immune regulation". As often happens in biology, both the mechanisms and the efficient induction of the inhibitory processes underlying this type of immunotherapy are still unclear, with ongoing research providing challenges and new perspectives that are driving the development of monoclonal antibodies against additional targets.

Monoclonal antibodies are also being developed to control infectious diseases – following the concept of protective antibodies that goes back to von Behring and Kitasato. Prevalent diseases such as malaria, influenza and AIDS call for the development of what are termed broadly neutralizing monoclonal antibodies, which, applied individually or in cocktails, might provide broad protection[8].

Intensive work in this direction has yielded promising results, including engineering antibody specificity through the substitution of variable domains by ligand-binding domains from non-antibody receptors[9]. Yet the immune system itself uses similar tricks[10] and, by and large, antibody design is still unable to outdo it in terms of generating and selecting antibody specificities[11]. Nevertheless, the manifold modern molecular, cellular and genetic approaches to selecting and engineering antibodies have had, and continue to have, a tremendous impact on the field, whether by producing partly or fully human antibodies of different classes, making bi-specific or toxin-conjugated antibodies for specific therapeutic purposes, or incorporating antibody variable regions into chimaeric antigen receptors on T cells for use in an anticancer treatment called CAR-T cell therapy.

Monoclonal antibodies are nowadays often generated by isolating or transforming antibody-producing cells taken directly from immunized animals or patients, and transplanting the antibody-encoding genes of these cells into suitable producer cell lines, rather than using hybridoma technology[12–14]. But they started their spectacular career in 1975, secreted by hybridoma cells in Köhler and Milstein's SRBC-containing agar plates.

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1. Köhler, G. & Milstein, C. *Nature* **256**, 495–497 (1975).
2. Behring, E. & Kitasato, S. *Dtsch Med. Wochenschr.* **49**, 1113–1114 (1890).
3. Potter, M. & Boyce, C. R. *Nature* **193**, 1086–1087 (1962).
4. Jerne, N. K. & Nordin, A. A. *Science* **140**, 405 (1963).
5. Kearney, J. F., Radbruch, A., Liesegang, B. & Rajewsky, K. *J. Immunol.* **123**, 1548–1550 (1979).
6. Galfrè, G, & Milstein, C. *Methods Enzymol.* **73**, 3–46 (1981).
7. Todorovic, V. *Nature Methods* **14**, 1028–1029 (2017).
8. Walker, L. M. *et al. Science* **326**, 285–289 (2009).
9. Gardner, M. R. *et al. Nature* **519**, 87–91 (2015).
10. Tan, J. *et al. Nature* **529**, 105–109 (2016).
11. Verkoczy, L., Alt, F. W. & Tian, M. *Immunol. Rev.* **275**, 89–107 (2017).
12. Scheid, J. F. *et al. Nature* **458**, 636–640 (2009).
13. Steinitz, M., Klein, G., Koskimies, S. & Mäkelä, O. *Nature* **269**, 420–422 (1977).
14. Traggiai, E. *et al. Nature Med.* **10**, 871–875 (2004).

Materials science

The nano-revolution spawned by carbon

Pulickel M. Ajayan

In 1985, scientists reported the discovery of the cage-like carbon molecule C_{60}. The finding paved the way for materials such as graphene and carbon nanotubes, and was a landmark in the emergence of nanotechnology.

The history of the carbon molecule C_{60} highlights the fact that discoveries do not happen in a predefined sequence. C_{60}, carbon nanotubes and graphene (single layers of graphite) are essentially members of the same family: all are nanoscale structures that consist of carbon atoms arranged in a periodic crystal lattice. Graphite has been known for a few hundred years, and individual layers of the material could be separated easily. However, the identification of C_{60} by Kroto *et al.*[1] did not occur until 1985. This, in turn, led to the discovery of graphene nearly two decades later[2]. Both of these breakthroughs led to Nobel prizes, in chemistry for C_{60} (1996) and in physics for graphene (2010).

The discovery of C_{60} occurred on the campus of Rice University in Houston, Texas. Eiji Osawa, a Japanese theoretical chemist, had predicted[3] the stable structure of a 60-atom carbon molecule in 1970, but this finding did not come to the attention of the mainstream scientific community. Experimental results from mass spectrometry were also beginning to emerge, showing the stability of 60-atom carbon clusters. However, no one made the connection that these clusters would have the structure that Osawa had predicted. It

150 years ago

Aphorisms by Goethe — the opening article of the first issue of *Nature*, 4 November 1869.

