better understanding of the highly diverse intracellular domain, will probably provide a solid framework for structure-guided drug design and open up new avenues for drug-discovery research. ■

Michaela Jansen *is in the Department of Cell Physiology and Molecular Biophysics, Center for Membrane Protein Research, School of Medicine, Texas Tech University Health Sciences Center, Lubbock, Texas 79430, USA.*
e-mail: michaela.jansen@ttuhsc.edu

1. Laverty, D. *et al. Nature* **565**, 516–520 (2019).
2. Masiulis, S. *et al. Nature* **565**, 454–459 (2019).
3. Möhler, H. & Okada, T. *Science* **198**, 849–851 (1977).
4. Sigel, E., Stephenson, F. A., Mamalaki, C. & Barnard, E. A. *J. Biol. Chem.* **258**, 6965–6971 (1983).
5. Belelli, D. & Lambert, J. J. *Nature Rev. Neurosci.* **6**, 565–575 (2005).
6. Zhu, S. *et al. Nature* **559**, 67–72 (2018).
7. Phulera, S. *et al. eLife* **7**, e39383 (2018).
8. Unwin, N. *J. Mol. Biol.* **346**, 967–989 (2005).
9. Basak, S., Gicheru, Y., Rao, S., Sansom, M. S. P. & Chakrapani, S. *Nature* **563**, 270–274 (2018).
10. Basak, S. *et al. Nature Commun.* **9**, 514 (2018).
11. Polovinkin, L. *et al. Nature* **563**, 275–279 (2018).
12. Pandhare, A., Grozdanov, P. N. & Jansen, M. *Sci. Rep.* **6**, 23921 (2016).

This article was published online on 2 January 2019.

MATERIALS SCIENCE

Gel sandwich smartens up windows

Polymeric gel particles have been used to make windows that highly effectively allow or block heat-generating wavelengths of sunlight in response to temperature. Such windows might increase the energy efficiency of buildings.

MICHAEL J. SERPE

Smart polymers can sense and react to environmental conditions, and have been used in myriad technologies for decades[1]. Writing in *Joule*, Li *et al.*[2] report that such polymers can be used to make smart windows that strongly modulate the amount of ultraviolet, visible and — most notably — near-infrared light that enters a building. Because these components of sunlight can generate heat, this regulation could reduce the monetary and energy costs associated with heating and cooling buildings.

Estimates show that about half of the energy used in a typical US home is for heating and cooling (see, go.nature.com/2c4ypxw), making temperature control the most energy-consuming process in residential properties. It therefore follows that the heating and cooling of homes in the United States contributes more to greenhouse-gas emissions, and hence global warming, than any other process associated with household maintenance. The discovery and use of energy-efficient building materials, including windows, could thus have a profound impact for society.

A common approach to reduce heating and cooling demand in buildings is to open or close window coverings such as blinds and curtains. To begin to make this process less dependent on human intervention and hence more efficient, 'electrochromic' windows, which darken in response to the application of small electrical potentials, have been developed. Such windows are used on the Boeing 787 Dreamliner aeroplane, for example. The windows still require someone to decide when to darken them, but a simple feedback mechanism could be used to allow the windows to be darkened in response to room temperature.

Electrochromic windows are effective, but have several drawbacks[3–5]: they require the application of an electrical potential, are expensive to make, have inconsistent light-blocking efficiency and are unlikely to be durable in the long term. As a result, 'thermochromic' smart-window technologies that directly respond to the local temperature by changing their ability to allow sunlight into a space are highly desirable. Such technologies exist, but have limitations. For example, films of the thermochromic compound vanadium dioxide show promising sunlight-modulating properties, but are activated (darkened) at impractically high temperatures of up to 90 °C (ref. 6). Furthermore, the amount of light they allow through — their transmittance — in the inactivated, transparent state is relatively low, on the order of 50% (refs 6, 7).

