# The Bright Future of Fabulous Materials Based on Carbon

## Fred Wudl

*Abstract : Our current civilization belongs to the organic materials age. Organic materials science pervades nearly all aspects of our daily life. This essay sketches the evolution of materials science up to the present day. Plastics as textiles and structural materials dominate human civilization. The element carbon is at the core of this development because of its diverse interconnections with itself and other elements of the periodic table. While silicon will not be supplanted from its role in electronics, carbon will provide the most versatile electronics applications, through inexpensive, flexible electronic devices.*

Mr. McGuire: Ben, just one word.
Ben: Yes, sir?
Mr. McGuire: Are you listening?
Ben: Yes, I am.
Mr. McGuire: Plastics!
Ben: How do you mean?
Mr. McGuire: There is a great future in plastics, think about it.

– *The Graduate* (1967)

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Mr. McGuire was right in his assessment. Plastics, or better yet, organic materials, contribute significantly to making our everyday lives exciting and productive. It is hard to imagine a world without plastics. Over the last several decades, organic materials have given us polyesters, polystyrene, formica, lightweight containers, fiberglass boats, airplanes that consume less fuel (thanks to lighter structural materials), fibers that are stronger, nylon, and much more recently, flat screen displays with brilliant, vibrant colors. And organic materials are today leading us into a much less energy-intensive future, thanks to organic solar cells ("plastic solar cells") and organic transistors.

How have we come so far so quickly: from unimaginable to reality in as little as sixty years? Let's

backtrack to examine this history a bit more closely.

Materials science might well be labeled the "central science," a moniker given to the discipline of chemistry in the recent past.[1] Materials predate chemistry by millennia, and human civilization is inextricably connected with materials. In fact, the stages of early human civilization have been characterized by the materials that humans used as civilization evolved. Thus the progress in prehistory follows the sequence stone age (Neolithic), followed by bronze age, and then iron age. Thereafter (c. 5000 BCE), civilization became rather complex; but if we were to jump forward to the present day, we would find that *every aspect of current civilization is touched by electronics*, and specifically, electronics based on highly processed silicon. This brings us to *electronic materials* that have been dominated by semiconductor elements, in particular silicon, germanium, and compound semiconductors such as gallium arsenide, indium gallium arsenide, and so on. In parallel with the evolution of solid-state electronics, organic materials (particularly plastics) have fully permeated civilization, hence a proper name for the current civilization, in terms of materials, would be the *silicon age*, or the *organic materials age*. The much more modern aspect of materials science, namely, *organic electronic materials*, is in its nascency; its origin can be traced to the second half of the twentieth century, specifically to 1973[2] and 1987.[3]

Inherent in the definition of organic materials is the classic definition of organic chemistry as the chemistry of carbon compounds. The foundation of organic materials is based on the unique way in which carbon atoms interact with one another and with other elements of the periodic table. The key difference, at the atomic level, between carbon and all the elements below it in its column of the periodic table (that is, silicon, germanium, tin, and lead)

is its ability to form *stable double bonds* (π bonds), *particularly with itself*. The π bonds consisting of two pairs of shared electrons are the lowest common denominator in organic electronic materials. Another fundamental difference between organic solids and inorganic solids (again at the atomic level) is that the former are *molecular solids* while the latter are *extended solids*. Extended solids are materials in which the entire bulk has all atoms bonded to each other: for example, a chunk of silicon, a diamond, a gold nugget, iron, silicon oxide (quartz, glass), or iron oxide (magnetite). On the other hand, molecular solids are composed of discrete molecules that are not bonded to each other. The molecules themselves can consist of a diverse number of atoms, ranging from two (iodine) to millions (ultra high molecular weight poly[ethylene], VECTRA, DNA). The molecules pack into a solid in which intermolecular forces hold the bulk material together. Intermolecular attractive forces are many orders of magnitude weaker than the interatomic bonds of solids. Thus, molecular solids in general are soluble in most solvents and have relatively low melting points, whereas *all* extended solids are insoluble in all solvents, and with the exceptions of mercury, cesium, gallium, rubidium, and potassium, as well as their alloys, extended solids have rather high melting points.

