

A PLACE FOR MAKING

If you could make anything, what would it be? A materials scientist will probably come up with a long list rather easily, but most other people are likely to find themselves trapped between their imagination (which might exceed the creativity of many scientists) and their ignorance of what is possible and how it might be done. The Institute of Making (www.instituteofmaking.org.uk), which opened at University College London in March, hopes to offer a way to bridge that gap between ideas and means.

The principle is elegantly simple. Anyone at UCL (and hopefully soon a wider public) can pay a modest membership fee, which entitles them to come along to the institute — an old loading bay wedged between the Petrie Archaeological Museum and the Department of Engineering, now converted into a space both stylish and functional — and use the battery of fabrication equipment to make whatever they want. The institute houses, among other things, a state-of-the-art laser cutter, a 3D printer, and various milling, moulding, casting, calcining and cutting devices, along with some wet-chemical facilities and a cooker — for experimenting with food, not for making lunch (although a bar remains under discussion).

But as director Mark Miodownik realizes, it is not enough — indeed, positively unwise — simply to make all this gear accessible to all comers. To turn an idea into a product, you need to understand the materials issues: to appreciate the virtues and limitations of different kinds of material, so as to select those that are best suited to the task in hand. This is the kind of issue on which Miodownik and the institute's creative director Zoe Laughlin regularly offered advice when they ran its previous incarnation, the Materials Library at King's College London. Much of that library — a collection of materials new and old, from pewter to aerogels and ferrofluids — is now housed in a mouth-watering display in the institute's entrance. There are no glass windows to protect the samples: visitors can pick them up and examine them, and, if they desire, use them.

The Institute of Making will offer regular workshops and ongoing instruction on the considerations that surround materials choices and use, from physical properties to aesthetic, ethical and environmental issues. This isn't merely a facility that allows people to make, but one that will teach people how to make.

That is really the institute's motivation: to disseminate the art and science of creating things.



PHILIP BALL

Miodownik imagines that some members will be researchers needing bespoke experimental equipment, but hopes that others will come from farther afield both geographically and intellectually: artists, musicians, textiles specialists — and, if all goes to plan, school children, for whom the Institute may offer a Saturday club at which, under careful supervision, they can spend the day inventing and making. “It's OK if people just come in here and mend their bikes”, Miodownik says.

It's not hard, on visiting the institute, to imagine every university principal saying “I want one too”. But what the institute's team has understood is that this is about more than creating a gallery of tools. It is about crafting an environment that is approachable, informative, safe (of course), unthreatening to non-scientists and most of all, inspirational. □

THERMAL TRANSPORT

Breaking through barriers

Understanding heat flow across interfaces remains an open question for thermal science. Nanocrystal arrays may play a key role in unlocking this mystery.

Mark D. Losego and David G. Cahill

Collective excitations such as phonons, the atomic or molecular vibrations that transport heat in a material, have always lagged behind electrons and photons, both in terms of their velocity and our scientific understanding of them. The relative difficulties of measuring heat and temperature has hindered thermal science from achieving the same level of

sophistication as electronics and photonics. Whereas electronic and optical transport have long been studied with high levels of precision (for example, reaching the manipulation of single electrons and photons), experiments on thermal energy transport have typically lacked the control and sensitivity needed to explore behaviour at the nano- and atomic scales.

Writing in *Nature Materials*, Ong *et al.* have significantly advanced this topic by examining in detail the flow of heat at organic/inorganic interfaces¹.

To illustrate the significance of this work, it is useful to contrast our understandings of electronic and thermal transport at an interface. For electronic interfacial transport, a simple model based on the aligning of work

functions may provide a degree of insight as to whether electrical conduction will follow an Ohmic or Schottky mechanism, but this ultimately fails as often as it succeeds. To achieve more predictive power, scientists have developed a fundamental understanding of interfacial electronic states and their contributions to electronic band alignment. Under this analogy, interfacial thermal transport is still at the 'simple model stage'. Acoustic impedance and vibrational densities of states influence heat flow across an interface, but simple models based only on these parameters do not fully describe experimental observations. Advances in experiment, simulation and theory aiming to isolate mechanisms and quantify magnitudes of parameters are needed if we expect to eventually generate models of predictive sophistication.

In this regard, research in heat transport is entering an exciting era. Over the past decade, optical pump–probe metrologies and micromachined test platforms² have been refined to the point of providing accurate measurements of heat flow at the nanoscale. As is often the case, advances in measurement technology enable discovery. For example, the significance of interfacial bond stiffness on heat flow was recently quantified³, while other recent studies have demonstrated significant enhancements of interfacial thermal conductance using covalently bonded molecular layers⁴ and chemically functionalized metal–graphene contacts⁵.

