reached 1 °C above pre-industrial levels, even though the safe boundary of 1.5 °C has not yet been exceeded. This is because, at 1 °C, tens of millions of people had already been exposed to temperature extremes (Fig. 1).

The 1 °C threshold is, then, one of seven 'safe and just' boundaries that the authors identify as having already been transgressed globally (with aerosols being the exception). They find that, in areas spanning 52% of the world's land surface, two or more of these boundaries have been crossed, and that these transgressions have affected 86% of the global population. In areas containing 28% of the world's people, four or more boundaries have been crossed.

The proposition of a safe operating space for humanity can be thought of in terms of homeostasis[4]: the proposed boundaries are tipping points whose transgression could send the planet into destabilizing paroxysms hostile to life. The earlier, influential 'planetary boundaries' suggestion has since been discussed by many scholars, including British economist Kate Raworth (ref. 5; see also go.nature.com/3mqnjwq) whose 'doughnut economics' provides a prescient framework for the updated boundaries. Raworth's model describes how social imperatives — such as the widely accepted goal of eradicating global poverty — impose constraints on already-limited planetary resources. The doughnut hole represents a lower bound to resource use (termed the 'access foundation' by Rockström and colleagues), and the edge of the doughnut is defined by the planetary boundaries. The space in between is conceived of as a 'corridor' within which humanity must ensure that resources are used justly as well as safely.

Rockström *et al.* have rejigged Raworth's boundaries and repositioned the just thresholds at the outside edge of the corridor. The thresholds no longer indicate merely the minimum resource use necessary to achieve just ends, but also maximum use to avoid harm, effectively recalibrating the safe boundaries. In practice, the authors seek to establish what they call 'Earth system justice' by converting sociopolitical ideas into biophysical quantities. The goal is to find a common language in which to express the fragility of Earth's system in the face of human impacts, as well as the point at which the resulting harm to human and non-human well-being, from the point of view of both environmental change and policies to address it, becomes unacceptable.

But translating between the natural and social sciences is not an easy task. To quantify harm, the authors have relied on new ideas of intergenerational, intragenerational and interspecies justice published this year in *Nature Sustainability*[6]. In each case, they calculated the just threshold as the point at which the impact of biophysical changes will cause 'significant harm', which is defined in a domain-specific way. The authors' conclusion is that safe Earth-system boundaries are themselves unsustainable in a world in which inequality is high and resources are unjustly distributed. The implications are immense.

The need for further research is potentially vast, and future work will certainly need to be interdisciplinary. For example, whereas homeostasis might be desirable for Earth as a biophysical system[1], it is much less obviously desirable for Earth's sociopolitical system: the definition of safe boundaries assumes that the status quo has inherent value, whereas most ideas of justice make no such assumption (given the huge variations in levels of human development across the world)[7,8]. The 'safe' boundaries and the 'just' ones are thus not merely in tension but potentially in outright contradiction. The world, after all, has been marked by high inequality and unjust resource distribution for a very long time: what, then, are the consequences of having now transgressed seven out of eight safe and just Earth-system boundaries?

At a minimum, the idea of just boundaries demands a reappraisal of long-standing debates about justice in the light of new circumstances — an immense task not undertaken by Rockström and colleagues. How can planetary-level effects be understood within the conventional framework of justice, given their varying impacts and distributional effects on different groups, which each have vastly different levels of responsibility for both causing and mitigating these effects[9]? The authors posit the need for policies that account for what they call distributive justice, but stop short of articulating what these policies might be. How can a good life for all be ensured within such tight constraints?

The sketch of interspecies justice is similarly minimal: human exceptionalism is rejected, but it is unclear what should stand in its place. Restating the obligation to conserve biodiversity is a start, but reducing the rate of species extermination hardly amounts to justice (see the discussion in ref. 6). The other thresholds (intergenerational and intragenerational) are subjects of a large and growing literature in which there is little agreement as to what they encompass or how they interact — factors that look very different when viewed locally or globally[9].

These are among the many questions opened up by Rockström and colleagues' study, and they will occupy scholars at the nexus of biophysical and sociopolitical research for some time to come. But although the work seems to raise more questions than it answers, it takes a crucial step towards bridging the divide between these research areas. In doing so, there is hope that it moves us closer to the realization of a truly safe and just Earth system.

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1. Rockström, J. *et al. Nature* **461**, 472–475 (2009).
2. Rockström, J. *et al. Ecol. Soc.* **14**, 32 (2009).
3. Rockström, J. *et al. Nature* **619**, 102–111 (2023).
4. Lenton, T. M., Dutreuil, S. & Latour, B. *Anthropocene Rev.* **7**, 248–272 (2020).
5. Raworth, K. *Doughnut Economics: Seven Ways to Think Like a 21st-Century Economist* (Random House, 2017).
6. Gupta, J. *et al. Nature Sustain.* https://doi.org/10.1038/s41893-023-01064-1 (2023).
7. Hickel, J. *Third World Q.* **40**, 18–35 (2019).
8. Hickel, J. *Lancet Planet. Health* **4**, e399–e404 (2020).
9. Humphreys, S. *Eur. J. Int. Law* **44**, 1061–1092 (2022).