The obvious advantage of organic materials is that they are *much easier to process (that is, convert to useful items) than are traditional inorganic materials*. Thus, organic materials are considerably less energy intensive in the procedures employed to convert them to useful objects. Organic materials have had profound effects on society via their roles as *textiles*, *structural materials*, and very recently, *electronic materials*. The latter will be the main subject of this essay.

Organic materials in textiles had their start with natural flax fibers going back to

the Neolithic age, roughly thirty thousand years ago;[4] this was followed by cotton[5] at least seven thousand years ago. It was not until the beginning of the twentieth century that synthetic, organic polymer–based ("plastics") fibers became prevalent. They had originated in the mid-nineteenth century with celluloid, the first film and bulk plastic-parts-forming material. Celluloid had its origin with nitrocellulose, the explosive guncotton. In 1855, in Birmingham, England, Alexander Parkes was the first to convert nitrocellulose into a plastic by mixing a nitrocellulose solution, known as collodion, with camphor and then evaporating the solvent. He named his invention Parkesine, and the material is thought to mark the start of the plastics industry.[6]

By the 1870s, it became clear that certain objects made from elephant tusk ivory, such as billiard balls and piano keys, were becoming very expensive. Enter John Wesley Hyatt, an entrepreneur and inventor who expanded on Parkes's invention and labeled his material celluloid. A myriad of articles were made of celluloid between the second half of the nineteenth century and the early twentieth century, including cinematographic film. Not surprisingly, the film was very unstable and almost "spontaneously" combustible, resulting in tragic movie theater fires. These semi-synthetic plastics had a limited lifetime, either suffering discoloration or breaking down. In 1907, Leo Baekeland invented a synthetic resin made out of inexpensive synthetic materials (phenol and formaldehyde) and called it Bakelite. Bakelite was stronger than celluloid, was very stable, and was not nearly as combustible. Soon a wide range of everyday objects were made of Bakelite: fountain pens, telephone housings, knife handles, art deco objects, and phonograph records, among many others.

In 1924, another semi-synthetic material was obtained from wood cellulose processed into rayon fibers,[7] yet very little was

known about these materials at either the atomic or molecular level. Many chemists were convinced that plastics consisted of another form of matter, one that did not involve traditional chemical bonds. It was not until the fundamental contributions of Herman Staudinger at the turn of the twentieth century[8] and Paul Flory[9] in the mid-twentieth century that we were able to explain all the properties of plastics as resulting from the properties of giant molecules (macromolecules or polymers). Both Staudinger and Flory received Nobel Prizes (in 1953 and 1974, respectively) for their contributions to polymer chemistry. Nylon and all its successors (for example, polyester, acrylic, saran, and spandex) were invented based on our understanding of the chemistry of macromolecules at a fundamental level.

The terms *polymer* and *macromolecule* have become synonymous, while plastic usually refers to a material made of synthetic polymers. As the name implies, a polymer consists of many (Greek, *poly*) identical units or parts (Greek, *mer*) joined together. The simplest plastics are those in which a long molecular chain is formed of repeat units (chain links) that are all identical (homopolymers), as is the case with polyethylene, polypropylene, and polystyrene. One can imagine that because carbon is so versatile in its bonding ability, the potential for different homopolymers is almost infinite. Now imagine combining two different monomers to form a molecular chain. They could be joined in at least three different types of arrangements: they could alternate, occur at random, or occur in blocks. Each of these arrangements can be achieved, and each results in *designable* properties. Chemists and materials scientists, thanks to carbon's unique chemistry, have at their disposal an almost infinite number of organic plastic materials that lend themselves to the production of everything from rubber bands to airplanes.

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Although the natural polymers making up linen, cotton, and wool are still major textile fibers, the highest strength fibers, as well as those with special applications, are all synthetic. For the same weight, a Kevlar fiber is stronger than steel. How is it possible to have a material that, in fiber form, is stronger than steel and yet is a molecular solid? There are two reasons: 1) the macromolecules are very long, resulting in their forming regions of entanglements or "mechanical bonds"; and 2) the extensive regions that are not entangled are highly ordered and have enhanced intermolecular attractive forces. These intermolecular attractions are hydrogen bonding, dipole-dipole, π-π stacking, and Van der Waals attractive forces. They were known to chemists for decades but were not exploited until the second half of the twentieth century, at which point organic chemists were able to design molecules exploiting these weaker attractive forces. These "designer molecules" would then order themselves into a predetermined structure by "self assembly."