Ong *et al.* use an optical pump–probe technique known as frequency domain thermoreflectance⁶ to measure thermal conductivity in nanocrystal arrays (NCAs)⁷. These are a hybrid organic–inorganic material composed of crystalline nanoparticles of up to 20 nm in diameter arranged in self-assembled three-dimensional arrays (Fig. 1a). Molecular ligands chemically bound to the nanocrystal surface, and used to prevent aggregation during wet chemical synthesis, function as the matrix material in these nanocomposites. The precise control and broad selection of nanocrystal material, ligand type and periodic spacing make NCAs ideal for systematically exploring structure–property relations of interfacial thermal transport. The authors demonstrate this by measuring thermal conductivity as a function of nanoparticle size and composition, as well as ligand type. With increasing nanoparticle size, they observe an increase in thermal conductivity, in agreement with work carried out on nanolaminate structures⁸. This behaviour is easily explained using a combination of effective medium theory and reduced interface density.

Perhaps more uniquely, Ong *et al.* also establish a clear relationship between nanoparticle composition and interfacial thermal conductance. With support from atomistic simulations, they conclude that the upper limit of the nanocrystals' vibrational frequencies limits interfacial heat transport in these systems (Fig. 1b). Whereas organic ligands containing light elements can sustain high-frequency vibrational modes, nanoparticles such as PbTe are characterized by a low Debye temperature (a parameter assessing the highest vibrational frequency of a crystal). By using nanocrystals with higher Debye temperatures, such as Fe₂O₃, the authors show more than a twofold increase in thermal conductivity of the NCA. This is a direct consequence of the increased number of overlapping, heat-carrying vibrational modes between the nanoparticles and the ligands.

Beyond the tuning of the thermal conductivity itself, these results provide evidence that inelastic scattering is minimal at organic/inorganic interfaces. Its presence would allow two low-frequency modes to excite a high-frequency mode or vice versa thereby reducing thermal resistance between

two vibrationally dissimilar materials. For several years, organic materials have been speculated to facilitate inelastic scattering because of their bonding anharmonicity^{9,10}. The current work provides compelling evidence that such inelastic scattering is not a significant contributor to interfacial heat transport in these hybrid systems.

The low thermal conductivity reported for NCAs (less than 0.4 W m⁻¹ K⁻¹) has mixed implications for their eventual use in device applications. With a thermal conductivity that is nearly two orders of magnitude smaller than typical semiconductors used in micro- and optoelectronics, the temperature rise of an active layer may limit high-power operation. Perhaps more promising are the opportunities for developing a new class of thermoelectric materials for thermal-to-energy conversion. In this context, the low thermal conductivity combined with a potential boost in the Seebeck coefficient (a measure of the ability to convert a temperature difference across the material into a voltage difference) due to the nanocrystal's altered electronic density of states¹¹ could position these hybrid materials

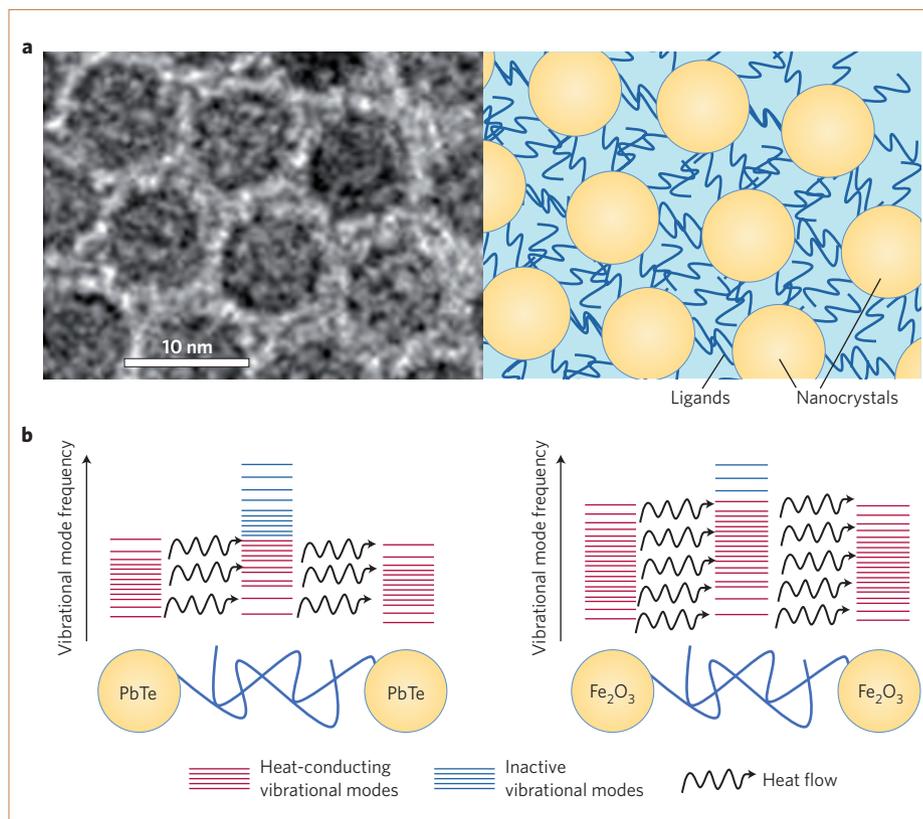


Figure 1 | Thermal transport in NCAs. **a**, Transmission electron micrograph¹ (left) and a schematic illustration (right) showing the morphology of NCAs. **b**, The proposed vibrational energy landscape at the organic/inorganic interface of NCAs with low (left) and high (right) Debye temperature nanoparticles. Increasing the number of overlapping states allows increased interfacial heat transport in the higher Debye temperature system.

to perform close to today's state-of-the-art thermoelectrics. Considering their relatively low-cost solution manufacturing, NCAs seem poised for further exploration as a thermoelectric platform and as a model system for understanding heat flow across interfaces.

