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Twenty years of 2D materials

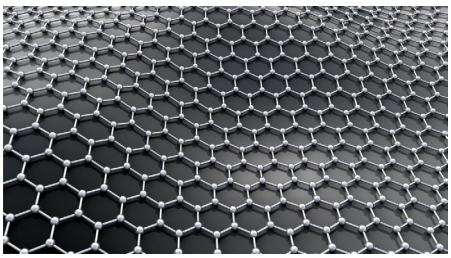
Two-dimensional crystals have revolutionized fundamental research across a staggering range of disciplines. We take stock of the progress gained after twenty years of work.

In 2004, a group of experimentalists published a paper in *Science*[1] that included an atomic force microscopy image of a micron-sized monolayer of carbon atoms that had been exfoliated from a larger chunk of graphite — this was graphene. In the following twenty years, the study of this and other two-dimensional materials ballooned into a field that continues to inspire researchers from condensed-matter physics, optics and photonics, chemistry, applied physics, and many other disciplines besides. To celebrate this anniversary, we look back at some of the achievements and open challenges in the field of 2D materials.

In some ways, the isolation of the first flakes of graphene and other two-dimensional crystals was a surprise. There was a long-standing prediction that they should not be structurally stable — thermodynamic arguments suggested that such materials should be unstable to thermal fluctuations. But a combination of the nuances in that argument and the stabilizing role of an underlying substrate eventually won the day.

The initial synthesis technique was also disarmingly simple: the exfoliation process essentially involved peeling random flakes from the top of a bulk crystal using sticky tape, depositing them on a substrate, and searching for the thinnest ones with an optical microscope. Clearly this was not a very scalable process, but it was efficient enough that it could be done in basically any lab in the world.

From a fundamental point of view, the most fascinating thing about graphene is its electronic properties. Before its synthesis, the vast majority of materials that people in condensed-matter physics studied had a quadratic low-energy band structure. But graphene was different: its low-energy band structure was almost perfectly linear, meaning that



electrons in the material mimicked the Dirac equation. Suddenly, an analogue of relativistic physics was available in tabletop experiments. This was effectively confirmed in 2005 when two groups showed that the properties of this material in a strong magnetic field perfectly imitated Dirac-like particles[2,3].

Another category of 2D materials that have been similarly successful to graphene were the transition metal dichalcogenides in the tungsten and molybdenum family, which were first reported in monolayer form as early as 2005[4]. These have since been employed in a huge amount of work on optoelectronics and photonics. One reason for this is that the reduced screening that is inherent to a 2D geometry (the field lines for interactions between electrons can reach out into the 'vacuum' above and below the flake) means that the exciton binding energy is much larger than in 3D materials. This led to the identification of a veritable zoo of excitonic states (some with surprisingly long lifetimes) that have great potential for optoelectronic device applications.

Contrary to the apparent prediction of the Mermin–Wagner theorem, monolayers of materials such as CrI_3 exhibit strong magnetic states that can be controlled electronically and optically, and which therefore have promise for applications in spintronics. Materials such as $NbSe_2$ have also provided a lot of insight into superconductivity in two dimensions and the unusual phase transitions into and out of that phase.

But it is not just the electronic properties of two-dimensional materials that have found potential applications. Being just a monolayer sheet, these materials have an astronomical surface area to mass ratio, suggesting that they could be excellent catalysts. There has also been much work to employ them as battery materials, as the relevant ions have a large surface to adhere to. The fact that graphene is both metallic and soluble means that it can be used in conducting inks for printing electronic circuits at very low cost.

More recently, the ability to create structures where a moiré pattern emerges from the effective interaction between two adjacent 2D layers has sparked a new wave of fundamental interest. Initially, researchers realized that fractal structures in the electronic properties could be observed, but the scope of studies have now expanded to examine topological strongly correlated phases. Heterostructures of twisted transition metal dichalcogenides are now employed in quantum simulations of the Hubbard model, and many of the features of that paradigmatic framework are now open for experimental study.

Perhaps the only disappointing thing about the last twenty years of two-dimensional materials is that they have yet to make a large impact in commercial products (graphene-infused tennis rackets and running shoes notwithstanding). There have been some products brought to market, although they mainly rely on the mechanical properties of multi-layer materials, rather than their electronic properties. However, the ERC's Graphene Flagship — which had the explicit intention to " bring graphene innovation out of the lab and into commercial applications" — did not achieve as much as its participants probably hoped it would, as its stated aim was to see impactful commercialization in the early 2020s.

So, while there are undoubtedly many more fundamental physics problems to solve in two dimensions, the next big challenge is to make these wonder-materials truly useful for society.

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