The slender bow of the Infinity Bridge in Stockton, UK, is tied together through the deck to avoid the need for massive foundations.

ECO-ENGINEERING

Living in a materials world

From concrete to plastics, the megatonnes of stuff in the built environment are mostly manufactured and used with little thought for waste and pollution. Radical moves are afoot to refashion the urban fabric.

To the eco-engineer, the glass is neither half-full nor half-empty. It is simply twice as big as it needs to be. Building with maximum efficiency and minimal materials is increasingly urgent in our resource-strapped times. Many of today's structural engineers and designers are looking to natural forms and materials as the tried-and-tested guide.

The power and economy of evolved 'design' — eggshell, spiderwebs, bone — are inspiring architects to experiment with solutions that work in harmony with physical forces and mimic biological form. Meanwhile, others are embracing 'extreme upcycling' in the flow of materials through the urban fabric, exploring ideas from edible upholstery to walls created from substances sourced in beetle exoskeletons.

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Here, we look to the design ideas of three top players in the materials world: Olympic Velodrome engineer Chris Wise on lean, intelligent structures; architect and biomimicist Michael Pawlyn on a 3D-printed built environment; and chemist Michael Braungart on manufacturing beyond sustainability. ■

CHRIS WISE

Build with an eye on nature

The Olympic Velodrome engineer on designing for strength and elegance.

More than 300 years ago, Antonio Stradivari was making beautiful violins, each weighing a few hundred grams yet able to fill the largest concert hall with soul-lifting sound. Stradivari would never have said, "For safety, I'll double the thickness of the wood". If designed like most modern buildings, his violins would play like tree trunks. Stradivari's structures are balanced, natural systems: no imitations of birds' nests or deliberate distortions of geometry in the name of 'architecture' here.

Today's engineering is too full of 'tree-trunk' buildings: underdesigned, and over the whole planet. Astonishingly, the materials used in every three buildings designed in this lazy way could make at least four buildings — and with intelligence, even six.

Yet although humans have known about harmony between materials and structure for generations, every engineer, on every project, faces a mental battle with fear and hope.

RUSSELL SMITH/STOCKTON-ON-TEES BOROUGH COUNCIL

Engineers are taught to design from fear, to avoid failure. The construction industry reinforces this, rewarding those who take the fewest risks, sacrificing our global material and energy stock on the altar of expediency. Dare we hope for wiser engineering, with beautiful performance from the least material?

Occasionally, special projects allow us to try. My firm Expedition Engineering was structural designer for the Velodrome in London's 2012 Olympic Park and the Infinity Bridge in Stockton, UK. Both won Britain's top prize in structural engineering, the Institution of Structural Engineers' Supreme Award for Engineering Excellence.

Both structures are 'form-found', shaped to be in equilibrium with the forces acting on them. Catalonian architect Antoni Gaudí first popularized the technique. His Sagrada Familia cathedral in Barcelona, Spain, begun in the 1880s, was effectively shaped upside-down — Gaudí's models were bags of sand hung from tension strings. Form-finding now uses digital-analysis engines for the behaviour of everything from cats' cradles and soap bubbles to giant basket-like grid shells. This way, structures can be sculpted to carry loads either in pure tension (like a spider's web) or in pure compression (like an eggshell).

Such structures embody the ancient Greek ideal of an inner beauty, carrying maximum load with minimum material in a way that cannot be bettered. Despite humanity's love of graceful curves and our need to use materials wisely, form-finding is still the exception. It should be the rule.

The Velodrome spans 130 metres with a tension roof structure only 76 millimetres thick; roofs of other stadia worldwide covering a comparable area are often metres deep. The Velodrome design achieved that lightness by letting nature lead, following the forces until they reached the equilibrium shape of a saddle in pure tension, anchored directly to the curved seating bowl. The forces are carried in harmony completely within the structural geometry, rather than outside it. It's an old trick much loved by the builders of Gothic cathedrals, although now we use a tension system of machine-woven steel cables, rather than a compression system of individually hand-cut stones.

If the Velodrome is a structure acting in tension, Stockton's double-arched Infinity Bridge is its complementary opposite. Through pure compression, the arches' shapes carry their own weight and the suspended deck: all the heavy forces are carried down the absolute centre of the structure. Because they are linked into a structure resembling an archer's bow, the two arches also act like a giant see-saw to resist the much lighter fluctuating weight of crossing pedestrians. (An adaptive bridge geometry, that changes continually in response to pedestrians' movement, could be coming soon.)

The ancient Roman Alcántara Bridge in Spain shows how far arches have evolved. The Romans did not know exactly where their forces went, so hedged their bets by infilling the massive individual masonry arches with cemented rubble to guarantee a pure compression line at least somewhere within the structure. Centuries later, the suspension bridge emerged. From Bristol's Clifton Suspension Bridge to San Francisco's Golden Gate, these are structures of great efficiency, but demand extraordinary tension anchorages buried at each end to hold the main suspension cables.