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STEM CELL DIFFERENTIATION

Post-degradation forces kick in

Stem cells alter their morphology and differentiate to particular lineages in response to biophysical cues from the surrounding matrix. When the matrix is degradable, however, cell fate is morphology-independent and is directed by the traction forces that the cells actively apply after they have degraded the matrix.

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In their native environment adult stem cells are surrounded by a matrix, which provides biochemical signals and a structure for physical cell–matrix interactions to occur. In fact, cells actively deform and remodel their extracellular matrix (ECM), probe its rigidity and porosity, and undergo lineage-specific differentiation in part by integrating various biophysical signals. Although the underlying signalling pathways are still a matter of debate, it is clear that cell-generated traction forces play an integral role in detecting biophysical cues and in inducing subsequent differentiation. Indeed, it has been demonstrated that stem cells on substrates respond to these cues, and recent experiments with mesenchymal stem cells (MSCs) encapsulated in non-degradable, ionically crosslinked alginate hydrogels have implicated matrix rigidity as a regulator of cell fate in three dimensions¹. Writing in *Nature Materials*, Jason Burdick and colleagues now show that the differentiation of MSCs encapsulated in degradable, covalently crosslinked hyaluronic hydrogels is mediated by degradation-specific traction stresses².

Burdick and co-authors noticed that MSCs encapsulated within non-degradable methacrylated hyaluronic hydrogels maintained a rounded morphology and differentiated into adipocytes independently of matrix rigidity, unlike in previous observations where stem cells were deposited on substrates of varying rigidity. However, natural ECM, which these hydrogels are meant to mimic,

consists of polymers that have both crosslinks and a degradable backbone. To make their gels degradable, the researchers first incorporated both methacrylate and maleimide functional groups onto the hyaluronic backbone, and used the reactions of the maleimide groups with the thiols on degradable peptides to form a primary gel. The gel could then be covalently crosslinked by radical polymerization of the methacrylate groups in the presence of both a photoinitiator and ultraviolet light (Fig. 1a). This is particularly useful as it allows for unrestricted stem cell behaviour initially, and also the possibility to irreversibly constrain cell movement in a matter of minutes.

When using the degradable hydrogel, Burdick and co-authors found that local degradability was needed for entrapped cells to be able to rearrange their cytoskeletal structure and undergo osteogenesis. Moreover, using traction force microscopy they determined that osteogenic differentiation in these degradable hydrogels was independent of cell morphology and dependent on cell-generated traction forces (Fig. 1b). On the other hand, restricting cell rearrangement with contractile inhibitors, or introducing non-degradable crosslinks either right after initial seeding or a week after the cells were allowed to spread and migrate, attenuated osteogenesis and favoured adipogenesis. These findings imply that cell fate decisions in three-dimensional hydrogels are directed by force-dependent,

cell–substrate interactions that require a degradable matrix in which MSCs can spread.

Importantly, the findings from Burdick and colleagues support the notion that, unlike in two dimensions, in three dimensions matrix-driven cell tension drives cell fate irrespective of cell morphology and spread area. Similar conclusions were reached in a study involving MSCs encapsulated in ionically crosslinked alginate hydrogels¹, but in that case the authors found that matrix rigidity directly, rather than indirectly, regulated cell fate. It thus seems that cell tractions and ultimately differentiation are directly influenced by the cells' ability to deform rigid substrates or indirectly affected by the cells first degrading the matrix and then contracting it. Indeed, it is the type of crosslink — covalent versus ionic — that affects the behaviour of the hydrogel matrix at the molecular scale: whereas ionic crosslinks enable cells to locally reorganize their focal adhesions without undergoing large morphological changes, cells encapsulated in relatively rigid hyaluronic hydrogels must alter their cytoskeletal structure by locally degrading the surrounding matrix to reach otherwise unavailable adhesive ligands. Therefore, the crosslinking nature of the matrix, and thus the feasibility of ligand tethering³, modulate the mechanical feedback of encapsulated cell–matrix interactions.

Yet, what are the underpinnings of particular matrix interactions that drive stem cell differentiation in both ionic

Correction

In the version of the News & Views article 'Breaking through barriers' originally published online (*Nature Materials* <http://dx.doi.org/10.1038/nmat3599>; 2013), in ref. 1, the first initial of the fourth author's name was missing, it should have read "McGaughey, A. J. H." This error has now been corrected in all versions of the News & Views article.