rapidly than those threats are realized.

Beyond Kahn, optimism that political consensus will outpace the threats of climate change is in short supply. There are numerous examples of long-lasting policy distortions that seem inviolate to change. Jared Diamond's *Collapse* (Allen Lane, 2005) offers a litany of disturbing tales of unchanged behaviour in response to fundamental societal threats. It is more probable that we will behave like the proverbial frog that remains in a pot of slowly warming water brought to the boil than like the real frog that jumps out.

Kahn is adamant that the best way to deal with the risks of climate change is to rely on private insurers to decide how to price them. There is much to be said for relying on pricing mechanisms to deal with uncertain risks, and one does not have to look far for examples of failed public interventions in financial markets that have stopped these mechanisms from working. However, one wonders where Kahn has been over the past few years. Few people in Greece, shocked by the lack of transparency in their country's finances, are likely to share his view that "mutually beneficial trades" between cities and Wall Street will result in safer municipalities.

The private sector will have an important part to play in pricing and allocating the risks of climate change. But to suggest that its unfettered pursuit of its own ends will be socially optimal is so simplistic that it could undermine the reader's confidence in one of Kahn's central points — that an economic perspective on climate adaptation has value. That would be a shame, because he has a great deal to offer even if his presentation is incomplete. The question of how to price the risks of climate change has received attention in reports such as the 2006 *Stern Review on the Economics of Climate Change*, which show how small changes in assumptions can have enormous effects on policy. Simply saying that we must allow these risks to be priced by markets is not enough.

Climatopolis documents the thinking of a first-rate economist on one of the most pressing issues of our time. It is breezy but robust. I recommend it to those who would ensure their scientific and environmental perspectives on climate change are accompanied by a sound economic perspective. Kahn shows the range of linkages between science, geography, the accidents of history and behaviour. Although he takes some liberties with his prescriptions, he does so with verve. I hope he keeps at it, either on his blog or as a more-precisely argued text for university courses. ■

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SYNTHETIC BIOLOGY

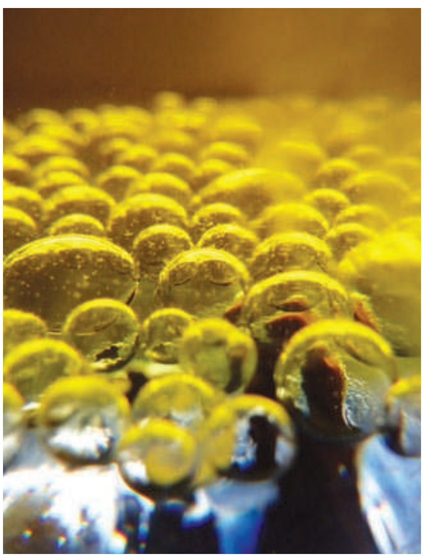
Living quarters

Synthetic biology could offer truly sustainable approaches to the built environment, predict **Rachel Armstrong** and **Neil Spiller**.

Architects have long drawn inspiration from the forms and functions of natural systems. Yet biological cells and organisms have requirements — such as nutrition and growth-support structures — that limit their use in construction. Synthetic biology offers new ways to combine the advantages of living systems with the robustness of traditional materials to produce genuinely sustainable and environmentally responsive architecture.

In the context of climate change and urbanization, there is a pressing need to replace construction methods that are harmful to our habitat with sustainable ones. Architecture is currently responsible for 40% of the urban carbon footprint, mostly due to emissions from fossil fuels burned during the various stages of materials manufacture and building construction. As global populations rise — approaching 9 billion people in 2050, 70% of whom will live in cities — carbon emissions from the built environment will increase. If we continue to build with steel and concrete, even the most stringent energy-saving measures will not curtail greenhouse-gas production. Even green roofs and walls need energy-intensive support systems to maintain them within an artificial setting.

Strategies will be required to achieve 'carbon negative' buildings, including innovative retrofitting, energy harvesting, recycling of materials and the use of elements that interact with and respond directly to the environment. Chemically active interfaces could alter microclimates around surfaces and act as 'environmental pharmaceuticals'. For example, coatings could absorb carbon dioxide on building surfaces, adsorb pollutants or trap dust particles electrostatically.



R. ARMSTRONG

Surfaces containing artificial 'cells' that absorb carbon dioxide could make buildings greener.