Kevlar was designed to maximize all these intermolecular forces, starting with the monomer, the method to link the monomers to each other (polymerization), and finally the processing into fibers. The chain entanglements are the main reason why polymeric materials are plastic (flexible, malleable, and ductile), and hence convertible into fibers, films, devices, and machine parts. The latter are in the realm of structural or engineering materials.

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Our everyday objects are lighter, more durable, cheaper to manufacture, sleeker and more sanitary than their predecessors. The world before plastics was that of butcher paper, tin soldiers, wooden crates, broken glass and rusting metal – less convenient and less abundant in consumer goods than today. . . .

Engineering polymers – developed for the purpose of replacing metals – made up the last major class of materials to spring from the Golden Age of Plastics.

– Alexander H. Tullo, *Chemical & Engineering News*, September 9, 2013

The mechanically stronger and, in general, more brittle plastics such as Bakelite or Formica have their long molecules connected to each other, with interchain bonds or crosslinks. In essence they are a form of extended solids. Hence, they are insoluble and infusible. The only way to process them is by forming the part from its monomer components in a mold through a method called *thermosetting*. Because polymeric solids are so easily manipulated, by further chemical transformation, by dissolution, or by melting, they can also be converted to very strong and tough materials, particularly by forming composites with strengthening ingredients such as glass fibers, carbon fibers, or steel mesh. Our most advanced airplanes (the F-117 stealth fighter, the B-2 bomber, the Boeing 787 Dreamliner) now feature extensive use of plastic-carbon fiber composites.

The giant molecules used in structural materials, while often containing π bonds, do not take advantage of the π bonds' exquisite electronic properties. Thanks to the fundamental research of organic chemists, mostly in the twentieth century, π bonds can be tailored to have a useful electronic property and this ability is the essence of organic electronic materials. An isolated double bond between two carbon atoms is relatively uninteresting from an organic electronics perspective because the energy required to manipulate these π electrons is too high for electronic devices. Figure 1 shows that as π bonds are connected, the energy required to excite their electrons becomes smaller. Thus the wavelength of light required to excite electrons from the

relatively high-energy ultraviolet region of the spectrum for ethylene (one π bond) to the lower energy visible region in carotene (eleven π bonds). By increasing the number of alternating π bonds in a molecule and including other elements that interact with the electrons of π bonds (oxygen, sulfur, nitrogen), one can extend the absorption of light to wavelengths of light corresponding to relatively low energies (to the near infrared region of the spectrum).

Ethylene and all other π-bonded carbon atoms are planar: that is, all four hydrogen atoms of ethylene are in the same plane; deforming the plane results in a highly "strained" bond. The most extremely interconnected π-bonded carbon structure known is graphene, a small section of which is shown in Figure 2.

In nature, carbon occurs in two major "allotropes": diamond and graphite. The former, as mentioned above, is an extended three-dimensional solid. The structure of a very tiny piece of diamond is shown below.
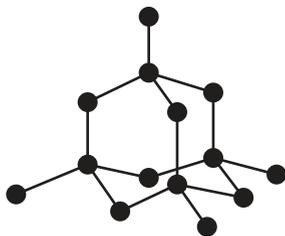


In this structure, each carbon atom is joined to four other carbon atoms by single bonds. On the other hand, graphite is composed of a very large number of planar graphene sheets stacked on top of each other, with perfect registry from graphene layer to layer, held together by weak Van der Waals forces. Each sheet contains many bonds. Because these inter-graphene forces are so weak, in writing with a graphite pencil, one scrapes off layers of graphene onto the paper. In 2010, the Nobel Prize in Physics was awarded to A. K. Geim and K. S. Novoselov[10] for their discovery of the very

unusual properties of graphene.[11] Graphene can in fact be considered the conceptual germ of two other new forms of carbon, buckminsterfullerene[12] and carbon nanotubes, illustrated in Figure 3.[13]

