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J. E. Gordon: The New Science of Strong Materials or Why You Don't Fall through the Floor

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Introduction

by Philip Ball

Any popular-science book written at the end of the 1960s must almost by definition be old fashioned. And since they will not yet have acquired the antique glamour of, say, Darwin's *Origin of Species*, and since science now moves so fast, it is rare that such books are read anymore—and surely rarer still that they are reprinted more than three decades later.

One might argue that, since it deals with basic principles that cannot be tarnished by the passing years, Jim Gordon's *The New Science of Strong Materials* is more resistant to obsolescence than many similar attempts to bring science to a lay audience. That, however, is no guarantee of longevity. Gordon's book is indeed “old fashioned” in a sense, and, for books probably more than for any other cultural artifact, that is usually enough to banish a work to oblivion—which in this case tends to mean those curious shelves of secondhand bookshops that do not quite know what to do with science, lined with dusty manuals on valve electronics and monochrome paeans to the wonders of rocketry. Instead, here we have a new edition for a new audience, for the book remains as popular as ever.

The reason for this is, of course, that *The New Science of Strong Materials* belongs to that prestigious group of popular-science books—among them, James Watson's *The Double Helix*, Richard Dawkins's *The Selfish Gene*, and Jacob Bronowski's *The Ascent of Man*—that can be read not simply for edification but for pleasure. And the reason why this is so is obvious, although desperately hard to reproduce: Gordon has evidently written it for pleasure too. He is enjoying himself on every page.

In the manner of a certain kind of British academic of the early postwar era, he sometimes conspires to mask that enjoyment by adopting the guise of a grumpy man who has little patience with the foolishness of the modern world: “Many products wear out—or rather go out of service—for silly, shoddy reasons (Oh no, sir, we don't stock spares for out-of-date models).” But the reader

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knows that this is part of the performance. The role being performed here is that of the down-to-earth engineer who speaks to you in plain, simple language, neither condescending nor aloof, someone who can convince you that everyday questions like that posed in the book's subtitle have everyday answers that anyone can understand.

It is certainly "old fashioned" to speak this way today. Increasingly, science books, in an ever more crowded market, must make grand claims, enticing us with promises to uncover the secrets of consciousness, or of the origin of the universe, or of "what it means to be human." One wonders how easy Gordon would have found it to secure a publisher today with his tables of Young's moduli, his stress-strain curves, and, most of all, his equations. Not for him the "Hawking rule" that every equation in a text aimed at a lay audience will cut sales by a factor of ten; he simply tells the reader that "I have cut out the whole of the mathematics except for a very little genuinely childish elementary algebra which can be followed by anybody with a negligible effort." What could be more effective in warning the reader that claims of mathematical incompetence will not be tolerated, when all they are being asked to do is to process a few ratios and square roots?

A book written by a scientist primarily for his or her own enjoyment is often a doomed project, partly because he or she will find little satisfaction in laboriously setting out the basic concepts that any nonspecialist reader needs to grasp before the light of understanding dawns. But Gordon is blessed with that rare combination, best known from the writings of the physicist Richard Feynman: a clear, concise, and eloquent writing style coupled with an inexhaustible delight at how things work. The clarity comes from a sense that Gordon is never explaining facts dutifully, but is doing so because the process of explanation is genuinely illuminating to him too. "It's so beautifully simple," you can sense him thinking as he contemplates along with us an image of the SS *Schenectady* cracked neatly in half—echoing Feynman's famous rubber-ring experiment at the hearings of the Space Shuttle *Challenger* disaster.

