

Fibre-optical features of a glass sponge

Some superior technological secrets have come to light from a deep-sea organism.

Modern technology cannot yet compete with some of the sophisticated optical systems possessed by biological organisms^{1–3}. Here we show that the spicules of the deep-sea ‘glass’ sponge *Euplectella* have remarkable fibre-optical properties, which are surprisingly similar to those of commercial telecommunication fibres — except that the spicules themselves are formed under normal ambient conditions and have some technological advantages over man-made versions.

The skeleton of the hexactinellid class of sponges is constructed from amorphous, hydrated silica^{3–6}. *Euplectella* builds an intricate cage (Fig. 1a), which typically houses a mating pair of shrimp (hence its nickname, ‘Venus flower-basket’) and is composed of a lattice of fused spicules⁴ that provide extended structural support.

A network of anchorage spicules (basalia) extend outwards in a crown-like formation. These spicules are generally 5–15 cm long and 40–70 μm in diameter; their native cross-section is homogeneous and they have no structural boundaries. Under stress or etching, the spicules reveal a characteristic layered morphology⁶ and cross-sectional variations in composition that appear as three distinct regions: a pure silica core of about 2 μm in diameter that encloses an organic filament; a central cylinder that has the greatest organic content of the three; and a striated shell that has a gradually decreasing organic content and which is glued together by organic films (Fig. 1b).

We anticipated that the spicules’ rich substructure should be reflected in their optical properties as well. Indeed, interferometric refractive-index profiling⁷ revealed three regions that correspond to the three regions of structural composition (Fig. 1c): a core with high refractive index that is comparable to (or higher than) that of vitreous silica; a cylinder of lower refractive index that surrounds the core; and an oscillating pattern with progressively increasing refractive index at the outer part of the spicule.

To determine whether this typical ‘core-cladding’ refractive-index profile endows the spicules with wave-guiding properties, we investigated their transmission characteristics. We found that embedded spicules act as single- or few-mode waveguides — that is, light waves are effectively confined to the core, where refractive index is highest (Fig. 1d, left). When light was coupled into free-standing spicules, they functioned as multi-mode fibres, with most of the light filling the entire cladding, because of the enhanced refractive-index contrast

between the spicule and air (Fig. 1d, right).

These biological fibres therefore resemble commercial telecommunication fibres, in that they are made of the same material and have comparable dimensions, as well as similar refractive indices for the high-index core and a low-index cladding. They also function as efficient single-mode, few-mode or multi-mode waveguides, depending on the optical launch conditions.

The principal weakness of commercial optical fibres is that they fracture as a result of crack growth, whereas the spicules’ lamellar layers, connected by organic ligands at the fibre’s exterior, provide an effective crack-arresting mechanism and enhance fracture toughness^{6,8,9}. Another superior feature of the spicules is their formation under ambient conditions, a process that is regulated by organic molecules^{10,11}. This ambient-temperature process, unlike the high-temperature manufacture of man-made fibres, allows the structure to be doped with specialized impurities that improve the refractive index and therefore the wave-guiding properties. Our preliminary elemental analysis

shows, for example, that sodium ions are present throughout the spicules, particularly in the core. Although sodium ions (and many other additives) are desirable fibre-optic dopants, they present a manufacturing challenge, for example by causing devitrification at high temperatures.

Our results suggest the intriguing possibility that the spicules of *Euplectella*, beyond structural anchorage support, could also provide a highly effective fibre-optical network, which may be useful in distributing light in its deep-sea environment. This illuminating sponge should also shed light on low-temperature, biologically inspired processes that could give rise to better fibre-optical materials and networks.

Vikram C. Sundar*, **Andrew D. Yablon†**, **John L. Grazul***, **Micha Ilan‡**, **Joanna Aizenberg***

*Bell Laboratories/Lucent Technologies, Murray Hill, New Jersey 07974, USA
e-mail: jaizenberg@lucent.com