Li and co-workers now report a useful advance in the development of thermochromic smart windows that depend on smart polymers for their function. The authors' system consists simply of a thin layer of a concentrated solution of polymeric gel particles (known as microgels), trapped between two glass layers (Fig. 1). The resulting windows had an infrared transmittance of up to 81.6% in their inactivated transparent state, but a much lower transmittance of about 6% when activated — which represents an extremely high modulation of solar energy. In addition, the authors' windows are activated at about

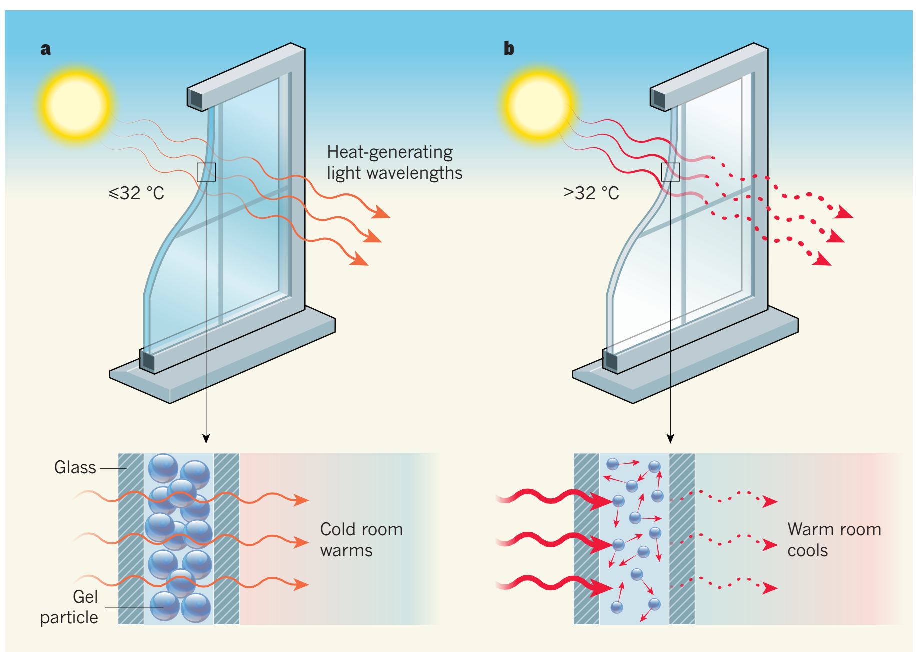

Figure 1 | Smart windows that incorporate temperature-sensitive polymeric gel microparticles. Li *et al.*[2] have made windows in which a solution of precisely prepared, microscopic polymer particles in water is sandwiched between two panes of glass. **a**, At or below about 32 °C, the gel particles are swollen by water. This makes them essentially transparent to the heat-generating components of sunlight (near-infrared, visible and ultraviolet light), which can, therefore, pass through the window and warm up any space on the other side. **b**, Above 32 °C, the particles collapse and expel water. The collapsed particles scatter the heat-generating components of sunlight, preventing them from passing through the window and limiting the temperature increase on the other side. The glass also becomes visually opaque.

32 °C. This is a much more useful activation temperature than that of many other technologies, although similar activation temperatures have been reported for other systems based on smart polymers[8].

The superior modulatory properties were achieved by paying close attention to the conditions used to synthesize the microgels. Li *et al*. developed conditions that allowed the generation of microgels that have an extremely uniform density of crosslinks between polymer chains, and a structure that allows the particles to swell greatly in water. The authors also fine-tuned the reactions to produce microgels that swell to a diameter of 1.4 micrometres at 25 °C. The resulting particles scatter very little light, and are highly transparent below temperatures of about 32 °C. Crucially, however, the microgels collapse and expel water at higher temperatures, whereupon they scatter light at wavelengths primarily dictated by their collapsed-state diameter and refractive index.

Smart windows need to scatter the near-infrared (NIR) wavelengths that are predominantly responsible for heating up spaces. The collapsed microgels in Li and colleagues' windows have a diameter of 546 nm and a refractive index of about 1.4 at NIR wavelengths — which means that they scatter NIR wavelengths effectively. They also scatter shorter wavelengths in the ultraviolet and visible regions of the spectrum, which means that the activated windows are opaque to the human eye. Most importantly, when Li and co-workers exposed a chamber fitted with a microgel-based smart window to a solar simulator (a device that produces radiation that approximates sunlight), they observed that the temperature increase in the chamber was significantly reduced compared with the increase obtained when a standard double-pane window was fitted.

Li *et al.* also showed that the windows could be activated and inactivated at least 1,000 times with no noticeable systematic loss in performance, and are also seemingly unaffected by freezing. As an added benefit, visible light scattered by the windows could, in principle, be used to illuminate a room, reducing the need for interior lighting and thereby saving even more energy. Finally, the cost of generating the microgels should not prohibit the commercialization of the technology. Taken together, these properties suggest that Li and colleagues' smart windows are suitable for real-world applications.