BIOLOGICAL BUILDING BLOCKS

The tools of synthetic biology are galvanizing the development of new forms of architecture that respond to environmental change by incorporating the dynamic properties of living systems, such as growth, repair, sensitivity and replication. Still at an early stage, diverse interdisciplinary collaborations are springing up to find new uses for top-down genome engineering and bottom-up chemical self-assembly techniques, including trapping carbon dioxide and producing energy-efficient materials. Challenges to be overcome include the sustenance and support of biological systems within the built environment, bioethical concerns and ensuring public safety.

Researchers are developing promising examples of biological systems that can fulfil architectural functions. Bacteria commonly found in the environment — such as *Micrococcus*, *Staphylococcus*, *Bacillus* and *Pseudomonas* species that also linger in air — may be adapted for use as biosensors. A new centre at the University of Oregon in Eugene plans to coordinate research that links architecture and microorganisms, both existing and designed. The university's Biology and the Built Environment (BioBE) Center, awarded funding this summer from the Alfred P. Sloan Foundation in New York, will investigate the 'microbiome of the built environment' — the complex bacterial ecosystems that occur within buildings and their interactions with humans and the environment. Such relationships are important, for example, for maintaining indoor air quality.

Species of another airborne bacterium, *Brevundimonas,* show promise as an indicator of indoor pollutants: some can metabolize toxins such as arsenic, and could be genetically

COURTESY C. KERRIGAN

Venice's sinking foundations might be supported by growing an artificial limestone reef generated by programmable man-made 'protocells'.

modified to change colour in the presence of a range of heavy metals. Other types of bacteria might be grown decoratively on walls or roofs to signal levels of harmful pollutants in cities. For example, undergraduates from the University of Cambridge, UK, engineered the bacterium *Escherichia coli* to change hue in the presence of an inducer, a system that could be adapted to detect heavy metals. This was just one of many pioneering entries in the 2009 International Genetically Engineered Machine (iGEM) synthetic-biology competition at the Massachusetts Institute of Technology in Cambridge.

Innovative forms of lighting that use bioluminescent bacteria are being investigated by microbiologist Simon Park at the University of Surrey in Guildford, UK. In 2009, with artist Anne Brodie, he demonstrated a photographic booth that takes portraits using the ethereal light generated by *Photobacterium phosphoreum*. A glowing Christmas tree produced in 2007 by biologist Edward Quinto of the University of Santo Tomas in Manila, using bioluminescent *Vibrio fischeri* bacteria from the guts of squid, raises the possibility of using luminous trees for street lighting.

Biological structures can inspire entirely new construction methods and materials. Terreform One, an interdisciplinary architectural design practice in New York, has envisaged growing a leathery skin for covering buildings, dubbed 'Meat House'. By transforming pig cells and using large-scale three-dimensional printing techniques to establish the structural framework, the skin would be grown to the required shape and size and then fixed with preservatives. Its biodegradable nature would avoid the need for later demolition. The technique is prohibitively expensive — around US$1,000 for three square centimetres of skin — but it demonstrates the alternative approaches offered by synthetic-biology techniques.

SCIENCE AND THE CITY
Full content and enhanced graphics at: nature.com/cities

The greatest challenge in applying synthetic biology to architecture is to fabricate accurate scaffoldings for the production of engineered tissue and materials. Natural forms are difficult to model with computers because they do not follow simple mathematical functions, and so translating them from the cellular to the architectural scale is difficult. The Norwegian company Uformia, based near Tromsø, is developing software that will allow irregular organic shapes — such as materials mimicking the porous matrix of bone, which combines high tensile strength with low density — to be modelled digitally for printing in three dimensions.

Bringing biological cultures out of the lab into the city raises other practical difficulties. Valuable bacterial populations, such as those that fix carbon dioxide in wetlands, would be difficult to sustain in dry urban locations lacking food sources. Exposed to predatory organisms such as moulds, biological materials must be protected with antifungal substrates. And safety concerns preclude the release of new genetically engineered organisms into the environment without strict controls. For architectural purposes, simple and safe biotechnologies are preferred. An alternative approach to genetic modification is to produce self-assembling materials that are not living but that mimic the dynamic traits of organisms and are optimized to function within their specific environment.

HALF LIFE

The architectural design potential of partially living materials is being investigated by Andy Adamatzky's Unconventional Computing group at the University of West England in Bristol, UK. He and his team are exploring how hybrids of simple organisms and robots — such as the Phi-Bot, whose electronics is controlled by a slime mould — can detect and respond to light, toxins and metabolites. The behaviours of these integrated systems are more complex than can be coordinated through traditional computing methods, broadening the range of applications. Molecules that self-organize can also generate evolving patterns within structures that are traditionally inert, such as dynamic stained-glass windows.