Nature! We are surrounded and embraced by her: powerless to separate ourselves from her, and powerless to penetrate beyond her. Without asking, or warning, she snatches us up into her circling dance, and whirls us on until we are tired, and drop from her arms. She is ever shaping new forms: what is, has never yet been; what has been, comes not again. Everything is new, and yet nought but the old ...
So far Goethe.

When my friend, the Editor of NATURE, asked me to write an opening article for his first number, there came into my mind this wonderful rhapsody on "Nature", which has been a delight to me from my youth up. It seemed to me that no more fitting preface could be put before a Journal, which aims to mirror the progress of that fashioning by Nature of a picture of herself, in the mind of man, which we call the progress of Science.

[*In a letter to Chancellor von Müller*] Goethe says, that about the date of this composition of "Nature" he was chiefly occupied with comparative anatomy; and in 1786, gave himself incredible trouble to get other people to take an interest in his discovery, that man has a intermaxillary bone. After that he went on to the metamorphosis of plants; and to the theory of the skull; and, at length, had the pleasure of his work being taken up by German naturalists. The letter ends thus :—"If we consider the high achievements by which all the phenomena of Nature have been gradually linked together in the human mind ... we shall, not without a smile ... rejoice in the progress of fifty years."...

When another half-century has passed, curious readers of the back numbers of NATURE will probably look on *our* best, "not without a smile;" and, it may be, that long after the theories of the philosophers whose achievements are recorded in these pages, are obsolete, the vision of the poet will remain as a truthful and efficient symbol of the wonder and the mystery of Nature.

T. H. Huxley

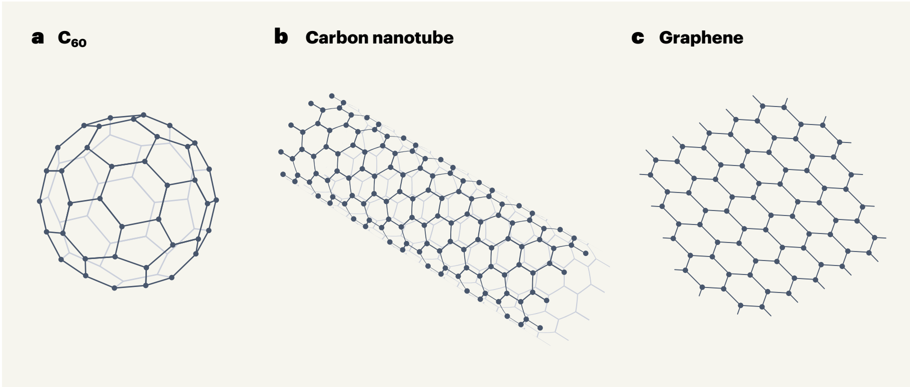

Figure 1 | Three major nanoscale carbon structures discovered in the past 35 years. **a**, In 1985, Kroto *et al.*[1] reported the discovery of the molecule C_{60}. It has a cage-like structure that consists of 12 pentagonal and 20 hexagonal faces. **b**, Following Kroto and colleagues' work, carbon nanotubes were first produced[10] in 1991. A carbon nanotube can be thought of as a 2D hexagonal lattice of carbon atoms that is rolled up to form a hollow cylinder. **c**, In 2004, scientists reported the isolation of graphene[2] – a single layer of carbon atoms in a 2D hexagonal lattice.

was against this backdrop that the visit of the British chemist Harry Kroto to the laboratories of Rice scientists Richard Smalley and Robert Curl proved significant.

Kroto was an expert in molecular spectroscopy and had an interest in the molecules that exist in interstellar space. He proposed a simple mechanism for the formation of the small carbon-chain molecules that had been observed in interstellar gas clouds, and suggested that this idea could be tested using Smalley's experimental apparatus. Smalley, Curl and their students were making many different atomic clusters, such as those of silicon, through ablation – the removal of material from the surface of a target – and were analysing the masses of these clusters in detail. After some delay, Kroto's proposal was accepted and he journeyed to Houston.

In previous work by other groups[4], a peak corresponding to C_{60} was somewhat prominent in mass spectra. During the experiments at Rice to test the mechanism of carbon-chain formation, it became clear that the C_{60} peak could be made extremely strong under certain conditions. However, the structure of the C_{60} molecule was the main puzzle that needed to be solved. The team accomplished this task, and published the first report in 1985.

The structure of C_{60} turned out to be a beauty (Fig. 1a). It looked exactly like the classic design of a football (soccer ball). More precisely, the structure is about 0.7 nanometres across and is a truncated icosahedron – a polyhedron that has 12 pentagonal and 20 hexagonal faces. This highly symmetric, cage-like shape was first described by Archimedes, and the rules that guide the topology of polyhedra were first developed by Descartes.