For the discovery of fullerenes, R. F. Curl, H. W. Kroto, and R. E. Smalley received the Nobel Prize in Chemistry in 1996. Fullerenes, especially carbon nanotubes, can be envisioned as arising from the curving of a graphene sheet onto itself. The electronic properties of buckminsterfullerene and carbon nanotubes are directly related to the strain of their bent π bonds. In buckminsterfullerene, the strain is manifested by an increase in electronegativity, meaning that each π bond becomes mildly electron-attracting, making buckminsterfullerene an electron acceptor (EA) molecule. With the advent of buckminsterfullerene, chemists were presented for the first time with a set of π bonds arranged on a spherical surface. Buckminsterfullerene is also the first carbon allotrope in the form of a molecular solid that is soluble in several solvents and sublimable under vacuum at readily accessible temperatures. Buckminsterfullerene molecules tend to aggregate, a property that is auspicious for the development of organic solar cells, as discussed below.

Buckminsterfullerene and carbon nanotubes are *at the heart of organic nanoscience and nanotechnology*, a relatively new branch of chemistry, physics, and materials science.[14] Nanotechnology and nanoscience deal with properties of matter in the realm of 1–100 nm. In this scale, properties may be dominated by quantum mechanical effects. Two typical examples (of many)[15] of current nanotechnology applications in materials science are bandages impregnated with silver nanoparticles, to take advantage of their remarkable antibiotic properties, and nano-sized titanium dioxide as well as zinc oxide for particularly effective sun screen ointments.[16] A truly up-to-date

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*Figure 1*

Carotene, with Its Eleven Linked (Conjugated) π Bonds
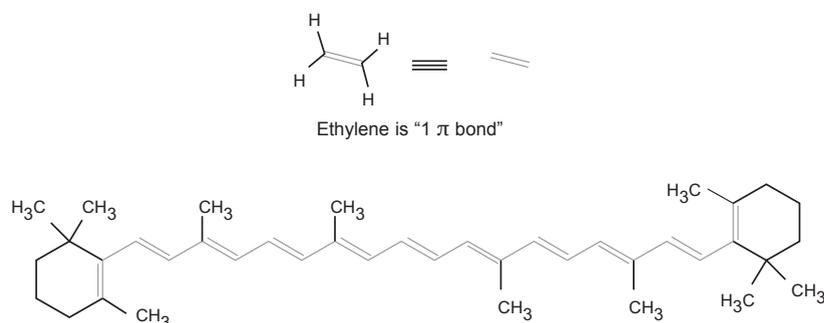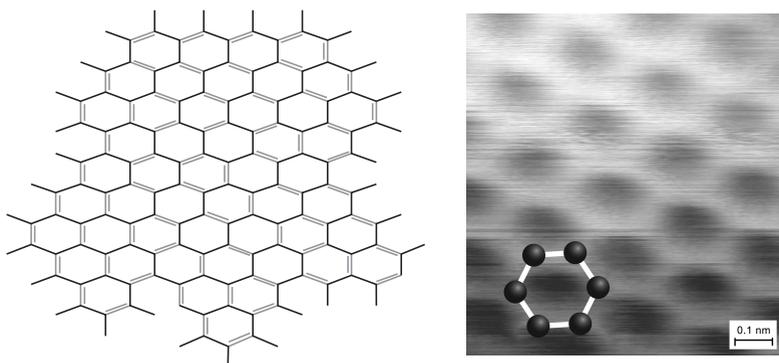
Ethylene is "1 π bond"

*Figure 2*

The π Bonds in Graphene (left); an Atomic Force Micrograph of Graphene (right)

One nanometer (nm) is approximately one ten-billionth of an inch. Source : E. Stolyarova, K. T. Rim, S. Ryu, J. Maultzsch, P. Kim, L. E. Brus, T. E. Heinz, M. S. Hybertsen, and G. W. Flynn, "High-Resolution Scanning Tunneling Microscopy Imaging of Mesoscopic Graphene Sheets on an Insulating Surface," *Proceedings of the National Academy of Sciences* 104 (2007) : 9209 – 9212.

application of carbon nanotubes is in computing, where nanotubes are beginning to take the place of silicon in a computer's integrated circuit.[17]

To make significant advances in organic electronics, scientists need to be truly interdisciplinary. Equal participation of chemists, physicists, and engineers is required. The chemists design and synthesize the organic materials, the physicists provide the theory and experimental procedures for transporting electrons through organic molecular solids, and the engineers

provide the design and fabrication of devices for the consumer.