What is perhaps most astonishing about the continuing allure of *The New Science of Strong Materials*, however, is that it is really a book about engineering and technology. The literary category of

“popular engineering” is one that does not really exist, and shows no sign of emerging. This is not to say that there are no good or even moderately successful books for a general audience about applied science; but they hardly feature in the current excitement about the interactions of science and culture, evidenced for example in talk of a “third culture” where, echoing the Renaissance, the sciences and the arts meet and cross-fertilize one another. Isambard Kingdom Brunel, the designer of such engineering marvels as the iron-hulled SS *Great Britain* and the Clifton Suspension Bridge in Bristol, was recently voted the second “Greatest Briton” by the British people; but it seems unlikely that the vast majority of his advocates would have been able to name a single living engineer—a fact lamented by Lord Alec Broers, president of the Royal Academy of Engineering, in the prestigious BBC Reith Lectures in 2005. The reader of Gordon’s book can have no illusions that it is going to reveal deep and recondite answers to the questions raised by our own existence. Instead, Gordon says at the outset, his themes are such issues as “Why do things break?” “Why is steel tough and why is glass brittle?” and “Why does wood split?”

There’s no denying that the audience interested in such questions is going to be rather select (congratulations on being part of it). But this wasn’t always so. *The New Science of Strong Materials* begins by quoting Michael Faraday as he ponders the mystery of cohesion, and that is a nice reminder that, when Faraday and his mentor Humphry Davy drew crowds from the most refined society to the lecture theatre of the Royal Institution in Albemarle Street, London, the audience commonly came not to hear about the brain or cosmology but about tarmac and rubber—about the application of these and other technologies to their lives. This is the tradition that Gordon’s book perpetuates, and one can hope that it will one day seem equally important to the public to know how a silicon chip is put together, or why abalone shell is so tough, or how plastics can be manufactured without organic solvents. For these are the kinds of problems that are changing our lives, every day, in ways that we can barely anticipate. “More and more,” Gordon says, “one comes to see that it is the everyday things which are interesting, important and intellectually difficult.”

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The benefits of the broad view

Born in England's Lake District in Cumbria in 1913, Jim Gordon graduated as a naval architect from Glasgow University. He worked as a young man in the Scottish shipyards, but it was clear that he was going to be no ordinary engineer. His interests were eclectic, and he took them all seriously. He not only helped to build boats but sailed in them too: sailing was his joy, and undoubtedly this pursuit fed his appreciation of how important it is to match materials and structures to function, and how one can hardly overstate the virtues of traditional materials. Both *The New Science of Strong Materials* and its popular sequel, *Structures: Or Why Things Don't Fall Down*, draw heavily on examples from naval history past and present. His passion for naval design informed his work on aircraft, as did his interests in gliding and falconry.

Gordon's knowledge of classics shines out clearly in his discussions of the architecture and structural engineering of the ancient world, and he counted several classical scholars among his friends. (He learned Greek during the long nights on wartime duty for the Home Guard, waiting to fight fires.) This interest stimulated Gordon's later work on the armor of ancient cultures, and he was convinced that materials have played a pivotal role in shaping historical events, anticipating the modern interest in "materials culture." Indeed, after he was appointed professor of materials science by the University of Reading in 1968, Gordon established a joint degree in engineering and classics—a combination whose extraordinarily rich potential was never quite realized because few students proved to possess the catholic interests and diverse talents that Gordon had. In this regard, he was a cultural bridge very much in the mold of D'Arcy Wentworth Thompson, the Scottish zoologist (and classicist) who more or less founded the field of biomechanics with his blend of biology and engineering in *On Growth and Form* (1917). Gordon admired Thompson's book, and *Structures* echoes its juxtaposition of bridges and vertebrate skeletons, while admitting that "for all its many virtues, the engineering principles expressed are not always sound."

Gordon was a devotee of the arts, and was himself a keen amateur painter and photographer. He confessed to having dodged out of many a lecture as an undergraduate at Glasgow, "panting for

air,” and taken himself off to Glasgow Art Gallery. While certainly no misty-eyed romantic, he expressed the regret that we seem to live in “an age rather noticeably lacking in inherent grace and charm.” He wrote passionately about the need to marry technology to good design—in the manner of Walter Gropius’s Bauhaus school, perhaps, although Gordon makes clear that the functionalist aesthetic was not at all what he had in mind: he felt that the scientific and aesthetic functions of an artifact could and should be considered independently. That led him to propose measures that would have collided messily with contemporary design values, such as making suspension bridges look like medieval castles. “What is wrong with eighteenth-century ‘Gothick’ buildings?” he asked. “Let us have lots of ornament.” What a shame he is not here now to defend that case against the modernists and structuralists—it would have been an entertaining battle, and Gordon a formidable opponent.