Infinity avoids such foundations by using tension cables in the deck to tie the ends of the arches together: the whole bridge just kisses the ground lightly at each end. The flow of the forces is written into the air in ultra-slender structural steel, rather than hidden inside approximately shaped stonework weighing thousands of tonnes.

Confident engineering comes from proper understanding of the natural phenomena to which it will be subject, and the more experimental, the more chance there is that something will catch us out. In the late 1990s, I was the engineering firm Arup's director for London's Millennium Bridge spanning the River Thames. It, too, was an off-piste, pure-tension natural structure. Too natural, perhaps: on its opening day, it wobbled harmonically like a giant guitar as the lateral sway of pedestrians' gaits became the vibration of the bridge. That wobble, however, forced a research project to find the cure: energy-absorbing dampers, choreographed by the late Arup engineer Tony Fitzpatrick and published for all to use. The lessons learnt there fed into Infinity a decade later.

Despite these examples, and others from the likes of German architect and engineer Frei Otto, the late Peter Rice, and Tristram Carfrae at Arup, engineering suffers from a chronic sickness for which the construction industry is both cause and potential cure. 'Normal' fees for most engineering commissions are still based on a percentage of the construction cost: the more material you use, the more expensive the project, and the bigger your payout as an engineer.

Construction regulations are full of emotive words, such as 'collapse' (avoid it) and 'vibration' (get rid of it). Beyond these sanctions, they are largely silent. There is nothing in most commissions to encourage engineers to use less material, so they don't. Yet if engineers were educated to design, say, perfectly tailored beams instead of off-the-shelf steel joists, we would cut about 30% from the millions of tonnes of steel beams used yearly. This should become the industry norm.

Confident engineering comes from proper understanding of natural phenomena.

The huge construction supply chain also requires huge investment in new technologies. If manufacturers will not retool on a speculative basis, engineers need other research partners for innovative alternatives, such as those 'perfect' beams whose shape is tuned to the bending in them.

Infinity, the Velodrome, Otto's Olympic Stadium in Munich, Germany, and the Strad violin demonstrate what is possible. It may be ancient, this job of doing for a penny what any fool can do for a pound, but some of us seek performance through harmony between materials and natural forces. We design in hope, not fear — and with an eye on nature. ■

Chris Wise *is a design engineer, co-founder of Expedition Engineering, Professor of Civil Engineering Design at University College London, and last year was awarded the gold medals of both the UK Structural and Civil Engineering Institutions for his design work.*
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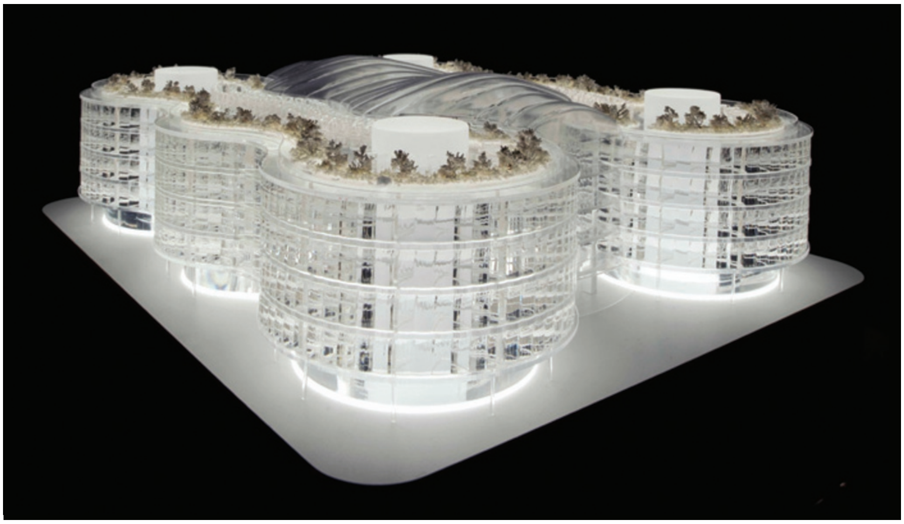
DAVID POULTNEY/ODA

London's 2012 Olympic Velodrome was built with the minimum of materials.



EXPLORATION

Exploration Architecture's biomimetic office building borrows from skulls and shells for form and function.

MICHAEL PAWLYN

Push the limits of 3D printing

The biomimicist and architect on materials that borrow from nature.

Biomimicry — the development of solutions based on biological adaptations — is one of the most exciting frontiers in design. After 3.8 billion years of natural research and development, organisms have solved many of the technical design problems that humans grapple with, but with a much greater economy of means. A key challenge for designers and architects is how to duplicate that finely realized engineering with the right materials.