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Medical research

Close to the finish of the polio endgame

Alan D. T. Barrett

Efforts to eradicate polio globally have been under way for more than 35 years. The development of modified versions of a vaccine in current use now makes eradication a real possibility. **See p.135**

Vaccination has been crucial for the control of certain infectious diseases. However, only two have so far been eradicated — the human disease smallpox and an animal infection called rinderpest. In both cases, the virus responsible was eradicated using a vaccination approach based on a 'weakened' version of the infectious virus (termed a live attenuated vaccine). On page 135, Yeh *et al.*[1] report their development of a live attenuated vaccine that might offer a way to eradicate poliomyelitis (polio).

Polio is a potentially life-threatening muscle-wasting disease, often associated

with paralysis. It is caused by three strains, or serotypes, of poliovirus. Both types of polio vaccine now in use — the inactivated virus (Salk vaccine) and the live attenuated virus of oral polio vaccines (OPVs; Sabin) — have been successful in controlling the disease.

Humans are the only species providing a reservoir for poliovirus, so there is potential for the eradication of the virus. With this goal in mind, the Global Polio Eradication Initiative was launched in 1988 (https://polioeradication.org), with a completion goal of 2000. However, this proved more difficult than expected. So far, eradication of all three poliovirus serotypes has been elusive despite the elimination of wild-type poliovirus serotype 2 in 2015, and wild-type poliovirus serotype 3 in 2019. The virus continues to circulate: as wild-type poliovirus serotype 1 and as two other types of the virus – vaccine-associated paralytic poliomyelitis (VAPP) and vaccine-derived poliovirus (VDPV) – that arose from the virus in vaccines reverting to a virulent form (Fig. 1).

Moreover, polio outbreaks occur semi-regularly in two countries, Afghanistan and Pakistan. Eradication will not be possible until transmission is eliminated in all countries.

Thus, the Polio Eradication and Endgame Strategic Plan began in 2013 with the goal of eliminating wild-type poliovirus type 1 and managing VAPP and VDPV. Despite some success, the hoped-for 'endgame' has not been achieved. Therefore, other approaches are needed.

A 1981 study[2] reported the development of a method, called reverse genetics, for transcribing a copy of the single-stranded RNA poliovirus genome, encoded on a type of circular DNA called a plasmid, into a messenger RNA equivalent to the virus genome. This mRNA could then be transferred into cells to generate poliovirus. The development revolutionized polio research, and led to the discovery of molecular determinants of wild-type disease and the determinants of attenuation for the attenuated vaccines[3].

The breakthrough needed for eradication could depend on using technology to genetically engineer a live attenuated vaccine to improve its safety profile while retaining its ability to elicit an immune response (immunogenicity). This is extremely difficult to achieve for live attenuated vaccines that have an RNA genome because the viruses with an RNA genome exist as a 'swarm' of genomes consisting of many distinct sequences. This is due to the low fidelity of RNA-dependent RNA polymerase, the viral enzyme that replicates the viral sequences.

Unsurprisingly, the live attenuated viruses of the Sabin vaccine can evolve as they multiply. This can result in reversion of attenuating mutations, and thus the emergence of virulent

