FORUM OPTICS

Perfect lenses in focus

Materials that refract light backwards are thought to be required for making super-resolution lenses. An alternative proposal — that conventional, positively refracting media can do the job — has met with controversy. Two experts from either side of the debate lay out their views on the matter.

Positive thinking

TOMÁŠ TYC

In 2000, Pendry showed[1] that a slab of material that bends light at a negative angle can work as a lens with the ability to resolve details much smaller than the wavelength of light. This is due to the fact that, unlike conventional lenses, which refract light at a positive angle (Fig. 1), this device transfers not only the propagating (long-range) waves of light from an object to its image, but also the object's evanescent waves — short-range light that carries smallest-scale information about the object. However, such a perfect lens, although based on a neat idea, has some serious drawbacks. For example, it turns out[2] that, for fundamental reasons, negative refraction is always connected with light absorption, and such absorption destroys the super-resolution ability of the lens. Moreover, perfect lenses based on negative refraction are difficult to manufacture and can work only in narrow bands of the electromagnetic spectrum.

A natural question to ask, therefore, is whether super-resolution lenses could be achieved by using materials that have a purely positive refractive index. In my opinion, the answer is definitely yes. As Leonhardt has shown[3] by analytical calculations, Maxwell's fish eye[4] — a prototype of a positively refracting perfect lens — can provide imaging that has, in principle, unlimited resolution. This theoretical prediction was confirmed experimentally by Ma, Leonhardt and colleagues[5], who showed that images of two sources of microwave radiation (used instead of light), separated by one-fifth of the radiation's wavelength, could be clearly distinguished.

However, to achieve such super-resolution by Maxwell's fish eye, an outlet (drain) is required so that the radiation reaching the point of image formation can be absorbed or otherwise extracted. And it is this feature that is at the root of the controversy surrounding the issue of using positive refraction to make perfect lenses. Using a drain is not a problem, however, because the very reason for imaging is to record the image on some photosensitive medium, which naturally provides the outlet.

There are some similarities between imaging by Maxwell's fish eye and by time-reversal mirrors[6,7]. In both cases, the object's electromagnetic waves converge at the image point from all directions to create a subwavelength-resolution image. To produce a time-reversal mirror, the electromagnetic field must be recorded, inverted in time and then re-emitted using a complicated set-up involving active elements (additional sources of radiation). By contrast, Maxwell's fish eye and other positively refracting perfect lenses form the converging waves naturally, without the need for active elements or field recording.

Although the theoretical[3] and experimental results[5] are promising, there are still many unresolved challenges relating to super-resolution with positive refraction. Probably the most exciting one is how to apply Maxwell's fish eye and other perfect lenses in microscopy or nanolithography — the two fields that these devices are most likely to revolutionize.

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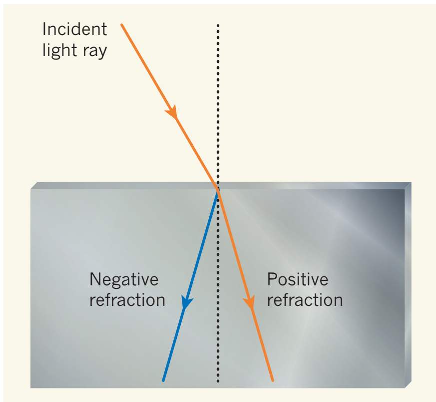

Figure 1 | Positive versus negative refraction. Unlike conventional materials, which refract incident light at a positive angle, artificially engineered materials that have a negative refractive index bend light at a negative angle.

No drain, no gain

XIANG ZHANG

I take issue with Leonhardt and colleagues' claim[3,5] that Maxwell's fish eye is a perfect lens. Maxwell's fish eye, proposed[4] more than 150 years ago, is subject to a diffraction limit: it cannot resolve any feature smaller than a fraction of the wavelength of the light being used.

Over the past decade, negative-index metamaterials, which are made of artificially structured composites, have been used as a means to overcome the diffraction limit and to make a perfect lens by focusing all wave components of light emitted or scattered from the object[1,8]. The key to such a perfect lens is its very ability to restore the smallest features of the object by enhancing the evanescent waves, which often decay in space.

Leonhardt and colleagues argued[3,5] that a metal-coated Maxwell's fish eye, which is made of a positive-index material, can also act as a perfect lens by collecting all wave components. Their trick for attaining a perfect lens was to place an additional optical active element (the drain) exactly where the object's image is formed.

The problem with this approach lies in the physical interpretation of the imaging resolution beyond the diffraction limit. An image formed using the drain-assisted fish-eye system involves electromagnetic waves not only from the object but also from a new source — the drain. The image is therefore no longer an intrinsic property of the fish eye itself. It was shown[9,10] that removal of the drain destroys the sub-diffractional object details, resulting in a diffraction-limited image. It is therefore not justified to claim that a general positive-refracting material can make a perfect lens.

Placing the drain at the image position supplies, through an electromagnetic field induced in the fish eye, the time-reversed form of the object's electromagnetic waves, and the superposition of the time-reversed waves yields an apparently perfect image. The device thus falls within well-known super-resolution image schemes based on time reversal[7].