Birds, for example, have evolved in response to particularly intense selective pressure on weight. The result is maximum strength, minimum mass. A magnified cross-section of a crow or magpie skull shows multiple bony shells connected by a matrix of ties and struts: an astounding combination of shell action (delivering material efficiency through its stiff shape) with space-frame technology (an inner structure subdivided for strength). Folding, vaulting and ribs in natural morphology can give organisms great structural efficiency.

But, as biomimetics expert Julian Vincent says, in nature "shape is cheap but material is expensive". In architecture the opposite applies: manufacturing complex forms for a building is nearly always more costly than handling simpler, more monolithic elements.

A digital manufacturing revolution is dawning that could dramatically change that equation. Three-dimensional (3D) printing or 'rapid prototyping' emerged in the 1980s, allowing designers to turn a computer model into a physical one accurately, with minimal labour, and at ambient temperatures and pressures. Architects have long used 3D printing to create design-development prototypes, and it is also used to manufacture custom-designed small objects. Now, the possibility of mass production beckons, thanks to three advances: 3D printers big enough to produce the larger elements needed, a greater range of printing materials, and the plummeting cost of the technology.

My architectural practice has been working on designs for a biomimetic office building that strive for the material efficiencies found in biology. The aim is to create floor slabs that get close to the substantially hollow structure of bird skulls, and glazing systems with extremely thin glass, curved to mimic shell forms, to provide the required stiffness.

Since 2009, several small buildings have been 3D printed from materials similar to concrete. But these lack the efficient microstructures found in biology, such as the fine latticework of glass sponges or the complex of voids in bone, and have limited potential for recycling. In the next few decades, it should be possible to use natural, endlessly recyclable polymers such as cellulose, which is found in wood, or chitin, a component of insect and shellfish exoskeletons. Materials made with 1% of the embodied energy of conventional ones, in structures ten times as efficient, could revolutionize manufacturing and construction.

Much of this may be beyond our current capabilities, but it is not the realm of fantasy: the natural world is living proof. ■

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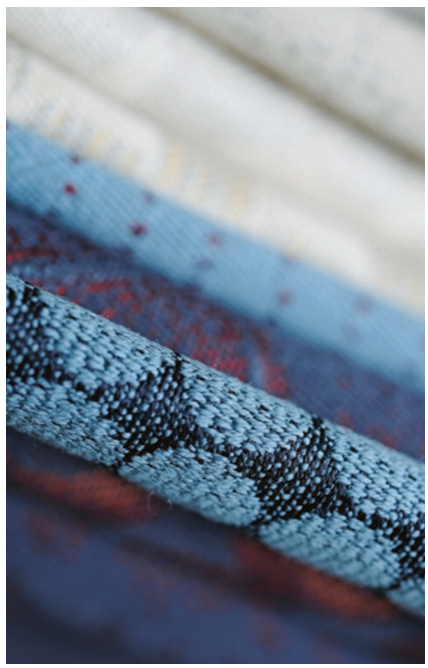
MICHAEL BRAUNGART

Upcycle to eliminate waste

The chemist recasts materials as 'nutrients' in an endless loop.

Fundamentally rethinking materials as either harmlessly biodegradable or endlessly recyclable substances can transform them into something akin to nutrients nourishing the 'metabolism' of industry. Using these overarching principles of 'cradle to cradle' design and 'upcycling' (recycling to improve a material's value), architect William McDonough and I developed guidelines and criteria for products to fit this frame. More than 400 products have been certified, from bricks and plastics to babies' nappies and lighting.

Biodegradable, non-hazardous materials have a vast array of uses in products ranging from car tyres to textiles. When the products are worn out, the constituents are broken down to renew the raw materials. For example, the Climatex Lifecycle fabric produced by Swiss company Gessner in Wädenswil, and widely used on office furniture, is the first textile safe enough to eat. It is 100% recyclable and made with cellulose fibres, non-toxic dyes and wool from sheep that have been cared for ethically and responsibly. The water coming out of the plant is tested by the local ministry and is cleaner than when it went in. Textile scraps from the factory are sold to local farmers to use as mulch, helping to renew the soil.



GESSNER

Climatex 100% recyclable textiles are safe enough to eat.

Non-biodegradable products, such as glass bottles and television sets, can be recycled in safe, perpetual cycles, eliminating the need to use anything but recyclable raw materials. These metals, rare elements and approved synthetic materials do not physically degrade, and because they are not discarded will not come into direct contact with the environment.