Yet Gordon’s own tastes appear to have been more restrained. He designed the spacious garden of his house near Didcot in Oxfordshire: a formal, neoclassical composition of lawn and hedge decorated with stone urns that became the venue for lavish lunch parties (the wine and sherry flowed so liberally on these occasions that guests often found themselves staying the night). Gordon favored an informal yet modest literary style—he treasured the works of Jane Austen and Rudyard Kipling—and that is reflected in his own writing, which is never dry but achieves an airy conversational tone that belies its carefully crafted nature. Gordon worked very hard, a dogged two-fingered typist who eschewed word processors and accumulated draft after draft of text, to attain a prose style that sounds as though it has flowed casually from the well-stocked storehouse of his head. When his colleagues remarked breezily of his popular books, “Oh well, of course you have a flair for that kind of thing,” Gordon responded that “to make money by writing it probably helps to possess some tiny spark of ingrained talent but I most solemnly assure you that 99% of the matter is a question, not of genteel perspiration, but of sheer labourer’s sweat.”

During the Second World War, Gordon was brought to the Royal Aircraft Establishment at Farnborough in England, where his boat-designing skills were applied to aircraft. (Even here, however, he managed also to work on the inflatable dinghies car-

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ried by bomber aircraft, which he tested in person.) Engineering was at that time largely a matter of working with tried-and-tested materials, particularly metals: to the extent that the discipline of materials science existed at all, it was typically all about metallurgy. At Farnborough, however, Gordon helped to introduce other materials into aircraft design—not just the wood that he had learned to trust from his naval experience, but also new fabrics such as plastics and fiber composites. One such composite material found its way into the seat of a Spitfire fighter.

After the war, Gordon continued this work on new materials at the research laboratory of the company Tube Investments at Hinxton Hall, near Cambridge. It was a productive time, but Gordon watched bitterly as the company gradually lost interest in research and, in his view, squandered its technological opportunities—a lack of foresight that he found distressingly common (some would say it still is) in British industry. As a result, he returned to work on aeronautical engineering for the Air Ministry at the Explosives Research and Development Establishment (ERDE) at Waltham Abbey, northeast of London. Here he began to introduce tough composite materials, such as ceramic “whisker” fibers made from silicon carbide embedded in a softer matrix, into the body of aircraft. Gordon’s legacy at Farnborough meanwhile spawned the development there of stiff carbon fibers in the early 1960s. In 1968 he was wooed by Reading University—initially this was to be a joint appointment with the ERDE, but for someone with Gordon’s “relaxed” organizational approach this did not work out so well. Even his wife, Theodora, sometimes found it hard to know where, between his various bases, he might be found.

As is common with many inspirational figures, Gordon did not excel at the administrative duties that academia imposes: he tended to ignore them until they went away. But his lectures were as engaging and as popular as his books—where communication was concerned, the one fault he would not tolerate was dullness. The acerbic wit of his two books presented endless headaches to the translators of the many foreign-language editions they engendered. In conversation, Gordon developed a fine line in polite expressions of deep skepticism: one always knew that trouble would follow when he began, “Well, you know far more about this than I do, but . . .” Such comments were put to most effect in deflat-

ing pomposity, since the only fools that Gordon really would not suffer gladly were conceited ones.

Gordon was justly proud of his books, delighting in the fact that they were translated into over twenty languages and were used simultaneously in the Cold War military academies of both the United States and the Soviet Union. In British schools, they were assigned as study texts for both physics and English. And we might have had more from him before he died in 1998. He wrote a draft of a book on the development of warships, and another on “Kipling and engineering”: both apparently await the attentions of an editor. And he discussed with his colleague George Jeronmidis at Reading the idea of a book called “Wood, Trees and People,” which would have expounded on the sound natural engineering of this most beloved of his traditional materials. What the materials and engineering communities did get from Gordon, however, was the valuable notion that there is nothing more beneficial to their fields than interdisciplinarity: the art of thinking broadly.

