understand their result is to observe how it was achieved, starting from previous work[10] by some of the current authors and their colleagues in 2017. In that paper, the researchers demonstrated the distribution of entangled states generated on board the satellite Micius and sent through two communication links to optical ground stations in China separated by 1,200 km.

Although that work was a milestone for the field, the transmission efficiency achieved was too low for QKD to be carried out in practical conditions. In particular, because only a finite number of states can be transmitted during a short data-collection window, the many errors involved prevented a secret key from being extracted. Taking into account the use of a finite number of transmitted states is crucial for achieving security, especially in the case of a satellite-based experiment, in which data are collected only during the brief time the satellite is visible from the ground stations.

Yin *et al.* remedied this problem by implementing major technological enhancements. These included installing highly efficient telescopes at the ground stations and optimizing equipment components at all stages of the optical path. The authors' meticulous optimization also involved cutting-edge signal acquisition, pointing and tracking systems and synchronization techniques for both the satellite and the ground stations. Their efforts led to a fourfold increase in transmission efficiency compared with the previous experiment and, consequently, produced low enough error rates for a secret key to be extracted. The authors also verified the stability and reliability of their findings over multiple satellite orbits.

From a security perspective, this demonstration does not remove the need for trust in the receiving stations. Therefore, assumptions must be made about the internal workings of the devices in these stations. Yin *et al.* did two things to minimize the risk that these assumptions would not hold in practice. First, they used a systematic approach to tackling imperfections that might inadvertently leak information to a potential eavesdropper. Second, they used a range of solutions to actively control the properties of the photonic information carriers. Combined with security from this quantum approach that should be guaranteed against all possible attacks, this makes the authors' result the most advanced QKD demonstration so far.

However, several shortcomings will need to be overcome for these findings to become relevant for truly practical high-security applications. For instance, the experiment produced keys at extremely low rates. Also, the experiment was carried out only at night, and using a wavelength that is incompatible with the optical-fibre networks used for telecommunication that would interface with space-based networks in infrastructures for global quantum communication. Moreover, QKD can be achieved only between ground stations that are visible simultaneously from the satellite.

Progress in all these areas requires the development of high-performance devices operating at a longer wavelength than that used in this work, the use of satellites in higher orbits than that of Micius and — in the long term —integration of the demonstrated technology with quantum repeaters and other promising architectures allowing for untrusted nodes[13]. Such advances would then unlock the full potential of quantum technologies for executing cryptographic tasks at a global scale.

Eleni Diamanti is at the National Centre for Scientific Research (CNRS), Sorbonne University, 75005 Paris, France.
e-mail: eleni.diamanti@lip6.fr

1. Yin, J. *et al. Nature* **582**, 501–505 (2020).
2. Diamanti, E., Lo, H.-K., Qi, B. & Yuan, Z. *npj Quantum Inf.* **2**, 16025 (2016).
3. Boaron, A. *et al. Phys. Rev. Lett.* **121**, 190502 (2018).
4. Liao, S.-K. *et al. Nature* **549**, 43–47 (2017).
5. Peev, M. *et al. N. J. Phys.* **11**, 075001 (2009).
6. Liao, S.-K. *et al. Phys. Rev. Lett.* **120**, 030501 (2018).
7. Bhaskar, M. K. *et al. Nature* **580**, 60–64 (2020).
8. Aktas, D. *et al. Laser Photon. Rev.* **10**, 451–457 (2016).
9. Wengerowsky, S. *et al. Proc. Natl Acad. Sci. USA* **116**, 6684–6688 (2019).
10. Yin, J. *et al. Science* **356**, 1140–1144 (2017).
11. Ekert, A. K. *Phys. Rev. Lett.* **67**, 661–663 (1991).
12. Bennett, C. H., Brassard, G. & Mermin, N. D. *Phys. Rev. Lett.* **68**, 557–559 (1992).
13. Lo, H.-K., Curty, M. & Qi, B. *Phys. Rev. Lett.* **108**, 130503 (2012).

Ecology

Model system might reveal how coral cells evict algae

Alejandro Sánchez Alvarado

Global warming is threatening the survival of coral reefs. A laboratory model system has now been developed that should aid efforts to understand reef biology and the processes that underlie harmful bleaching events. **See p.534**

From the late Precambrian era (around 650 million years ago) to the present day, a singular, carbon-based 'economy' has been operating between corals and algae that has fuelled the building of untold expanses of barrier reefs in oceans around the globe. On page 534, Hu *et al.*[1] now set the stage for efforts to gain a deeper understanding of how corals and algae interact in coral reefs.

Corals — multicellular marine invertebrates belonging to the class Anthozoa of the phylum Cnidaria — usually live in compact colonies composed of individual structures called polyps. Most reef-building corals harbour algae in their cells in a specialized, membrane-bound compartment called a symbiosome. As its name implies, this specialized structure is home to one of nature's most remarkable, mutually beneficial, endosymbiotic relationships. Corals provide specific species of alga with a protected environment and with compounds needed to carry out photosynthesis. In return, the algae supply the coral with the products of photosynthesis: oxygen, glucose, glycerol and amino acids. This biomolecular bounty is then transformed by the corals into proteins, fats, carbohydrates and a calcium carbonate skeleton.

"The authors confirmed that they had correctly identified the coral cells that host algae."