The close collaboration of chemists and physicists helped establish that the most effective way to generate and delocalize electrons in organic solids is to use two types of π bond–containing molecules : electron acceptors (EA) and electron donors (ED).[18] We already saw that buckminsterfullerene is an electron acceptor. Electron donor molecules have π electrons that are relatively loose and easily given up, leaving behind a positive charge or "hole." The solid resulting from transferring an

Structure of Buckminsterfullerene with Sixty Carbon Atoms ($C_{60}$) Containing Thirty π Bonds (left); Artist's rendering of a Single and Multiwall (Double) Carbon Nanotube (right)

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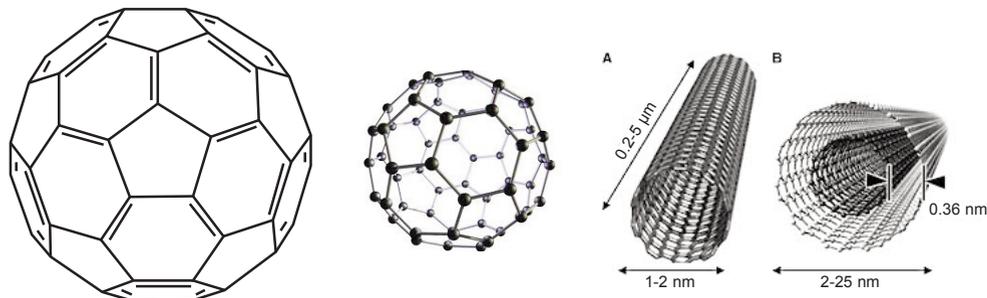


Source: http://en.wikipedia.org/wiki/File:Buckminsterfullerene-2D-skeletal.png; A. Hirsch, "Funktionalisierung von einwandigen Kohlenstoffnanoröhrern," *Angewandte Chemie* 114 (2002): 1933–1939; R. M. Reilly, "Carbon Nanotubes: Potential Benefits and Risks of Nanotechnology in Nuclear Medicine," *Journal of Nuclear Medicine* 48 (7) (2007): 1039–1042; and S. Iijima, "Carbon Nanotubes: Past, Present, and Future," *Physica B* (323) (2002): 1–5.

electron from an ED to the EA is known as "a charge transfer complex." It was further established that both ED and EA molecules had to form infinite pancake-like stacks in the solid state. Electrons and holes travel along these stacks much more readily than they do between stacks. With this fundamental knowledge, scientists were able to invent organic solids that conduct electricity just as well as many metals do (but still not as well as copper). Another property that these organic solids shared with metals was that their conductivity *increased* with decreasing temperature and as a result, these solids were known as *organic metals*.

Up to the time of this momentous discovery, organic materials were useful in electrical engineering and electronics because they were excellent *insulators*, not conductors. Prior to this breakthrough point in the history of organic electronics,[19] the measurement of conductivity as a function of temperature of organic solids afforded only very low conductivity that *decreased* with decreasing temperature, a property that defines semiconductors in general. Further

research on organic metals ultimately led to the discovery of organic superconductors. These are materials that exhibit infinite conductivity (zero resistance) below a particular transition temperature.[20] This was a truly amazing development because up to that point it was believed by all experts in the field that in order to observe superconductivity, one needed an extended solid.

From a fundamental point of view, achieving metallic and superconducting properties with organic materials was clearly a remarkable accomplishment. But from a materials engineering viewpoint this was not the case, because organic metals were tiny, brittle crystals that could not be processed into useful devices. What was required was a polymer or plastic that would exhibit high conductivity when converted to a charge transfer complex. Not until 1977 did this momentous discovery take place, when collaborating scientists in Japan and the United States identified an electrically conducting polymer.[21] This finding led to the 2000 Nobel Prize in Chemistry being awarded to A. J. Heeger, A. MacDiarmid,

and H. Shirakawa. From an organic chemist's perspective, this was a deceptively simple polymer, a polyacetylene. It was simply a solid made up of molecules that consisted of long chains of conjugated π bonds (where $n$ is a difficult-to-determine large number in the hundreds to thousands).



