trapped in the device. Various strategies have attempted to address this issue in OLEDs, such as using diffraction gratings[7] and buckling the device[8].

But Cao and colleagues took a simpler approach: they optimized their perovskite-processing conditions so that the emissive layer spontaneously forms as distinct sub-micrometre-scale crystal platelets (Fig. 1). The authors' computational modelling shows that this submicrometre structuring increases the fraction of light that makes it out of the emissive layer to 30%, compared with 22% for an equivalent 'flat-layer' perovskite device (a device in which the perovskite layer does not have submicrometre structuring). In combination with the reduction in non-radiative losses, this results in an EQE of 20.7%.

By contrast, Lin *et al*. used a flat emissive layer, but tried to optimize the balance of electrons and holes injected into the perovskite, to make the most efficient use of every charge. This seems to be facilitated by the MABr shells that enclose the perovskite crystals. The resulting PLEDs have an EQE of 20.3%.

But caution is advised before ordering your PLED ultrahigh-definition television. OLEDs, and indeed all optoelectronic devices based on organic semiconductors, suffered for many years from stability issues. The first polymer OLEDs[9] could emit light for only seconds, and subsequent advances were needed to ensure that smartphone screens and OLED televisions last for tens of thousands of hours. The lifetime of LEDs can be measured by the T_{50} metric, which is the time for the performance of the device to drop by half. The T_{50} values of Cao and colleagues' and Lin and colleagues' PLEDs are currently modest: 20 hours and 100 hours, respectively.

Furthermore, displays require a minimum of three colours (and preferably more) to create high-quality colour images. Developing a range of colours for OLEDs was a big challenge. Cao and co-workers' PLED emits in the near-infrared region of the electromagnetic spectrum, and Lin and co-workers' PLED emits green light — which is definitely a good start. Multiple colours of PLEDs could be generated by altering the composition of the devices, but the same developmental journey as was needed for OLEDs lies ahead.

The two papers also highlight problems that occur every time new optoelectronic materials emerge as a technological platform: inconsistent characterization and a lack of standards. Because Cao and colleagues' PLED emits light from outside the visible spectrum, they report the metrics of their devices radiometrically — they use a measure that simply takes into account the total emitted power. By contrast, Lin and colleagues describe the emission of their green PLED using photometric measures, which are weighted by the response of the human eye. The two groups also report the peak EQEs at different brightnesses, and therefore at different driving currents. This makes direct comparison somewhat problematic.

Caveats aside, the two papers are a milestone in PLED development. For now, LEDs based on compound semiconductors remain the dominant technology: they outclass the competition in many respects, including cost, efficiency, colour and brightness. They will be hard to beat. But that should not stop the pioneers of perovskite (or, indeed, organic) LEDs from trying. ■

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ANIMAL BEHAVIOUR

Foraging skills develop over generations

The movements of relocated wild animals reveal that a lost migratory skill was regained over successive generations. This suggests that skill improvements can occur over time as animals learn expertise from each other.

ANDREW WHITEN

The transmission of behavioural traditions by learning from others — cultural learning — was once thought to be a uniquely human attribute. However, evidence increasingly indicates that this phenomenon is widespread among animals, shaping behaviours from foraging for food to mate choice to predator avoidance[1]. Claims for human uniqueness in our cultural skills have therefore been pinned on our species' capacity for what is called cumulative culture: the ramping up of cultural sophistication as each generation builds on their ancestors' cultural achievements[2,3]. Writing in *Science*, Jesmer *et al*.[4] now challenge this view in a study of the development of migratory skill in wild populations of bighorn sheep (*Ovis canadensis*) and moose (*Alces alces*) populations that have been moved to unfamiliar locations. Their findings have implications for understanding the evolution of cumulative culture in both humans and other animals, and for conservation policies[5,6].

In the wild, bighorn sheep (Fig. 1) and moose normally migrate in spring and move between distinct seasonal ranges. These movements follow a pattern known as green-wave surfing, whereby the animals' migration tracks the availability of high-quality vegetation, which peaks at different times in different places depending on factors such as altitude. How animals evolved the capacity for this type of migratory behaviour remains unknown.

Jesmer and colleagues investigated the migration of bighorn sheep and moose that had been moved to unfamiliar areas in recent decades to repopulate regions in which these types of animal had been wiped out by disease or hunting. The authors compared the migration of such relocated populations with that of animals in long-established populations that had been migrating for many generations in a particular region. They noted that when individuals had been moved to an unfamiliar location, the animals usually ceased migrating, although migratory behaviour gradually re-emerged in subsequent generations.