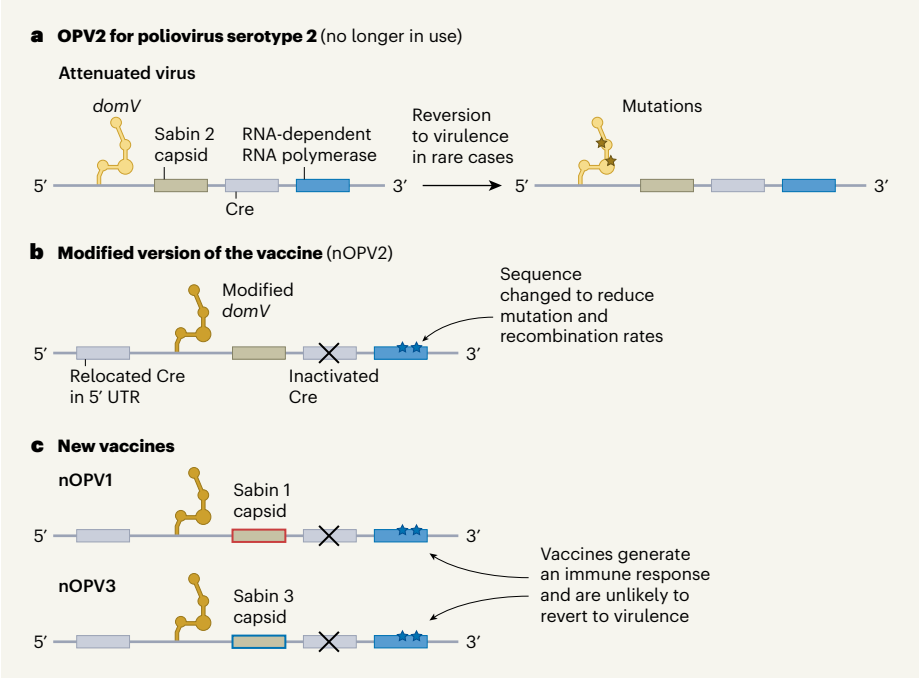

Figure 1 | Polio-vaccine design. Three poliovirus strains exist, termed serotypes 1, 2 and 3, and these can be targeted using what is known as a live attenuated virus in an oral polio vaccine (called OPV or a Sabin vaccine). These vaccines encode a non-virulent virus, and they include a sequence called *domV* (a 'stem–loop' structure in a non-coding part of the RNA) and sequences that encode a viral coat structure called a capsid, an enzyme termed Cre and an RNA-dependent RNA polymerase enzyme. **a**, A problem arose with OPV vaccines because, in rare cases, as shown here for OPV2, the virus reverted to a virulent form — for example, as a result of mutations in *domV* and a genetic alteration called recombination (not shown). **b**, A modified version of OPV2 (nOPV2) was engineered[4] to combat the re-emergence of virulence. These changes include the relocation of functional Cre to a region at the start of the RNA (the 5′ untranslated region, or UTR), an altered *domV* sequence to lessen the chance of unwanted changes associated with reversion to virulence, and sequence alterations to the gene encoding the RNA-dependent RNA polymerase to limit its possible role in reversion. **c**, Yeh *et al.*[1] used the nOPV2 backbone, and replaced the capsid sequence with those encoding capsids of other serotypes. This generated the vaccines nOPV1 and nOPV3, which target serotypes 1 and 3, respectively.

VDPV variants. Circulation of such variants can lead to the continual evolution of viruses that generate VDPVs with a high capacity for transmission.

All three polioviruses can mutate into VDPVs, although the proportions vary by serotype. Thus, genetically stable OPVs would be an important tool in polio eradication. In the past few years, reverse genetics has been used to produce a live attenuated oral vaccine for poliovirus serotype 2 (nOPV2)[4] that is genetically stable, safe and immunogenic in both animal (preclinical) and clinical studies[4,5]. Indeed, clinical trials indicate that nOPV2 generates immune responses comparable to those elicited by the original Sabin OPV2. Moreover, all of the genetic modifications of nOPV2 are retained, and its genetic stability means that it is unlikely either to cause VAPP or to evolve into VDPVs[5]. The vaccine has been approved by the World Health Organization for VDPV2 outbreaks, and has been used in 23 countries, with more than 500 million doses distributed (see https://polioeradication.org).

> **"There is potential for the eradication of the virus."**

Yeh and colleagues developed candidate vaccines for poliovirus serotypes 1 and 3 (nOPV1 and nOPV3). The authors used the nOPV2 genetic sequence, and incorporated genes that encode components of a viral coat structure called the capsid from either the OPV1 or OPV3 vaccines. The nOPV2 backbone contains a genetically 'stabilized' component (in the 5′ untranslated region) and has two mutations in the gene encoding the RNA-dependent RNA polymerase. The mutations enable the vaccine to retain an attenuated form even if mutational changes occur after vaccine administration.

Both nOPV1 and nOPV3 were highly immunogenic in the mouse model tested. They retained all the attenuated properties of parental nOPV2, were genetically stable, more highly attenuated, and had a lower rate of reversion to virulence than was the case for the original Sabin OPV strains. Even so, the vaccines induced similar protection and immunogenicity to those seen with their

original Sabin OPV 1 and OPV3 counterparts.

Of note, even when a mutant arose that had lost all the attenuating mutations of nOPV1 and nOPV3, such mutants were no more virulent than were their Sabin counterparts. Furthermore, when the three nOPVs were administered to mice in a trivalent formulation, antibodies were induced against all three poliovirus serotypes. This finding indicates that there was no interference between the three viruses in terms of their ability to multiply simultaneously. Thus, the mouse model offers a proof of principle that a trivalent nOPV vaccine would work in humans.