A sample of polyacetylene looks like a piece of aluminum foil, but it tarnishes quickly when exposed to the atmosphere. This material was chiefly of academic interest, but it provided a trove of fundamental information, much like fruit flies do for the field of genetics. In quick succession, the organic electronics community developed much more stable polymers that could be useful as materials. The paradigm of the day was to achieve ever higher conductivities, even conductivities that might be achievable without having to resort to charge transfer complex formation. As a result, the chemistry and physics community concentrated on achieving metal-like properties until Richard Friend's group (in 1990) discovered that one of the most stable polymers could be processed into a light-emitting diode.[22] This was a semiconductor property, not a metal property. A light-emitting diode is a particular semiconductor device that emits light when a voltage is applied across it.

The discovery caused an immediate paradigm shift by the research community, from the search for metal properties to the search for semiconductor properties. In fact, judging from the number of publications, research on organic metals appears to have ceased in the United States, although it is still pursued in Japan and Europe. While the discovery of the polymeric light emitting diode (PLED) was clearly an important step in the development of organic electronics, the first organic electronics device that was reported came in 1987;[23] it was also a light-emitting device, but was not based on polymers. Rather, it was a small-molecule organic light-emitting diode (OLED). Both kinds of devices are very bright and colorful, but so far, PLEDs are still in the development stage while OLEDs have advanced into the commercial sphere, seen everywhere from flat screen display devices to smartphones.

Because electrons and holes carry opposite charges, they attract each other and can actually combine, resulting in loss of charge carriers. The origin of the light emitted by OLEDs and PLEDs is based on the fact that when electrons recombine with holes, they raise molecules to a high-energy excited state. When the excited molecules return to a ground state they emit light or heat.

Again, π bonds have a greater tendency to emit light than heat. In OLEDs and PLEDs, the positive and negative electrodes of the diode create the holes and electrons, respectively. The excited state of an electron-hole pair is called an *exciton*. An exciton can also be created by absorption of light of the wavelength corresponding to the energy required to produce an electron-hole pair. So, if one were able to separate the holes from the electrons before they had a chance to recombine, then one would create an electric field or voltage by the absorption of light, and one would have a "photovoltaic device" or "solar cell" if the light absorbed were that corresponding to the solar spectrum. Many attempts to produce organic photovoltaic cells were made throughout the period from the 1960s to 1980s by combining EDs and EAs and irradiating them. Unfortunately, though the devices produced electricity, they had extremely low efficiencies, mostly because the electron-hole recombination rates were too high. Another way to view this observation is that the acceptors were "too

willing" to give the electron back to the holes.

As it turned out, the negatively charged fullerenes, resulting from accepting an electron, were less strained than the slightly smaller-diameter neutral fullerenes. This property resulted in a one thousand to ten thousand times slower recombination[24] with the hole of an exciton generated in an ED polymer than was observed previously with any other EA. Even though the first organic solar cells – "plastic solar cells" – based on fullerene, discovered in 1992, had much higher efficiencies (0.04 percent)[25] in the conversion of solar energy to electrical energy (power conversion efficiency [PCE]) than any previous organic device, it was still far too low to be of more than academic interest. Another important aspect of fullerenes for this application was that the very tight aggregates fullerenes tend to form allowed the negative charge to be carried quickly toward the negative electrode of the cell. With concentrated research efforts in the United States, Europe, Japan, and China, the PCE increased rapidly to the current record of 11 percent,[26] a 275-fold increase from the original efficiency. While this number may seem small, keep in mind that solar cells based on amorphous silicon exhibit a PCE of 10 to 11.9 percent. The most efficient solar cell reported to date is 38.8 percent efficient, and commercial cells are only 11 to 19 percent efficient.[27] The most efficient non-organic experimental cell is reported to be 44.4 percent efficient, but this involves the use of a solar concentrator, a device, like a magnifying lens, that concentrates light; without a concentrator, the maximum PCE is 32.6 percent.[28] There are now several small companies manufacturing plastic solar cells that are adequately efficient for relatively small applications, such as on the roof of a bus shelter for the minimal electricity needs there (lights, for example), or on the outer flap of a woman's purse for the powering of a cell phone. None of these devices use fullerene $C_{60}$ as the acceptor, but rather a derivative called PCBM (shown below), an acronym for [6,6]-phenyl-$C_{61}$-butyric acid methyl ester.
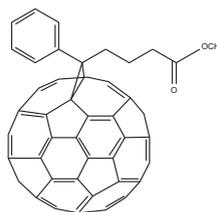


