Graphene has become a household name over the last decade, but the truth is that there are many other allotropes of carbon and other elements that have equally exciting properties, the applications of which extend beyond even those of the original wonder material itself.

MORE THAN 10 years after the isolation of graphene, materials science abounds with a seemingly endless array of ‘wonder materials’ based on elemental 2D sheets; stanene, germanene, silicene, phosphorene, arsenene and antimonene have followed so quickly on one another’s heels, it is hardly surprising that the conventions used to name them have been so inconsistent. What is more, many of these sheets exceed graphene in terms of their properties: stanene, composed of tin atoms, is a better conductor of electricity; and silicene, though unstable, may be more promising as a transistor because of its tuneable band gap.

Each of these ‘-enes’ represents one possible allotrope of the element in question – one possible arrangement of its atoms into a molecule. Because carbon has only four electrons in its outer shell, the element has a comparatively high valence of +4 and can therefore form a number of allotropes that occur naturally – including coal, diamond and graphite. The structure of these substances at an atomic level determines their differing properties, and the same is true for graphene, in this molecule, carbon atoms bind to one another in a hexagonal honeycomb, with three bonds apiece. The free electron that each atom has left over is what makes the material such a great conductor.

Alongside a range of materials that share graphene’s 2D sheet-like form based on elements other than carbon, there is a multitude of nanostructures based on 2D carbon but with different characteristics caused by minute variations in their atomic arrangements. In fact, many of these structures were discovered long before graphene was isolated.
BUCKYBALLS

Buckminsterfullerene, a spherical carbon molecule made up of 60 atoms arranged in 12 pentagonal and 20 hexagonal rings, was first discovered in 1985, decades before graphene itself was isolated. Its discoverers Harold Kroto and Richard Smalley named it after the celebrated American architect Buckminster Fuller, and were also responsible for highlighting its novel properties. Among other potential applications, buckyballs – or spherical fullerenes, as they are generally known – are useful for encapsulating other atoms, and have been suggested as potential inhibitors of allergic reactions and the mechanisms of HIV, as well as possible components in solar and hydrogen cells.

Although the classic buckminsterfullerene has 60 carbon atoms, there are many larger buckyball configurations that can work – and other elements can form similar structures as well. The 40-atom boron buckyball, which was demonstrated in 2014, does not mirror the original’s football-like shape, it is more like an incomplete cage of triangles, with six evenly spaced hexagonal gaps. Using boron atoms to construct the fullerene makes the end result more reactive than its carbon counterpart, which opens the door to possibilities like joining these fullerenes together in larger structures, or adding atoms or molecules to functionalise them.

NANOTUBES

Carbon nanotubes were also isolated long before graphene – as early as the mid-20th Century – but only achieved recognition within the general scientific community in 1991 with their observation by Sumio Iijima in the soot of arc discharge at Japanese company NEC. These tiny tubes have myriad applications, especially in the field of optics, since radiation including visible light can easily become caught inside them. Vantablack, for example, is a material developed in 2014 which is currently the darkest known to man; made out of multitudes of nanotubes grown in parallel, this substance absorbs 99.965 per cent of visible light and traps it, allowing it to break down into heat over time. Nanotubes also have mechanical applications; because they can move against one another with no friction, concentric or multi-walled carbon nanotubes could be used to fabricate extremely small motors and other parts.

Silicon has a similar valence to carbon, and is also able to form nanotubes; albeit using more complex and expensive methods than those commonly used to generate their carbon counterparts. These silicon nanotubes may be more useful than carbon nanotubes in the storage of energy and fabrication of miniaturised, next-generation batteries. However, the expense currently associated with their production keeps research on this front purely theoretical for now.
COMPOUND INTEREST

Many novel 2D and 1D materials are based on single elements, but a structure does not need to be composed of only one element to have interesting properties. Molybdenum disulphide, for example, has been conjugated into 2D sheets that are likely to be highly suited to biosensing applications – more so than graphene, which is less scalable, less sensitive and more difficult to manufacture towards this purpose. Molybdenum disulphide can also form fullerenes, nanotubes, nanoribbons and nanowires. Boron nitride, likewise, can form stronger nanotubes than carbon, and may be protective against certain kinds of radiation. Perhaps most promising of all are the nanotubes formed by titanium dioxide, which are close to use in new, fast-charging lithium-ion batteries and advanced solar cells.

NANORIBBONS

The synthesis of nanotubes, even carbon ones, can be very complicated indeed, usually involving either laser ablation, chemical vapour deposition or the use of a plasma torch. Nanoribbons, however, can easily be made by slitting a nanotube down the middle and unwrapping it. These extremely thin strips of carbon, only a few atoms across, constitute one of the element’s most basic allotropes. They also offer interesting possibilities in the context of electronics, since they allow for the ballistic transport of electrons; usually, the movement of electrons is affected by scattering as the particles make contact with impurities in the conductor, but this is not the case with graphene nanoribbons. Because the material is almost 1D, electrons encounter almost no resistance. Interesingly, the electronic properties of the nanoribbon are governed by its edges; if the hexes making up the edge are joined vertically at their top and bottom sides, then the nanoribbon is said to be in a zigzag configuration, whereas if they join horizontally to their right and left sides it is said to be in an armchair configuration.

Boron nanoribbons also offer promising energy-conducting properties, although theirs are more attuned to thermal rather than electrical energy. Unlike other non-metallic nanostructures, which lose their ability to conduct heat when they are brought together in groups, boron nanoribbons are actually more conductive when bundled together. Researchers at the University of North Carolina at Charlotte, USA, were responsible for discovering this surprising property in 2011, and also identified the fact that the thermal conduction could be switched on and off by making simple adjustments to the physical layout of the ribbons. There are many applications for this phenomenon in heating systems, as well as in the conversion of waste heat into energy.

NANOWIRES

Nanoribbons exist on a small scale, but nanowires are smaller still. While the former have a width of up to 50 nm, the latter have diameters of around 1 nm. Although still confined to the experimental laboratory, it is hoped that they may one day overtake carbon nanotubes as the most promising candidates in many key applications. Nanowires are far from limited to carbon and in fact can be fabricated using metals like gold, platinum and nickel, or even silicon which produces semiconducting nanowires. In particular, meshes or nanonets of silver nanowire are already being utilised in commercial electronic applications. When creating touchscreens, for example, industry has long been faced with the inconvenient fact that most conductors are opaque – and touchscreens must be both highly conductive and also allow light to pass through them. With potential as touchscreens that are far more advanced than those currently on the market, silver nanowires allow more light to pass between them than the metal oxides currently used, and are better conductors at the same time.