New functions

In Gordon’s day, the science of materials was largely about *strength*, and that is reflected in the book’s title. What engineers wanted were new materials that would not break. It seems at first glance to be obvious that the science and technology of materials has long been a quest for strength: for materials with which one can build towers and bridges, and armor and ships, and then airplanes and spacecraft. But Gordon recognized that strength is not of much use in many applications without *toughness*. A ceramic material can be strong, but also brittle: the moment a crack appears, all is lost. The key issue is then that of how to stop cracks—to prevent them either from forming or from propagating. This is the territory that Gordon negotiates, as he explains why it is that cracks surge like lightning through a brittle solid, why they can be foiled by laminates and other composite materials, why glass fibers are so (nonintuitively) strong, and why metals tend to bend and stretch instead of just cracking.

But today that is only a part of the field known as materials science. Now there are new materials that can meld with human tissues, or emit light, or change their shape, or separate one gas from

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another. Today's "new science of materials" looks not only for strength but for flexibility, hardness, elasticity, electrical conductivity, adaptiveness, and responsiveness. "Bridges" are being built not just to carry trucks across rivers but, at the microscopic scale, to ferry electrons between microelectronic devices or to sense the weight of a virus particle. In short, materials science is diverse beyond belief, and it is hard to make any generalizable claims for it at all.

Gordon attempted to give a nod in this direction in his final chapter, "The materials of the future," which he says he was persuaded to add "rather against my judgement." One can see why this was so, since people of Gordon's exacting temperament are not generally given to speculation. Yet he needn't have been so reticent, for even if he says rather little about where his discipline was headed in the way of actual materials, he discerned precisely the trend that now characterizes the field. Increasingly, he said, we are "designing materials to suit ourselves."

And what is more, he indicates that these new materials are indeed not concerned solely to be "super strong," but have to meet more complicated and sometimes contradictory demands. "What is wanted," Gordon says, "is not one property in isolation but rather a balanced combination of properties." In consequence, "if we are going to set out to invent entirely new materials then we had better watch our step because the requirements for any really successful material are likely to be very complex indeed."

Let's have a brief look at what these two trends—designing materials to suit ourselves, and producing in them a balanced combination of properties—have entailed, and what they have produced. The first thing to note is that they are often related objectives. That is to say, the advanced materials of today are commonly tailor-made precisely because they exhibit a particular compromise or combination of properties that no simple material supplies.

Take silicon, for example. One might argue that this is the most significant material not considered in Gordon's book—an "oversight" that is perfectly reasonable because there is rather little in silicon's favor that stems from its *mechanical* properties. It doesn't matter that it is not especially strong or hard or tough—those are not the characteristics we demand from it. Rather, what counts are silicon's *electronic* properties. Its immense impact on our culture comes from its ability to conduct electricity.

More precisely, this impact is a consequence of its ability to conduct electricity rather poorly. Put like this, it sounds odd; but the fact is that silicon, as a semiconductor, is far less electrically conducting than a metal. Yet that is precisely the point. Because it has rather few mobile carriers of electrical charge—the basic constituents of electrical current—one can control and manipulate this conducting ability. Applying a voltage to a thin wire of silicon can block it as a current-carrying conduit—it is a wire that can be switched off without any moving parts. That is, in effect, the basis of the silicon transistor, an electronic switch that can be controlled by other electronic components. This “switchable” conductivity of semiconductors is what allows electronic components to talk to each other, and thus to perform logic operations, to be built into data-processing circuits—and ultimately to drive the production of these words on my computer screen, to enable me to send them at the push of a button to Princeton University Press, and to link the entire world into the most complex technological device that humankind has ever produced.