†OFS, Murray Hill, New Jersey 07974, USA

‡Department of Zoology, Tel Aviv University, Tel Aviv 69978, Israel

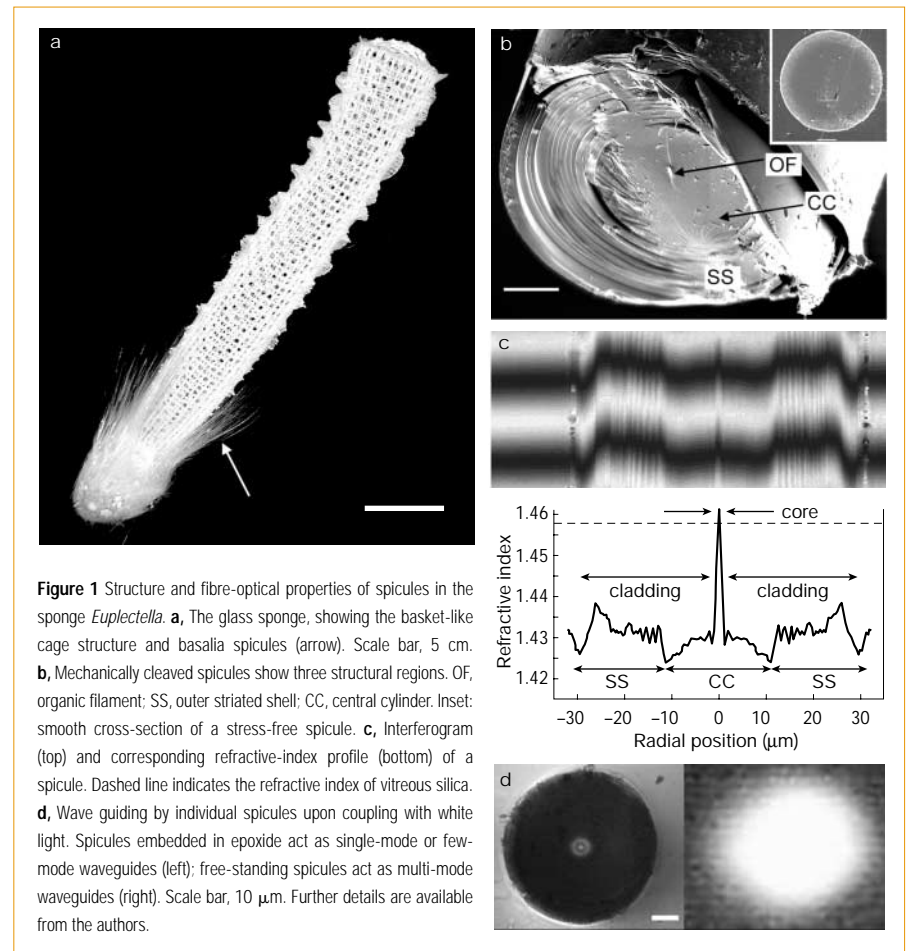


Figure 1 Structure and fibre-optical properties of spicules in the sponge *Euplectella*. **a**, The glass sponge, showing the basket-like cage structure and basalia spicules (arrow). Scale bar, 5 cm. **b**, Mechanically cleaved spicules show three structural regions. OF, organic filament; SS, outer striated shell; CC, central cylinder. Inset: smooth cross-section of a stress-free spicule. **c**, Interferogram (top) and corresponding refractive-index profile (bottom) of a spicule. Dashed line indicates the refractive index of vitreous silica. **d**, Wave guiding by individual spicules upon coupling with white light. Spicules embedded in epoxide act as single-mode or few-mode waveguides (left); free-standing spicules act as multi-mode waveguides (right). Scale bar, 10 μm. Further details are available from the authors.

1. Aizenberg, J., Tkachenko, A., Weiner, S., Addadi, L. & Hendler, G. *Nature* **412**, 819–822 (2001).
2. McPhedran, R. C. *et al. Aust. J. Chem.* **54**, 241–244 (2001).
3. Cattaneo-Vietti, R. *et al. Nature* **383**, 397–398 (1996).
4. Perry, C. C. & Keeling-Tucker, T. *J. Biol. Inorg. Chem.* **5**, 537–550 (2000).
5. Simpson, T. L. *The Cell Biology of Sponges* (Springer, New York, 1984).
6. Sarikaya, M. *et al. J. Mater. Res.* **16**, 1420–1428 (2001).
7. Marcuse, D. *Principles of Optical Fiber Measurements* (Academic, New York, 1981).
8. Clegg, W. J., Kendall, K., Alford, N. M., Button, T. W. & Birchall, J. D. *Nature* **347**, 455–457 (1990).
9. Kamat, S., Su, X., Ballarini, R. & Heuer, A. H. *Nature* **405**, 1036–1040 (2000).
10. Cha, J. N., Stucky, G. D., Morse, D. E. & Deming, T. J. *Nature* **403**, 289–292 (2000).
11. Kroger, N., Lorenz, S., Brunner, E. & Sumper, M. *Science* **298**, 584–586 (2002).

Competing financial interests: declared none.

Linguistics

Modelling the dynamics of language death

Thousands of the world’s languages are vanishing at an alarming rate, with 90% of them being expected to disappear with the current generation¹. Here we develop a simple model of language competition that explains historical data on the decline of Welsh, Scottish Gaelic, Quechua (the most common surviving indigenous language in the Americas) and other endangered languages. A linguistic parameter that quantifies the threat of language extinction can be derived from the model and may be useful in the design and evaluation of language-preservation programmes.

Previous models of language dynamics have focused on the transmission and evolution of syntax, grammar or other structural properties of a language itself^{2–7}. In contrast, the model we describe here idealizes languages as fixed, and as competing with each other for speakers. For simplicity, we also assume a highly connected population, with no spatial or social structure, in which all speakers are monolingual.