Around 90% of the organic material produced by these algal endosymbionts is ultimately transferred to the coral host[2], underpinning the quiet yet unceasing growth and productivity of coral reefs[3]. It has been estimated that this endosymbiotic relationship is responsible for an area of nearly 250,000 square kilometres of the most spectacular and crucial ecosystems on our planet, supporting some 2 million or more species[4]. However, the current rise in ocean temperatures is causing disruption, because exposure to prolonged heat causes corals to evict their symbiotic algae, resulting in a phenomenon known as coral bleaching — loss of the colourful algae leaves the coral white in appearance. Severe coral bleaching threatens to cause a marine calamity of global proportions. Unfortunately, we know little about the molecular basis that underlies how coral cells orchestrate algal expulsion, nor about how corals recognize, take up and maintain their algal endosymbionts.

Hu and colleagues' work heralds a new

ETHAN DANIELS/SPL

Figure 1 | *Xenia*, a fast-growing species of coral found in the Red Sea and Indian Ocean.

and valuable attempt at a rigorous and systematic understanding of the cellular and molecular basis of coral endosymbiosis, and, potentially, of coral bleaching. The authors selected a fast-growing species of *Xenia* coral (Fig. 1) that usually resides in waters stretching from the Red Sea to the Indian Ocean. *Xenia* establishes an endosymbiotic relationship with algae of the Symbiodiniaceae family. Hu *et al.* assembled a genome sequence for *Xenia*, complete with chromosome-level information. The authors also generated a map down to a resolution of single cells, revealing the RNA profiles of the cells present in a *Xenia* polyp. This approach has effectively brought the power of both genomics and bioinformatics to the study of coral biology. The authors report that the *Xenia* genome has approximately 24,000 genes, and the single-cell atlas reveals 16 cell clusters, each of which has a distinct gene-expression pattern.

Using this information, the authors sought to resolve a key mystery in coral biology: which cells in the organism are responsible for recognizing the appropriate algal species and establishing the endosymbiosis? By taking advantage of the visible autofluorescence of the algal partner, Hu *et al.* used a flow-cytometry approach to separate the alga-containing from the alga-free coral cells. RNA sequencing then enabled the authors to determine which genes were expressed in the two cell populations. By comparing this information with the RNA-sequencing data from their single-cell atlas, Hu *et al.* found that cluster 16 showed the highest overall similarity to the profile of the alga-containing cells. The authors confirmed that they had correctly identified the coral cells that host algae *in vivo* by using a technique called *in situ* hybridization to detect the expression of the cluster-16 genes associated with the proposed host cell. Remarkably, the authors found that these proposed endosymbiotic cells corresponded to a mere 1.4% of all the coral cells catalogued in their single-cell atlas.

Because single-cell RNA studies normally capture a single moment in time, the developmental provenance of the endosymbiotic cells in cluster 16 remained unclear. The authors addressed this concern by resorting to 'development on demand' — the regeneration of missing body parts after cellular 'amputation'. By surgically removing all the tentacles from *Xenia* polyps, restoration of the endosymbiotic cells could be followed from scratch. Using a combination of single-cell RNA sequencing, analysis of gene-expression patterns and a 'pulse–chase' method to label and track cells, the authors describe a lineage for endosymbiotic cells that progresses from progenitor cells to alga-uptake cells, and from mature alga-containing cells to cells devoid of algae. Hu and colleagues provide examples of differentially expressed genes that serve to mark each of the lineage stages and that might give insights into the molecular machinery driving the activities of coral endosymbiotic cells.

Nevertheless, Hu and colleagues' findings await detailed functional validation. Cause-and-effect relationships will need to be determined for the many molecules identified and for the cellular activities associated with algal recognition, uptake, maintenance and eviction. This should be possible in the near future by using methods to reduce the expression of targeted genes through the introduction of artificial molecules called short hairpin RNAs — either by microinjection or through an electroporation method used in another cnidarian, the starlet sea anemone *Nematostella vectensis*[5]. Alternatively, permanent modifications of the genome might be desirable, and thus might require harnessing the CRISPR gene-editing technique either to introduce mutations or to add desired sequences. This prospect should be helped by the high-quality *Xenia* genome that the authors have made available.

Future studies should focus on the cell biology of endosymbiosis. Visualizing the lineage progression from progenitor to endosymbiotic cell should reveal fascinating aspects of cell biology. For example, it could help us to understand the mechanisms by which coral cells expand to allow them to take up algae that are similar in size to themselves.

Coral reefs provide the foundation for an enduring and evolving legacy of progress in knowledge about aspects of their biology, even though many features of their existence are still poorly understood. The development of a laboratory-friendly, coral-research organism suitable for molecular and cellular experimentation is of great significance, and the importance of this achievement cannot be overemphasized. Hu and colleagues' work opens the door to the possibility of identifying the principles by which corals recognize, take up and expel their endosymbionts. Understanding the mechanisms underlying any of these processes will not only enhance our understanding of symbiosis, but also contribute to the study and, more crucially, to the development of possible solutions to one of the major problems affecting the health of our planet.

Alejandro Sánchez Alvarado is at the Stowers Institute for Medical Research and at the Howard Hughes Medical Institute, Kansas City, Missouri 64110, USA.
e-mail: asa@stowers.org

1. Hu, M., Zheng, X., Fan, C.-M. & Zheng, Y. *Nature* **582**, 534–538 (2020).
2. Sumich, J. L. *An Introduction to the Biology of Marine Life* 6th edn, Ch. 9, 255–269 (Brown, 1996).
3. Levinton, J. S. *Marine Biology: Function, Biodiversity, Ecology* Ch. 14, 306–319 (Oxford Univ. Press, 1995).
4. Spalding, M. D., Ravilious, C. & Green, E. P. *World Atlas of Coral Reefs* Ch. 1, 9–45 (Univ. California Press, 2001).
5. Karabulut, A., He, S., Chen, C. Y., McKinney, S. A. & Gibson, M. C. *Dev. Biol.* **448**, 7–15 (2019).

This article was published online on 17 June 2020.