Now, that is all very useful, but it doesn't stem at once from the raw silicon that is extracted from rocks and melted down into crystalline ingots that are then sliced into wafers. That material is a semiconductor, sure enough—but in order to do its job in silicon microcircuits, the material must be tailored with awe-inspiring precision. For one thing, it must be cut up into channels and blocks, each typically narrower than a red blood cell. And its chemical composition must be finely tuned by the addition of “dopants” such as boron and phosphorus, which determine the precise number and nature of the charge carriers it contains. In making microelectronic circuitry, layers of these doped forms of silicon, perhaps just a few hundred atoms thick, are allowed to settle on a silicon wafer from a carefully blended mixture of gases squirted into a vacuum.

If we wish for silicon to emit light—for example, so that we can add light-emitting diodes to our circuitry to create visual display panels or to encode and process information in light beams rather than as electrical pulses—then we can make further modifications to the material, for example by using acid to etch it into a spongy tangle of little “wires.” Or suppose we wish to deposit a layer of a quite different semiconducting material onto our silicon wafer—one that is a better light emitter, say, such as indium phosphide or

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gallium arsenide. Then we are faced with the problem that the rows of atoms in the two crystalline materials don't match up, so that thin films will be stressed and develop cracks and other defects. One answer is to continuously "tune" the atomic spacing in the silicon foundation by mixing it with ever increasing amounts of germanium (another semiconductor) until we have a comfortable match with the atomic lattice of our second material.

In other words, silicon does our bidding in microelectronic technology by being finely modified and mixed and manipulated, even down to the level of one atomic layer at a time. This is the point we have come to in our ability to "design materials to suit ourselves." It is a principle that Gordon would have grasped easily, because he saw much the same thing happen in the preparation of new alloys from iron: steel, of course, first perfected in the Bessemer process in the nineteenth century, but also, for example, chromium ("stainless") steel, which resists corrosion, and manganese steel, from which the detrimental impurity iron sulfide has been removed. The point is that we can now blend materials like this not just in the great vats of the steel foundry but in the microscopic world of the silicon chip.

Silicon, the impact of which surely equals that of paper in transforming our information culture, was only beginning to emerge as a transformative material when Gordon's book was first written, in the days when people spoke about the "solid-state transistor radio." The first transistor, made from germanium, was created in late 1947, and commercial silicon transistors went on sale in 1954. Jack Kilby at Texas Instruments and Robert Noyce at Fairchild Semiconductor Corporation more or less devised the integrated circuit—the prototype of the silicon chip—in 1959, and Fairchild produced them commercially two years later. The first chips were meager affairs of barely half a dozen electronic components, but Noyce went on to found Intel in the year *The New Science of Strong Materials* was first published. Three years later Intel announced the first microprocessor chip, the Intel 4004; but the company's cofounder, Gordon Moore, had already made his famous pronouncement of "Moore's Law" in 1965, when he observed that the number of components in an integrated circuit was increasing exponentially. This is usually now expressed in the form that the number of components in a given area on a chip doubles every eighteen months—not exactly what Moore said, but

nevertheless a statistic borne out by the microelectronics industry in the decades that followed. To an engineer like Gordon, who cut his wings building boats from wood and steel, all of this must have seemed in the late 1960s like an exciting advance—not yet a revolution, perhaps, although that was what it was—in another field entirely. Today we recognize that the science of materials underpins the construction of silicon chips just as it underpins the construction of aircraft.

Where Gordon did glimpse a broadening of the science of materials was in energy production—not least, perhaps, because traditional metallurgy and the development of strong, robust materials had much to contribute to the burgeoning nuclear power industry. But Gordon perceived—and he is being proved right—that the future of the energy industry might come to hinge, on the one hand, on developing new materials that could lead to lower energy use, and on the other, on making use of renewable resources. His work on composites and plastics had convinced him that it was possible to combine toughness and stiffness with light weight: the ideal combination for a vehicle that needed to be crash resistant without having to burn vast quantities of oil in order to move a load of metal armor-plating. And “if we are going to go out and actually collect energy from primary sources, such as the sun and the wind,” he said, “then we shall probably need to invent and to make use of a whole new range of materials.”