Consider a system of two competing languages, X and Y, in which the attractiveness of a language increases with both its number of speakers and its perceived status⁸ (a parameter that reflects the social or economic opportunities afforded to its speakers). Suppose an individual converts from Y to X with a probability, per unit of time, of $P_{yx}(x, s)$, where x is the fraction of the population speaking X, and $0 \leq s \leq 1$ is a measure of X’s relative status. A minimal model for language change is therefore

$$\frac{dx}{dt} = yP_{yx}(x, s) - xP_{xy}(x, s) \quad (1)$$

where $y = 1 - x$ is the complementary fraction of the population speaking Y at time t . By symmetry, interchanging languages

should yield the same transition probability as a swap in the fraction of speakers and relative status; thus $P_{xy}(x, s) = P_{yx}(1 - x, 1 - s)$. We also assume that no one will adopt a language that has no speakers ($P_{yx}(0, s) = 0$) or no status ($P_{yx}(x, 0) = 0$), and that P_{yx} is smooth and monotonically increasing in both arguments.

These mild assumptions imply that equation (1) generically has three fixed points. Of these, only $x = 0$ and $x = 1$ are stable. The model therefore predicts that two languages cannot coexist stably — one will eventually drive the other to extinction.

To test our model, we collected data on the number of speakers of endangered languages in 42 regions of Peru, Scotland, Wales, Bolivia, Ireland and Alsace-Lorraine, four instances of which are shown in Fig. 1. We fit the model’s solutions to the data, assuming transition functions of the forms $P_{yx}(x, s) = cx^a s$ and $P_{xy}(x, s) = c(1 - x)^a(1 - s)$. Unexpectedly, the exponent a was found to be roughly constant across cultures, with $a = 1.31 \pm 0.25$ (mean \pm standard deviation; further details are available from the authors).

Of the remaining parameters, status, s , is the most relevant linguistically; it could serve as a useful measure of the threat to a given language. Quechua, for example, still has many speakers in Huanuco, Peru, but its low status is driving a rapid shift to Spanish, which leads to an unfortunate situation in which a child cannot communicate with his or her grandparents.

Contrary to the model’s stark prediction, bilingual societies do, in fact, exist. But the

histories of countries where two languages coexist today generally involve split populations that lived without significant interaction, effectively in separate, monolingual societies. Only recently have these communities begun to mix, allowing language competition to begin.

So what can be done to prevent the rapid disintegration of our world’s linguistic heritage? The example of Quebec French demonstrates that language decline can be slowed by strategies such as policy-making, education and advertising, in essence increasing an endangered language’s status. An extension to equation (1) that incorporates such control on s through active feedback does indeed show stabilization of a bilingual fixed point.

Daniel M. Abrams, Steven H. Strogatz

Department of Theoretical and Applied Mechanics, Cornell University, Ithaca, New York 14853, USA
e-mail: dma32@cornell.edu

1. Krauss, M. *Language* **68**, 4–10 (1992).
2. Nowak, M. A., Komarova, N. L. & Niyogi, P. *Nature* **417**, 611–617 (2002).
3. Chomsky, N. A. *Syntactic Structures* (Mouton, New York, 1957).
4. Kroch, A. *Lang. Variat. Change* **1**, 199–244 (1989).
5. Hawkins, J. A. & Gell-Mann, M. *The Evolution of Human Languages* (Addison-Wesley, Reading, Massachusetts, 1992).
6. Niyogi, P. & Berwick, R. C. *Ling. Phil.* **20**, 697–719 (1997).
7. Lightfoot, D. *The Development of Language: Acquisition, Changes and Evolution* (Blackwell, Oxford, 1999).
8. Fishman, J. A. *Reversing Language Shift* (Multilingual Matters, Philadelphia, 1991).
9. Withers, C. W. J. *Gaelic in Scotland 1698–1981: The Geographical History of a Language* (Donald, Edinburgh, 1984).
10. Aitchison, J. & Carter, H. *A Geography of the Welsh Language* (Univ. Wales Press, Cardiff, 1994).
11. UK Office of Population Censuses and Surveys. *1991 Census Report for Wales, 1* (HMSO, London, 1993).

Competing financial interests: declared none.

Figure 1 The dynamics of language death. Symbols show the proportions of speakers over time of: **a**, Scottish Gaelic in Sutherland, Scotland⁹; **b**, Quechua in Huanuco, Peru; **c**, Welsh in Monmouthshire, Wales¹⁰; **d**, Welsh in all of Wales, from historical data¹⁰ (blue) and a single modern census¹¹ (red). Fitted curves show solutions of the model in equation (1), with parameters c , s , a and $x(0)$ estimated by least absolute-values regression. Where possible, data were obtained from several population censuses collected over a long timespan; otherwise, a single recent census with age-structured data was used (although errors are introduced, the size of which are reflected in the differing fits in **d**). Using the fraction of Catholic masses offered in Quechua in Peru as an indicator, we reconstructed an approximate history of the language’s decline.