Leasing and take-back systems (in which the manufacturer recycles the used product) are another way of making upcycling work, partly because they allow the use of higher-quality recyclable material that can take more wear. Companies already lease cars, but carpets — traditionally laden with chemicals such as chlorinated pigments, which persist in the environment and are often toxic — can also have many incarnations. The Dutch carpet manufacturer Desso, based in Waalwijk, makes polyvinyl chloride (PVC)-free carpets that improve air quality, because the patented fibres capture particulate matter from the atmosphere. Desso's take-back system even extends to PVC-free carpets that have been produced by other companies. In recycling, the carpet backing is reused and the yarn is rewoven into new carpets.

Raw materials and energy supplier Van Gansewinkel, headquartered in Eindhoven, the Netherlands, goes one step further. The company helped the Dutch mattress manufacturer Auping to design a take-back system for traditional mattresses as well as their own recyclable products. The steel in the mattresses is melted and reused; the foam is recycled as judo mats. Van Gansewinkel has also developed a continuous loop of high-quality recycling for office paper. It collects used paper from customers, sends it to the paper company Steinbeis in Stuttgart, Germany, for sustainable recycling, and with its partner Océ, based in Venlo, the Netherlands, supplies customers with the 100% recycled paper.

Nature does not respond to interdependence by seeking to minimize itself out of existence, but by growing and flourishing. Similarly, the key to generating a productive and sustainable economy is not through strategies of damage control and minimization, but through nourishing the industrial metabolism. ■

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THEATRE

The needle in Newton's eye

A play about Isaac Newton's self-experimentation illuminates scientific rivalry, finds **Alla Katsnelson**.

Scientists occasionally conduct experiments on themselves. Among the most famous was Isaac Newton's extraordinary method for probing the nature of colour. He stuck a bodkin, a long sewing needle with a blunt point, into his eye socket, between eye and bone, and recorded seeing coloured circles and other visual phenomena. In his new play, *Isaac's Eye*, Lucas Hnath uses this bizarre experiment to explore scientific rivalry, the nature of truth and knowledge, and how the narratives of science and life congeal.

Isaac's Eye headlines the fifteenth annual First Light festival, a collaboration between the Alfred P. Sloan Foundation and the Ensemble Studio Theatre in New York to fund drama that explores scientific concepts and personalities. Hnath has looked to science for creative fodder since his undergraduate days at New York University. His first such work, which won a Sloan-sponsored writing competition, was a screenplay whose protagonist, computer scientist Adan Turner, finds himself imitating Alan Turing.

> ***Perhaps the real story is in how truth is told and perceived.***

"I tend to write characters who try to push some kind of limit — who are trying to experience something that no one has ever before experienced," he says. "Inevitably, you have to deal with science if you go in that direction."

In his new drama, Hnath plays with history, presenting a fictional backstory to the legendary conflict between Newton, when he was still unknown, and the well-respected physicist Robert Hooke. "There's a law named after me," Hooke brags repeatedly throughout the play. In 1665, when the play is set, the plague is ravaging England while an ambitious Newton is being eaten away by the desire to join the Royal Society. Newton writes repeatedly to Hooke — then-Curator of Experiments — demanding that he be considered for membership. Receiving no reply, he sends Hooke a package containing the sole copy of all his writings. When Hooke sees that much of Newton's research treads the same ground as his own, he decides to visit Newton and take him down a peg or three. The fictional encounter shakes up the course of both men's lives, as well as that of Catherine Storer, an apothecary's daughter who may have been a youthful romantic interest of Newton's.

Isaac's Eye
ENSEMBLE STUDIO THEATRE, NEW YORK CITY
Until 24 February 2013

The tension between the childish Newton, with his unpleasant moralistic streak allied to a tendency to fight dirty, and the callous, hedonistic Hooke, fuels the gripping narrative. Catherine, a realist, grounds the saga by trying to tempt both men to give up research for a mundane life. But perhaps the real story here is in how truth is told and perceived. Historians have criticized Newton for embellishing facts: his theory of gravity, for example, might not have been inspired by a falling apple. This tendency towards myth-making emerges early in the play, when Hooke accuses Newton of writing up experiments as though they were conducted in a single afternoon. Newton can't grasp the criticism. "It's clearer that way," he responds.

Sensing Hooke's reluctance to support him, Newton tells a lie. He claims that he has stabbed a bodkin under his eye to prove his own theory about the nature of light — and disprove Hooke's. Hooke calls his bluff, but when the scientists perform the experiment for real — first on a semi-willing subject, then on Newton — the truth is no clearer. The wincing in the audience during these highly realistic scenes was almost palpable, however.

"In some ways, this play is about how many liberties you decide to take when trying to convey something that's true," says Hnath. To help viewers sort fact from fiction, Hnath employed the conceit of a nameless narrator who uses cardboard signs and a chalkboard to wrangle known facts about the two scientists' lives into a list of bullet points. It's the seventeenth-century version of PowerPoint. But in the end, tweaking reality — as Hnath so skillfully does — might provide the clearer picture of the human truths in this scientific tug-of-war. ■

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