Silicon, it turned out, was the answer here too. The first silicon solar cell was created by U.S. scientist Russell Ohl, working at Bell Laboratories in 1941 (where the transistor was invented six years later), and in 1954 a team of Bell researchers put together a practical silicon photovoltaic panel. Silicon is still the mainstay of photovoltaic technology today; but it is not the most efficient material in converting sunlight to electricity, and neither is it particularly cheap. These drawbacks still limit the application of solar energy. But Gordon hinted at a different approach: “plants are superbly good at collecting the energy of sunshine but the structures and materials which they use are different from those which are popular with the modern engineer.” Indeed they are: nature’s solar cells are the “photosystems” of plant and bacterial cells, made up of proteins and light-absorbing pigment molecules embedded in soft membranes. They are, even when operating at peak performance, no more energy efficient than silicon, but nature produces

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her solar cells so cheaply that she can afford to discard them every fall and grow them again in the springtime. Nature does not exactly power living cells using electrical current; rather, the energy of captured sunlight is used to pile up electrical charge on one side of a membrane, and as it is discharged, the energy that is released is used to make energy-rich molecules that drive the biochemical processes of the cell. But the initial stages of this process of photosynthesis are just the same as those in a silicon photovoltaic panel: light is absorbed, and its energy moves electrically charged particles (electrons), creating a current.

Now Gordon's implicit message is being heeded, as scientists seek to learn lessons from nature to devise entirely new types of solar cells. Making electrons mobile means freeing them from states in which they are more or less bound to individual atoms: it is rather like pulling them out of a hole in the ground so that they can roll about. But because the "hole" is left with a positive electrical charge, it attracts the negatively charged electron, which therefore has a tendency to fall back in and contribute nothing to the light-induced current. In the photosystems of living cells this "recombination" is prevented rather effectively by ferrying a free electron quickly away from its source on one molecule, passing it along a chain of other molecules. A slab of silicon in a photovoltaic panel, in contrast, is like a piece of ground dotted with holes that the mobile electrons must negotiate. So some of the new "biomimetic" solar cells seek to separate the *source* of the electrons from the materials or components that conduct them to the current collectors. They don't use the same materials as photosystems, but they exploit the same principles.

In fact, solar cells are even being developed that *do* use natural photosystems—extracted from spinach leaves, no less, and kept active in artificial membranes that could be coated onto a solid surface, creating a new kind of biosynthetic hybrid for generating clean energy.

What comes naturally

This kind of thing is considerably beyond anything that Gordon envisaged, but I don't believe he would have been perplexed by it. The notion of learning from nature's biological materials is implied in much of what he wrote. After all, no one can work on

composite materials without appreciating that nature had the idea first, particularly in developing toughness and flexibility from a combination of hard, brittle mineral and soft, deformable organic tissue. That is how bone is composed, for example, where grains of the mineral hydroxyapatite (a form of calcium phosphate) are deposited within a matrix of collagen protein. Scientists seeking artificial “bone substitutes” for biomedical implants have long appreciated that finding the right material is not about hardness or strength but about a highly sophisticated and fine-tuned combination of these characteristics with flexibility, toughness, lightness, and—crucially, but also most challengingly—compatibility with biological tissues, so that real, new bone can fuse with the implant. Composite materials, which combine metals with polymers, coated with a biocompatible ceramic, are proving to be some of the most promising bone substitutes.

And for lightweight armor, it is hard to improve on nacre, the laminated mother-of-pearl that encases some mollusks. Nacre is a composite in which sheets of hard mineral (calcium carbonate) are interleaved with soft, protein-based tissues that glue the sheets together. Gordon understood just what was going on here: the “weak interfaces” provided by the organic layers prevent cracks from propagating from one face of the shell to the other, by deflecting them sideways. This happens in the plate-like mineral mica too, Gordon explains, and also in the dentine of our teeth, which have a composition similar to bone. And the same principle is applied in plywood. At Farnborough, Gordon worked on the construction of airplanes from laminated wood, and he writes—as though the memory were as recent as yesterday—that “I suppose we could hardly have won the War without them.”