This is impressive science, and reveals the potential for generating a safe and effective trivalent live attenuated polio vaccine. Will it lead the endgame to the finish line? That is a big question. The data from the animal studies are exciting, but the big unknown is how a trivalent version of this polio vaccine will perform in humans. The results of clinical trials will be interesting because all three polioviruses have been simultaneously 'super-engineered' for attenuation.

It has taken 42 years from the original description of the reverse-genetics[2] approach to achieve this promising move towards completing the endgame. The goal of an improved live attenuated trivalent polio vaccine is within reach.

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1. Yeh, M. T. *et al. Nature* **619**, 135–142 (2023).
2. Racaniello, V. R. & Baltimore, D. *Science* **214**, 916–919 (1981).
3. Minor P. D., Macadam, A. J., Stone, D. M. & Almond, J. W. *Biologicals* **21**, 357–363 (1993).
4. Yeh, M. T. *et al. Cell Host Microbe* **27**, 736–751 (2020).
5. De Coster, I. *et al. Lancet* **397**, 39–50 (2021).

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Condensed-matter physics

First light on orbitronics as a viable form of electronics

Tatiana G. Rappoport

An effect that transfers information using the rotational motion of electrons has been detected with light, forging a path towards technologies that are cheaper – and less harmful to the environment – than existing electronics. **See p.52**

Almost two decades ago, physicists detected a phenomenon known as the spin Hall effect[1,2], in which an electric field separates the electrons in a material on the basis of their intrinsic angular momentum, or 'spin'. This discovery stimulated the field of spintronics, which is a branch of electronics that uses spin – as well as electric charge – to transfer and store data. On page 52, Choi *et al.*[3] report the direct detection of a related phenomenon, called the orbital Hall effect, in which the field sorts electrons according to their orbital angular momentum, which is related to their rotational motion. The prospect of encoding data in orbitals has been dubbed orbitronics, and could lead to the development of environmentally friendly electronic devices.

Conventional electronics uses electric charge to process information, but computer memories built in this way are volatile. By incorporating both charge and spin, spintronics offers a more stable alternative. However, it requires the information transmitted as charge to be converted into spin currents, and vice versa. This is usually achieved by making use of a phenomenon known as spin–orbit coupling, in which an electron's spin interacts with its orbital motion. In the presence of an electric field, this interaction causes electrons to move in a direction that depends on their spin, thereby generating a flow of spins that is perpendicular to the electric current. This is the spin Hall effect.

This mechanism for converting between spin and charge works best in metals that have strong spin–orbit coupling, such as gold, platinum and tungsten. But these metals are scarce and costly, and mining them can result in considerable environmental damage. Orbitronics aims to overcome these limitations by

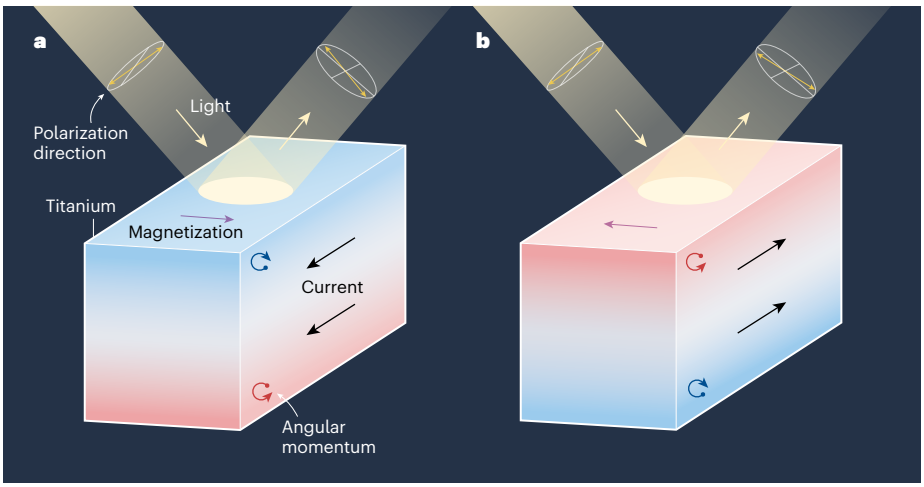

Figure 1 | Detecting the orbital Hall effect in titanium. a, The orbital Hall effect is a phenomenon in which an electric current causes electrons to separate on the basis of their orbital angular momentum, which is related to their orbital motion. This leads to the angular momentum on one surface of a material differing to that on the opposite surface, and manifests as surface magnetization in opposite directions. Choi *et al.*[3] induced this effect in titanium and then illuminated the sample with linearly polarized light, which has an electric field that oscillates in a single direction. The magnetization arising from the orbital Hall effect rotated the polarization of the reflected beam, making it detectable. **b**, When the direction of the electric field was reversed, the polarization rotated in the opposite direction, indicating that the surface magnetization had changed sign.