The researchers fitted animals with a collar containing a Global Positioning System (GPS) device that enables accurate tracking of an animal's position. They combined this information with the corresponding satellite imagery for the region that revealed where and when vegetation was at peak quality. To measure animals' green-wave surfing skills, the authors counted the number of days between the peak forage quality at a location and the arrival of an animal there. When the authors analysed bighorn sheep from migratory populations that had been relocated at times ranging from 0 to 35 years ago, these animals surfed the green wave approximately half as effectively as animals from populations that had been established in a particular region for more than 200 years.

Jesmer and colleagues then combined these and other bighorn records with similar data for moose that had been relocated to a given region between 10 and 110 years ago. The combined results for these 267 bighorn and 189 moose were consistent with a model in which it took up to 30 years (between 4 and 5 generations) for migration to distinct

DONALD M. JONES/MINDEN PICTURES/FLPA

Figure 1 | Bighorn sheep *(Ovis canadensis)* in Montana. Jesmer *et al.*[4] report that the migration of wild bighorn sheep so as to track the spring arrival of high-quality vegetation is a skill that develops over many generations.

seasonal ranges to re-emerge in these species. It took almost a century for a relocated population to reach a point at which half its number migrated in this way. Animals that do not migrate to distinct seasonal ranges might begin to undertake green-wave surfing over small distances.

The bighorn-sheep data span more than two centuries, and the authors found that migratory behaviour had spread to nearly all of the bighorn sheep individuals that had been established in a location for at least around 200 years. Most interestingly, green-wave-surfing knowledge steadily increased over the decades, indicating that migratory skill progressively rises to the highest levels over long time frames.

The authors suggest that their findings can be explained by a cumulative process of acquisition of migratory skill involving cycles of individual and cultural learning that span many decades and generations. Individuals might acquire some initial surfing knowledge by personal learning, which then becomes available to their young through social learning, and the next generation might build on this knowledge through further exploration. The refinement of skills in the next generation could be similarly enhanced, and so on. Repeated cycles of individual and social learning might thus generate a cumulative culture of progressively refined surfing expertise and an increase in the proportion of migrants in the population.

Unfortunately, no direct evidence of social learning in these animals has yet been documented in the wild to support this interesting idea. However, a previous analysis of the homing of domesticated pigeons[7] provides data suggesting that cumulative effects of social learning can occur in animals. In this study, two birds were tracked using GPS monitoring as they flew homing flights together. One animal of the pair was then replaced by a pigeon that had not flown the route before, and this pair of birds flew a series of homing flights. After a series of successive replacements of one bird of the pair, the efficiency of the homing flights improved significantly from that observed at the outset. The birds in the later pairings were different from those that made the initial flights, so this improvement is consistent with a model of individual learning coupled with social transmission across these 'cultural generations'.

"Migratory skill progressively rises to the highest levels over long time frames."

The bighorn and moose findings might well reflect similar learning processes. Moreover, for these animals, cultural learning will probably involve the acquisition of a diverse range of expertise relating to different aspects of migration in addition to green-wave surfing skill, such as knowledge of the predation risks in what are known as 'landscapes of fear'[8], which is of particular consequence given that offspring migrate with their mothers. The findings of Jesmer *et al.* provide an advance for this area of research by investigating learning in the wild, across multiple generations and over many decades, illuminating our understanding of animal culture and the collective behaviour of a population over time.

Jesmer and colleagues interpret the long-term growth over time in the populations' green-wave surfing skills to imply that, over successive generations, the individuals of a particular population develop more-refined migration skills than those in earlier generations. However, a possibility worth investigating is whether the improvements in a relocated population's ability to track peak vegetation might be driven mainly by an increase in the proportion of animals that learn migratory skills from others, rather than because the migratory skills of individuals increase over successive generations. Nevertheless, what would develop under this scenario is also the progressive, collective enhancement in migration skills of the population as a whole, an example that is relevant to the topic of collective intelligence in animal groups[9,10].

The United Nations Environment Programme has been considering how evidence for cultural learning in animals should inform conservation policies. This is of particular note for animal populations that migrate through, or are located in, areas that cross national borders. A panel of scientists has recently assembled key evidence and recommendations related to this in a report for policymakers[6]. The findings of Jesmer *et al.* underscore the importance of such considerations if wild-animal populations develop skills that enhance their survival over a time span of centuries. In the case of migratory skills, the blocking of traditional migratory routes by human-made barriers such as roads could lead to the loss of animals' hard-won cultural knowledge.