"The use of energy-efficient building materials could have a profound impact for society."

Nevertheless, there are some drawbacks to this technology. For example, the inability to darken the windows on demand means that they would be transparent at night when temperatures are cool, reducing privacy and, if used in bedrooms, potentially disrupting people's sleep cycles. These issues can, of course, be addressed by using curtains, but this would be inconvenient at best. Moreover, because the activated windows are opaque, users would be unable to see out of them. The bottom line is that this technology is one option out of many, and will not be the perfect solution for all situations.

In my view, smart windows should allow users to choose whether infrared and/or visible light enters a room. For example, windows could actively and continuously prevent NIR sunlight from entering a space when activated by a user, but still allow visible light to enter, so that the room could be warmed and illuminated. If windows could self-regulate their behaviour in a user-defined manner, then the technology would be perfect. Some emerging smart-window technologies can also generate energy while modulating sunlight[9], although much more development is needed to make them commercially viable. Finally, it should be noted that although energy-efficient windows can minimize the energy used by buildings, other energy-efficient building materials need to be developed in parallel. Together, they could have a tremendous impact on the world. ■

Michael J. Serpe *is in the Department of Chemistry, University of Alberta, Edmonton, Alberta T6G 2G2, Canada.*
e-mail: serpe@ualberta.ca

1. Cohen Stuart, M. A. *et al. Nature Mater.* **9**, 101–113 (2010).
2. Li, X.-H., Liu, C., Feng, S.-P. & Fang, N. X. *Joule* https://doi.org/10.1016/j.joule.2018.10.019 (2018).
3. Wang, Y., Runnerstrom, E. L. & Milliron, D. J. *Annu. Rev. Chem. Biomol. Eng.* **7**, 283–304 (2016).
4. Runnerstrom, E. L., Llordés, Lounis, S. D. & Milliron, D. J. *Chem. Commun.* **50,** 10555–10572 (2014).
5. Barile, C. J. *et al. Joule* **1,** 133–145 (2017).
6. Gao, Y. *et al. Energy Environ. Sci.* **5**, 8234–8237 (2012).
7. Kang, L. *et al. ACS Appl. Mater. Interfaces* **3**, 135–138 (2011).
8. Ke, Y. *et al. Adv. Funct. Mater.* **28**, 1800113 (2018).
9. Lin, J. *et al. Nature Mater.* **17**, 261–267 (2018).

This article was published online on 14 January 2019.

GENOMICS

A chromosomal hub to tell odours apart

A study shows that a multi-chromosomal hub assembles in mouse olfactory neurons to ensure that only one odour-sensing receptor is expressed in each neuron — a feature essential to odour discrimination. **SEE ARTICLE P.448**

FRANÇOIS SPITZ

Mammals can discriminate between a vast number of volatile compounds — perhaps more than a trillion[1]. This extraordinary capacity is encoded by a repertoire of hundreds of olfactory-receptor genes, distributed in small groups that are present on almost all chromosomes[2]. To ensure that the response to individual odours is specific, each olfactory sensory neuron (OSN) expresses a single, randomly selected olfactory-receptor gene.

On page 448, Monahan *et al.*[3] show that, in the nuclei of mouse OSNs, certain regions of multiple chromosomes assemble in a structure that controls the expression of the full repertoire of olfactory-receptor genes in the nose, while making sure that each cell expresses only one type of receptor. These exciting findings show that interchromosomal interactions can have a determinant role in regulating gene expression.

The expression of vertebrate genes is regulated by activating genomic elements called enhancers. Enhancers can be located far from the genes themselves[4], but they are typically present on the same chromosome as the gene they regulate (*cis* interactions). These regulatory interactions are mediated by transcription factors, assisted by other proteins, and require the participating proteins and DNA elements to be closely connected in the nucleus.

Molecular techniques, such as Hi-C (ref. 5), that capture the 3D folding of chromatin (DNA and associated proteins) have revealed that the interactions between genes and their enhancers occur in compact structures called topologically associating domains (TADs) that organize chromosomes into distinct *cis* neighbourhoods[6]. Hi-C analyses have also uncovered specific interactions between genes and genomic elements located much farther away from each other, in different TADs and even on different chromosomes (these are called *trans* interactions)[7,8]. These observations raised the possibility that *trans* interactions influence gene expression. However, because the frequency of *trans* interactions is so much lower than that of *cis* interactions, their functional relevance has remained debatable.

Olfactory-receptor genes were reported to form interchromosomal clusters more than a