When applied to polyhedra that are made of only pentagons and hexagons, these rules imply that every such closed structure can contain any number of hexagons but must have exactly 12 pentagons. Heptagons can also be introduced, producing negative curvature (saddle-shaped surfaces), but the topological effect of a heptagon is cancelled by that of a pentagon. In the mid-eighteenth century, the Swiss mathematician Leonhard Euler had proposed a formula[5] for these geometric rules, which were now profoundly manifested at the nanoscale in C_{60}. Larger closed carbon cages (such as C_{70} and C_{82}) also exist, and can be formed by simply adding more hexagons to the cage.

The family of C_{60} and larger molecules have come to be known as the fullerenes, after the US architect Buckminster Fuller. Fuller had become famous for designing stable domes and buildings[6] that have shapes similar to that of C_{60}. The correspondence was striking, although the scale differed by a factor of about 10 billion. So it was that the C_{60} family got its name (its members could well have been called soccerenes).

"The structure of C_{60} turned out to be a beauty. It looked exactly like the classic design of a soccer ball."

Kroto and colleagues' fullerene discovery took other scientists by surprise. Initially, there were quite a few sceptics; many thought that C_{60} was flat rather than cage-like. However, this perception changed after work by the German chemist Wolfgang Krätschmer, the US chemist Donald Huffman and their students. In 1990, these researchers succeeded[7] in isolating C_{60} molecules from carbon soot in bulk, thereby making the substance available for large-scale experiments.

The fullerene discovery immediately had two major consequences. First, fullerenes were used to synthesize a large variety of unconventional materials. For example, endohedrals[8] (fullerenes that enclose metal atoms), fullerene-assembled solids and superconducting fullerene materials[9] were produced and characterized with excitement. Fullerenes were seen as a distinctive, stable molecular system and as an ideal building block for making unprecedented materials. They were also touted as a new allotrope (structural form) of carbon that deviated from the familiar graphite and diamond.

Second, the discovery provided the impetus to seek other carbon allotropes – particularly nanoscale materials. The most substantial result from this search was the synthesis and development of carbon nanotubes (Fig. 1b) by the Japanese physicist Sumio Iijima[10] and colleagues[11] in the early 1990s. Carbon nanotubes showed that the electronic structures of carbon layers could be tuned by structural nanoscale engineering, suggesting possible uses in electronics and other applications.

Over the following two decades, a rush of research activities, publications and patents would make fullerenes and carbon nanotubes the poster children of nanotechnology. It was also during this period, in 2004, that the Russian physicists Andrei Geim and Konstantin Novoselov isolated graphene[2] (Fig. 1c). Graphene was the first example of a truly stable 2D material and revealed the physics associated with such 2D systems.

It has been nearly 35 years since Kroto and colleagues' fullerene paper was published. In spite of all the potential that fullerenes promised, these molecules have not led to any major applications, barring a few encouraging ideas in solar cells and biochemistry. However, the work paved the way for many innovations in nanomaterials that will ultimately find uses in nanotechnology. The fullerene discovery and what followed show the ingenuity of the human mind in solving a nanoscale puzzle. Fullerenes also provide a curious case in which an architect's name was dragged into a major scientific discovery. Buckminster Fuller would probably not have minded.

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1. Kroto, H. W., Heath, J. R., O'Brien, S. C., Curl, R. F. & Smalley, R. E. *Nature* **318**, 162–163 (1985).
2. Novoselov, K. S. *et al. Science* **306**, 666–669 (2004).
3. Osawa, E. *Kagaku* **25**, 854–863 (1970).
4. Rohlfing, E. A., Cox, D. M. & Kaldor, A. *J. Phys. Chem.* **81**, 3322–3330 (1984).
5. Euler, L. *Novi Comm. Acad. Sci. Imp. Petropol.* **4**, 109–140 (1758).
6. Sieden, L. S. *Buckminster Fuller's Universe: His Life and Work* (Basic, 2000).
7. Krätschmer, W., Lamb, L. D., Fostiropoulos, K. & Huffman, D. R. *Nature* **347**, 354–358 (1990).
8. Chai, Y. *et al. J. Phys. Chem.* **95**, 7564–7568 (1991).
9. Hebard, A. F. *et al. Nature* **350**, 600–601 (1991).
10. Iijima, S. *Nature* **354**, 56–58 (1991).
11. Ebbesen, T. W. & Ajayan, P. M. *Nature* **358**, 220–222 (1992).