While fullerene is relatively insoluble, its electronic structure makes it slightly too strong of an electron acceptor, whereas PCBM is more soluble and is a slightly weaker electron acceptor, better matching the electron-donating properties of most polymeric EDs. The development of PCBM provides yet another example of how many times science progresses by serendipity. This fullerene derivative was originally prepared as part of a program to make a water-soluble agent to inhibit the active site of HIV protease, an enzyme used by the AIDS virus in its replication process. The active site of the protease is a cavity of approximately 1 nm in diameter, corresponding to the diameter of fullerene. To be able to examine the biological properties of any molecule, the molecule needs to have some water solubility. Fullerene is insoluble in water, and PCBM was prepared as a water-soluble fullerene derivative. Another reason that fullerene PCBM was prepared is simply because the chemistry of fullerene was being explored in my research group as well as in several other groups around the world; and one of the better known methods to transform fullerene was by the reaction that led to PCBM. At the same time, the "materials" properties of fullerene, particularly the optoelectronic properties for organic electronics, were being examined by Dr. Saiciftci in Alan Heeger's group at the University of California, Santa Barbara. He wanted a soluble fullerene derivative

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because he had just determined that fullerene would accept an electron from a photo-excited ED polymer. Changing from fullerene as an electron acceptor to PCBM dramatically enhanced the PCE to 2.9 percent.[29] From 1995 to 2013, the PCE improved to 11 percent. This significant enhancement was a consequence of a change in the ED polymer architecture from homopolymers to alternating co-polymers. This structural modification allowed for more versatile design of electronic character of the π backbone of the polymer.

In order to fabricate a conventional silicon-based solar cell one must first process the silicon. Because the melting point of silicon is 1414 degrees C (2577 degrees F), and because in order to fabricate silicon-based devices one must crystallize silicon from the melt, the manufacture of solar cells is a very energy-intensive process. On the other hand, plastic solar cells are based on molecular solids. They can be processed from solution, called "inks," with very simple devices such as a dot matrix printer or a roll-to-roll printer. Thanks to their light weight, flexibility, ease of manufacture, and low cost, plastic solar cells can be expected to have a profound effect on the world's non-fossil fuel, non-nuclear electricity generating capacity. A similar bright future for the reduction of energy-consumption can be foreseen for OLED display devices, since these devices do not need strong backlighting. To observe a non-luminescent device, such as a liquid crystal display (LCD), one needs a source of illumination; for flat screens this is best accomplished from the back, hence "backlighting."

As stated above, when π bonds are not in charge transfer complexes, they behave as semiconductors, the backbone of modern electronics. Diodes and transistors are the simplest units of semiconductor electronic devices. We already saw an organic diode application in the form of OLEDs. Transistors are solid-state microscopic switches and amplifiers that are the main way to control electron flow in electronic devices, particularly in computing and displaying. Organic electronics is influencing the electronics industry with organic transistors. The easiest way to convert an organic semiconductor to a transistor is to use the tendency of organic materials to readily form thin films. Organic transistors are thin film transistors (TFT). A particularly simple TFT is the field effect transistor (FET); in this case an organic FET would be an OFET.[30] Pentacene, a 22-π-bonded carbon molecule, its derivatives, and some polymeric materials that are much better film-formers easily outperform amorphous silicon and have already yielded practical devices, such as drivers for flexible OLED and liquid crystalline displays.

In conclusion, by exploiting the π bonding capability of carbon, organic materials have been designed to exhibit unmatched advantages: they are lightweight, flexible, and low-cost; and they have low energy fabrication demands. Devices based on these materials can be expected to proliferate rapidly. Cheaper and lighter large-scale structures (dwellings and bridges, for instance); countless electronic devices; cheaper, lighter, and recyclable containers; more efficient modes of transportation; and improved techniques for the harvesting of solar energy: all will be part of this branch of organic chemistry's contribution to sustainable life on Earth.

Author's Note : This essay has benefited from the feedback of Linda Wudl and Jerrold Meinwald, to whom I am indebted for their kind help.

1  Attributed to Theodore E. Brown, who wrote a freshman chemistry text titled *Chemistry, the Central Science*.

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