Conservation efforts need to take into account the significance of such knowledge, the scope of which we are perhaps only starting to recognize[1,10], and our understanding of which is extended by long-term perspectives such as those reported by Jesmer and colleagues. Cumulative culture of this kind might be more widespread in nature than was previously assumed, and not unique to humans. Accordingly, understanding the gulf between these and our own species' cumulative cultures might require us to consider more-specific aspects of cultural transmission, including modes of learning such as intentional teaching, or cultural contents, such as adopting qualitatively improved materials for tools. As the latter example suggests, human culture could progress by incorporating qualitatively distinct innovations. It remains a controversial question whether this ability is also found in animals — can they go beyond just achieving gradual refinements in a skill, such as greenwave surfing, to add a transformative new approach to solve a particular problem? ■

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QUANTUM PHYSICS

Unexpected noise from hot electrons

Experiments reveal a previously unreported type of electronic noise that is caused by temperature gradients. The finding has practical implications, and could help in detecting unwanted hotspots in electrical circuits. SEE LETTER P.240

ELKE SCHEER & WOLFGANG BELZIG

A fundamental feature of any electrical measurement is noise — random and uncorrelated fluctuations of signals. Although noise is typically regarded as undesirable, it can be used to probe quantum effects and thermodynamic quantities. On page 240, Shein Lumbroso *et al.*[1] report the discovery of a type of electronic noise that is distinct from all others previously observed. Understanding such noise could be essential for designing efficient nanoscale electronics.

A century ago, the German physicist Walter Schottky published a seminal paper that described different causes and manifestations of noise in electrical measurements[2]. Schottky showed that an electric current produced by an applied voltage is noisy, even at absolute zero temperature, when all random heat-induced motion has stopped. This noise is a direct consequence of the fact that electric charge is quantized — it comes in discrete units. Because the noise results from the granularity of the charge flow, it is called shot noise.

It was already known at the time of Schottky's work that, in systems that are in thermal equilibrium, noise with distinctly different properties from shot noise comes into play at non-zero temperatures — this is known as thermal (Johnson–Nyquist) noise. Today, shot noise is a key tool for characterizing nanoscale electrical conductors, because it contains information about quantum-transport properties that cannot be revealed from mere electric-current measurements[3,4].

Shein Lumbroso *et al.* studied junctions composed of single atoms or molecules suspended between a pair of gold electrodes. The authors fabricated the electrodes by breaking a thin gold wire into two parts and bringing the parts gently back into contact. They evaporated hydrogen molecules on to this device, which is known as a mechanically controllable

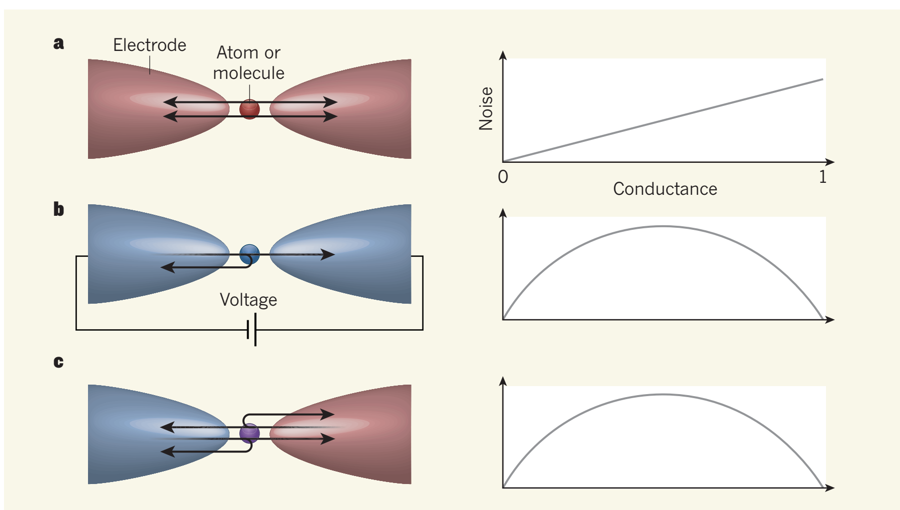

Figure 1 | Three types of electronic noise. Shein Lumbroso *et al.*[1] report experiments in which single atoms or molecules are suspended between the tips of two electrodes. **a**, At a non-zero temperature (red), electrons flow between the two electrodes (arrows). The electrical signal associated with this motion contains a type of noise called thermal noise, which varies linearly with electrical conductance (shown here in units of the quantum of conductance). **b**, If a voltage is applied to the device, electrons flow from one electrode to the other, and can be backscattered from the atom or molecule. The resulting signal contains 'shot' noise that is present even when the device is at absolute zero temperature (blue). Shot noise has a characteristic (non-monotonic) dependence on conductance. **c**, If a temperature gradient is applied to the device (indicated by rising temperatures from blue to purple to red), electrons flow from both of the electrodes and can be backscattered. The authors show that the resulting electrical signal contains a previously unreported type of noise, which they term delta-T noise. This noise has the same dependence on conductance as shot noise.