The same general principle of stopping cracks by dissipating their energy at weak “sacrificial” interfaces operates in other composites on which Gordon worked, such as fiberglass and whisker-reinforced ceramics. He tells us with glee how the notion of making tough materials from glass was still bizarre to many people in the 1940s: the suggestion of using fiberglass domes in the cockpits of Lancaster bombers was greeted by one air marshall with the exclamation “*Glass! – Glass!* I won’t have you putting glass on any of my bloody aeroplanes, damn you!”

But it was, as we have seen, wood that won Gordon’s greatest admiration, and the materials scientist will today read his praises

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of this paradigmatic natural material with a wry smile: “It is rather strange that so little attention has been given so far to the mechanical properties of biological materials, though perhaps in human terms this is understandable. . . . [E]ngineering has been going through a phase of rejecting natural materials. Metals are considered more ‘important’ than wood, which is hardly considered worthy of serious attention at all.” In that much, at least, the pendulum has swung since Gordon wrote his book, for today biological materials are very much in vogue, and are (rightly) regarded as supremely “engineered” materials to which modern synthetic “advanced materials” can only aspire.

A large part of this change was Gordon’s doing. He has been called, with justification, the founder of the modern field of biomimetics: the attempt to learn and replicate engineering principles used in the biological world. At Reading, Gordon’s faith in the virtues of natural materials such as wood and leather was shared by biologist Julian Vincent, now a world leader in the field of biomimetic materials. The word “biomimetics” itself was coined in the United States for a project funded by the air force. This was apparently instigated when the project leader happened to pick up a copy of Gordon’s *Structures* in an airport (I doubt that you would find a book about aircraft failure in such places today) and became an instant convert to his discussion of the shock resistance of bird feathers, the mechanical advantages of the flexible membrane of bat wings, the truss structure of muscles and tendons, and so forth. It was a compelling vision.

Wood itself illustrates many of the features that materials scientists now seek to emulate; for example,

- a cellular structure, providing flexibility and a high work of fracture, and localizing damage (“What really pays off for most of the common purposes of life is holes,” says Gordon. “Nature tumbled to this a long time ago when she invented wood.”);
- a composite structure of fibers held together in a matrix of “glue”;
- controlled orientation of fibers, providing toughness from the “woven” texture;
- a “hierarchical” structure, in which there are many different “levels” of structure at different scales of magnification—

from the scale of individual cellulose molecules to the scale of whole trees; and

- adaptability: being a “living” material, wood will adjust to the conditions it experiences, as for example a tree thickens its branches where they are most stressed.

The last of these properties is perhaps the most remarkable, and farthest from our grasp. Bone has the same characteristic, as it is actively being created and dismantled by specialized cells in response to the mechanical loads placed on it. This represents one of the major difficulties for bone-replacement materials, since their different mechanical properties can alter the loading on surrounding bone, causing it to be remodeled in ways that could make the implant come loose. In their natural setting, biological materials differ fundamentally from our synthetic materials in that they are always works-in-progress, being constantly degraded and reshaped. That reflects the stark contrast between how our materials are made—in laboratories and factories much bigger than themselves—and how nature fashions its fabrics in factories that can be seen only under the microscope. But even this may change, if advances in nanotechnology—science and engineering at the scale of nanometers—and in the even newer discipline of synthetic biology live up to their promise. Here, either artificial “machines” or living cells might be engineered to generate new substances, perhaps with hierarchical structures as complex as those of wood and bone.

Of course, wood is not perfect. It rots if it is damp, and that is often a disadvantage, especially if it is holding up your home. But even this can be beneficial in some situations, since it makes wood biodegradable, and without any toxic by-products. In this context, things have changed since Gordon wrote that “one of the biggest contributions to the economy would be to make consumer durables ‘durable.’” In his day, “the biggest single reason for throwing things away is probably rust,” and so plastics offered an attractive solution that seemed likely to cut down on waste. That the influence of durable plastics has not been wholly benign is an illustration that (as Gordon would doubtless have averred) materials culture cannot be considered in isolation from economics and social change. Plastic artifacts are thrown away in disturbing quantities, and not so much because they break or corrode but

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because their very cheapness suggests that they are “disposable”—when plastic shopping bags are free, why save them? The plastic casing of electronic goods such as personal computers and mobile phones might be as good as new when they are dumped—indeed, the devices as a whole might be fully functional—but they are obsolete or unfashionable within a year. And most of this plastic is anything but biodegradable, although the “embodied energy” in petrochemical products is distressingly high. It is not hard to understand the allure of plastics to the materials scientist of the 1960s, but not hard either to understand why that promise has in many ways not been fulfilled.