Environmentally responsive paints and coatings for building exteriors based on the principles of chemical self-assembly are being developed at the Center for Fundamental Living Technology at the University of Southern Denmark in Odense. 'Protocells' made from oil droplets in water — so named because of their life-like properties — allow soluble chemicals to be exchanged between the drops and the surrounding solution. Responding to shifts in chemical information in time, space and concentration, the protocells regulate their internal chemistry by 'conversing' with their surroundings.

As a potential practical application, the group has engineered protocells to capture carbon dioxide from solution and convert it into a solid carbonate form, similar to naturally occurring limestone or shell. Such layers might be used in carbon fixing or in carbon-negative architectures. Their experiments so far have shown that carbonate-producing material can be accumulated; further work to stabilize these irregular shells with silicates is ongoing. Protocell systems are also being developed for insulation and environmental remediation.

Chemist Lee Cronin's group at the University of Glasgow, UK, is pursuing another type of artificial inorganic chemical cell, or 'chell', which has potential architectural uses including chemical and biological sensing to detect carbon dioxide and pollutants. The internal chemistries of the chells can be finely controlled using a digital delivery system for the ingredients, making them useful for fuel-cell technology or as chemical delivery systems for responsive surfaces.

NEXT STEPS

Distributed, self-assembling systems may one day enable buildings to grow, self-repair and respond creatively to the unpredictable effects of climate change. For example, a collaboration between the University of Southern Denmark, the University of Glasgow and our research groups at University College London and the University of Greenwich is developing living claddings. Driven by gravity feed and chemical gradients, these might produce water in desert environments and harvest sunlight to produce biofuels.

The pressing environmental problems of Venice are amenable to some synthetic-biology solutions. Our installation entitled *Hylozoic Ground*, displayed at the Canadian Pavilion at the Venice Biennale 2010 and created with architect Philip Beesley from the University of Waterloo in Ontario, Canada, showcased the recycling of carbon dioxide exhaled by visitors into solid carbonate using protocell technology. Similar deposits could stabilize the city's foundations by growing an artificial limestone reef beneath it.

The application of synthetic biology to architecture holds promise for solving major environmental problems. Further collaborations between biologists, chemists, architects and industry are needed to expand the range of tools, methods and materials available. As with any new technology, engagement with the public and with policy-makers is vital to direct future regulation that will protect public safety and address perceived risks. ■

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GENES AND DEVELOPMENT

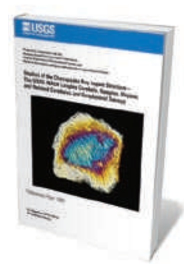
The importance of childhood

Our emotional brains are shaped by social interactions during infancy, finds **Morten Kringelbach**.

The late English poet Philip Larkin took a stark view of childhood, writing in *This Be The Verse*: "Man hands on misery to man. It deepens like a coastal shelf. Get out as early as you can, And don't have any kids yourself." Yet we clearly need to nurture children to survive as a species. And there is more to childhood than survival: our psychological state later in life is shaped by our extended infancy. Psychologist and anthropologist Melvin Konner places childhood firmly within an evolutionary framework in his magisterial book.

Synthesizing decades of research across many disciplines, *The Evolution of Childhood* highlights evidence for interactions between genes and the environment in what Konner calls the "behavioural biology of psychosocial development". He argues that it is the essence of life — and especially of childhood — to interact with, recognize and change in response to the environment. Such shifts are brought about on many levels by evolutionary algorithms.

The book is structured in four parts: evolution, maturation, socialization and culture. The first part firmly places ontogeny — the development of the individual — at the heart of evolution and explores our current understanding of the brain and behaviour in relation to it. The second section focuses on the physiological paths of maturation of neural and neuroendocrine systems, which allow psychosocial development. The third part turns to comparative cross-species and cross-cultural approaches to understanding and reconstructing phylogeny and history. The fourth considers interactions between genes and culture, and the effects of human cultural variation on their evolution.



The Evolution of Childhood: Relationships, Emotion, Mind
MELVIN KONNER
Belknap Press: 2010. 960 pp. $39.95, £29.95

The parent–infant relationship is central to Konner's understanding of childhood. Parents perceive infants' cues and respond appropriately and promptly. Such

E. MCCONNELL/GETTY

The early relationship between parent and child is crucial to later development.