The drain-assisted perfect lens is, however, an interesting use of Maxwell's fish eye, and it may offer opportunities from operations known as non-Euclidean optical transformations. Conventionally, the lens is an independent device that is separated from the object and its image. By contrast, with the fish-eye lens, both the object and image are embedded in it. How the embedded object and image affect the lens and its functions remains to be investigated. For example, displacement of the space inside the lens by an object of finite size can significantly alter how the refractive index varies across the lens and therefore the lens's optical functions. What's more, detecting the image from inside the fish eye can be a challenge for practical applications. Nevertheless, the 'entangled' or integrated approach of an object–lens–image with a drain is an idea worth exploring. ■

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EVOLUTION

Big brains explained

The expensive-tissue hypothesis proposes that brain enlargement during human evolution was offset by a reduced gut size. The finding that the typical trade-off in mammals is between brain size and fat reserves suggests otherwise. **SEE LETTER P.91**

RICHARD POTTS

Brain enlargement is one of the more conspicuous aspects of human evolutionary history. Although the benefits of a large brain seem obvious, the correlated survival and metabolic costs are immense and define much about the human condition. In *Homo sapiens*, giving birth to big-brained babies is risky. Furthermore, the energy consumed by the brain forms roughly 65% of a baby's total consumption and no less than 20–25% of an adult's, even though brain tissue accounts for only 2% of adult body mass.

An enduring question, then, is how the energetic costs of evolving a larger brain were overcome, eventually enabling a threefold increase in volume in the transition from the hominin *Australopithecus* to *H. sapiens* (Fig. 1). On page 91 of this issue, Navarrete *et al.*[1] address this problem by presenting an impressive data set comparing mammalian brain size with the mass of visceral organs and fat deposits. Their results challenge the compelling idea that brain enlargement in *Homo* and other mammals can be 'financed' by a reduction in gut size.

The idea contested by Navarrete *et al.* is known as the expensive-tissue hypothesis[2]. It argues that the gastrointestinal tract is the only energetically costly organ system in humans and other primates that correlates negatively with brain size. Furthermore, a reduced gut is characteristic of primates that have high-quality diets. Because access to substantial quantities of meat and other new food resources has improved the quality of the diet of ancestral humans over the past 2.5 million years, this is expected to have allowed the human gut to become smaller. A key part of the expensive-tissue hypothesis, therefore, is that the costs of brain expansion in *Homo* were covered by this reduction in gut size.

According to the opposing view now offered by Navarrete *et al.*, the gut–brain trade-off should be replaced by a fat–brain trade-off. The authors took on the ambitious task of dissecting and measuring fat tissue mass in 100 species of mammals. They discovered that brain size correlates negatively with the amount of body fat in most mammals, but not with the mass of the gut, liver or any other tissue that has been proposed to be energetically expensive in mammals.

The lack of a negative relationship between expensive tissues and brain size across many mammalian groups led the authors to dispute the idea that human brain enlargement was paid for by energy savings associated with a reduced gastrointestinal tract. Instead, they suggest that increasing body fat and brain size are complementary strategies for warding off starvation. In other words, an organism's capacity to store body fat, which is a relatively inexpensive way to buffer food scarcity, can be reduced in lineages in which a bigger brain allows better-quality food intake or lowers the energetic costs of other life functions.

But what about primates? And how does this finding[1] help to explain the particular case of *H. sapiens*? Navarrete *et al.* did not observe a reciprocal relationship between brain size and fat reserves in primate species. They attribute this result to the fact that the primates they studied were captive animals — and thus not truly representative of primates in their natural environment — and to the diverse ways in which primates store fat, among other factors. As for *H. sapiens*, our species is unusual in having not only a large brain, but also hefty fat deposits — a dual strategy for combating starvation that was apparently beneficial

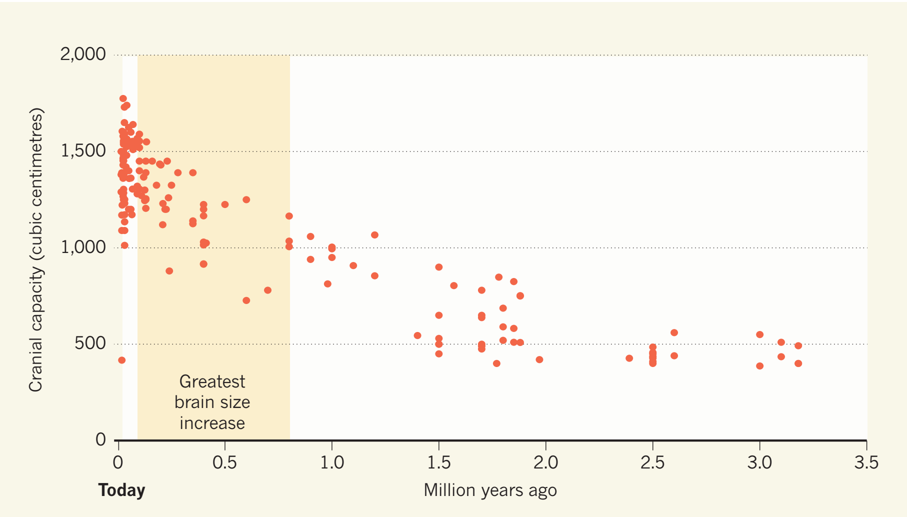

Figure 1 | Human brain expansion. The cranial capacities of hominin fossils illustrate an increase in brain size, largely within the genus *Homo*, over the past 2 million years. If *Homo floresiensis* (bottom-left data point) is omitted as an outlier, the data show that more than 50% of the increase occurred between 800,000 and 200,000 years ago. This suggests that the processes and pathways that caused brain expansion in *Homo* were concentrated in this period. (Cranial-capacity data from refs 3–5.)