From structures to functions

Time has not diminished the argument for why you should read *The New Science of Strong Materials*. Scientists and engineers are still interested in making some materials that are strong, and in fact they search for new extremes of strength and robustness and endurance, for example to extend the boundaries of aeronautical and space technologies. And the problems that they encounter in this quest have not changed significantly over the course of three and a half decades—they still need to stop cracks, to manage stress, to control creep and ductility and dislocations. There remains no finer and more enjoyable an introduction to these concepts than that which Gordon provides. But you don’t need to be a budding materials engineer to find the book fulfilling—you need only have an ounce of curiosity about the workings of the world, and in particular about why the human-made environment is designed the way it is. Gordon caters to sailors (of course) and architects, to silversmiths and natural historians, and perhaps most especially to anyone who cares about how to use language effectively to illuminate and captivate.

Yet there is no denying that materials science today is not what it was when Jim Gordon wrote his book; indeed, one would hope it weren’t. If one were to pick out a single theme to describe how the discipline has evolved over the past three or four decades, it could arguably be the shift from *structure* to *function*. Tomorrow’s floors might not just prevent us from falling through them, but may change color or texture or resilience, clean themselves, and detect our presence (and identify us individually and

sound the alarm if they don't recognize us). All of those things are in some sense already technologically possible, although it is not by any means clear that the demand for floors like this will be sufficient to make them economically viable. The point is that many advanced materials today *do things*. Plastics that emit light (of a tunable color) when stimulated by electrical currents offer television screens with the shape, weight, and consistency of a sheet of paper. "Electronic paper" with reconfigurable "ink" is almost ready for the marketplace. "Smart" materials act as sensors—of heat, light, sound and pressure, and chemicals—and release a warning signal when they detect their environmental trigger. Window glass coated so that absorbed sunlight burns up contaminants on its surface makes possible new extremes of architectural invention: you can now place windows where no cleaner could ever reach them. There is, in short, an ever more blurred boundary between what is a "material" and what is a "machine." In this sense, materials science is heading toward a possibly paradoxical destination in which it will have rendered its fruits invisible. The materials of former ages had a monumentalist tendency: they lent themselves to the construction of great structures such as Wells Cathedral (depicted in this book) and the Brooklyn Bridge. We are still building on this scale, of course, and quite possibly we always will, even if the result is something as clumsy and useless as the International Space Station. But tomorrow's materials—the materials not yet invented—will not advertise themselves. They may very well pretend to be something else, if we even see them at all. For one thing, much of engineering is getting smaller, so that form is not dictated by the issue of where to fit all the "machinery": computer design now has nothing to do with the silicon chips that make the whole thing possible, which you could fit into a wristwatch. But equally, it is as if materials are making engineering itself aspire to a kind of invisibility, as in, for example, the television screens that are becoming ever more slimlined until they have essentially lost an entire dimension. These materials are receding into the ambient, perhaps to the point where we will be surrounded by a "smart" environment that responds to our needs without any of the cogs and levers being visible, because indeed there will be no cogs and levers. We will speak to an empty room, and it will become what we ask of it.

That may sound to some like a rather bleak prospect, and I

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would not like to guess at what Jim Gordon would have made of it. I suspect he was the kind of person who delighted in the cogs and levers, who liked to see the wheels in motion, who relished the *materiality* of the world and would have lamented its disembodiment. But I don't feel he would have been disheartened by what materials science offers today, because we are as interested as ever in building things, whether that be a more efficient wind turbine or a "space elevator" that carries objects up a cable into earth orbit. There will be no lack of challenges for those who delight in devising strong materials and finding useful ways to put them into action.

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