heavy fermions and graphene systems have little in common. But twisted bilayer graphene has a

certain complexity that brings the two systems closer together. When two layers of graphene are twisted relative to each other, their crystal lattices overlap to give an interference pattern of light and dark patches known as the moiré effect (Fig. 1b). This kind of pattern will be familiar to anyone who has taken a digital image of a computer screen and noticed periodic artefacts on the image. For small angles, the moiré length (the distance between the dark patches) can be large, and in twisted bilayer graphene it can span thousands of atoms[6]. This means that the smallest repeating unit of the system is much larger than that of heavy fermions.

However, when the angle gets close to a value known as the magic angle, an imaging technique called scanning tunnelling microscopy reveals that the material actually contains localized electrons[7]. At the same time, certain properties, such as strange metal behaviour (electrical resistance that varies linearly with temperature[8]) and superconductivity[2,3], suggest that the material still contains delocalized electronic states. So the parallels between magic-angle twisted bilayer graphene and heavy fermions begin to emerge: the two systems display characteristics that are associated with both localized and delocalized electrons.

Aside from the appeal of comprising only a single element, twisted bilayer graphene is an attractive prospect for materials research because it is easily engineered to display various properties on demand. This applies to other 2D materials, too, in which various combinations of stacking and twisting can lead to diverse behaviours. In this context, twisted trilayer graphene[9] and twisted layers of semiconductor materials containing transition metals and chalcogen elements[10] have already been proposed to emulate heavy fermions. Now, Song and Bernevig have used the fact that magic-angle twisted bilayer graphene contains both localized and delocalized electrons as inspiration for a theoretical model that maps it directly to heavy fermions.

Describing magic-angle twisted bilayer graphene in terms of heavy fermions addresses some of the challenges associated with developing a theory for this material. The large moiré length makes it challenging to evaluate the exact electronic behaviour computationally, because the smallest repeating unit includes an extraordinary number of electrons. Furthermore, the geometry of the moiré pattern makes it impossible to construct a model based on atomic-like orbitals that correctly approximates the electronic behaviour[11].

Song and Bernevig's mapping offers a more pragmatic approach than do these brute-force methods, by associating the strongly interacting electrons in magic-angle twisted bilayer graphene with localized electron states, in analogy with those in heavy-fermion compounds. Still, the presence of these strong interactions leaves physicists with a challenge.

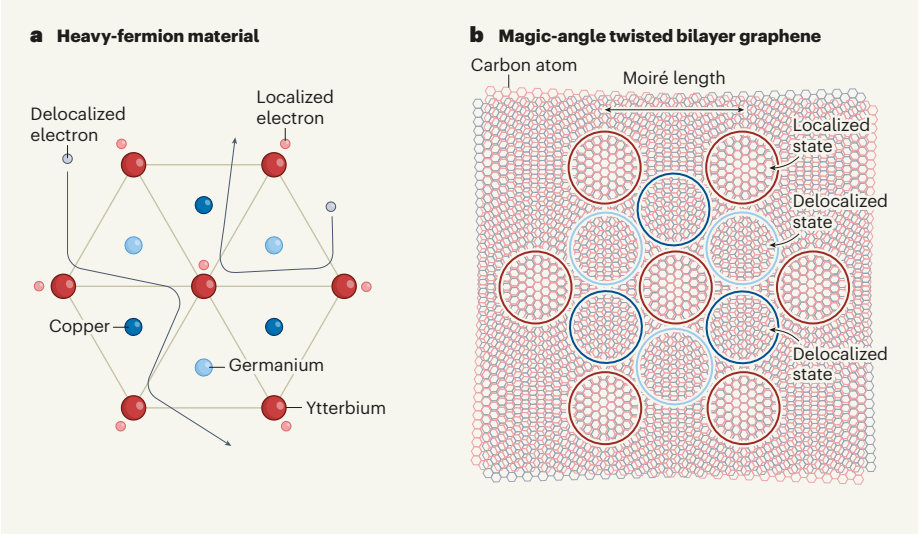

Figure 1 | Parallels between a carbon-based system and a heavy-fermion material. a, Heavy-fermion materials are compounds that contain heavy elements such as ytterbium (Yb), as well as lighter elements, such as copper (Cu) and germanium (Ge). The top view of the 3D structure for YbCuGe is shown here. The electrons associated with the heavy elements are localized (they can access only a very small region around the nucleus of a given atom), but they can mix with the delocalized electrons of other atoms (arrows show movement of these electrons). **b**, The electronic properties of graphene, a single layer of carbon atoms arranged on a honeycomb lattice, are dominated by delocalized electrons, but some electrons become localized when two sheets of graphene are twisted relative to each other by a 'magic' angle. The crystal lattices of the sheets overlap to make a pattern of localized and delocalized states that is reminiscent of the pattern in YbCuGe, albeit on a different scale, known as the moiré length. Song and Bernevig[4] used this parallel to map the theory for heavy-fermion materials to that for magic-angle twisted bilayer graphene.

Intriguingly, the similarities between magic-angle twisted bilayer graphene and heavy fermions seem to go beyond the properties of the electrons. Both systems exhibit multiple phases that can be tuned by external parameters, as well as strange metal behaviour[8] and superconductivity[2,3]. In this light, Song and Bernevig's mapping poses new questions, such as whether there is a fundamental distinction between magic-angle twisted bilayer graphene and heavy fermions, given the extremely different length scales associated with their localized electrons.

"The similarities between the two systems seem to go beyond the properties of the electrons."

It also raises the question of whether there are experimental signatures to indicate that a heavy-fermion-like state develops in magic-angle twisted bilayer graphene through a similar mechanism to that seen in heavy-fermion materials[5]. If this is the case, a theoretical estimate of the energies involved and an experimental investigation of this mechanism would be highly desirable. Finally, have we learnt anything from heavy-fermion superconductivity that could be useful in the context of magic-angle twisted bilayer graphene?

Song and Bernevig's work proposes an intuitive and faithful description of an interacting model for magic-angle twisted bilayer graphene, and establishes a deeper connection between 2D systems and heavy fermions, a family of materials characterized by strongly correlated electronic behaviours. Although this connection has been hinted at previously in experiments[12,13], the theoretical proposal offers a surprising simplicity. It is a welcome opportunity to foster stronger ties between researchers studying 2D systems and those investigating heavy-fermion materials.

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