microfluidic device was lined with trapezium-shaped posts 80 micrometres apart that created evenly spaced matrix pouches in which the stem cells could grow and differentiate.

The authors loaded stem cells into the device and, 18 hours later, pumped morphogen-containing fluids into either the liquid-containing channel on one side or the cell-loading channel on the other (Fig. 1b). After 36 hours, structures with 3D organization that mimicked a peri-implantation human embryonic sac had formed in each pocket. Furthermore, the authors could use different morphogens to induce anteriorization or posteriorization — that is, the development of characteristic features of the anterior or posterior ends of a normal embryo (Fig. 1c). However, the embryonic-like sacs did not anteriorize and posteriorize at the same time, which is crucial for further embryo development.

In posteriorized embryonic-like sacs measuring just over 100 micrometres in diameter, the authors observed cell populations that resembled a developing amniotic membrane (the membrane that lines the walls of the amniotic-fluid-filled sac), a posterior primitive streak (which forms the basis of the body's bilateral symmetry), mesoderm-like cells and, remarkably, PGC-like cells. In the anteriorized embryonic-like sacs, the authors saw anterior primitive streak-like cells and endoderm-like cells. Thus, this is one of the first humanized models that can enable study of the awesome complexity of spatial relationships between cells in the peri-implantation window of development.

At this point, readers might be asking whether these embryonic-like sacs are, in fact, human embryos. The structures can be considered imitations of the real things, but crucially, they are not viable (they could not develop into a normal fetus) and do not have certain essential structures, such as a primitive endoderm and a trophoblast cell layer, which are necessary for the formation of the placenta and further membranes that surround the embryo.

The model also brings up the question of the 14-day rule: the internationally recognized consensus that scientists can grow intact human embryos in the lab for only 14 days, or until the primitive streak forms, whichever happens first[11]. In this study, either anterior or posterior primitive-streak-like cells formed in the structures, enabling investigation of the cell-signalling events in this process. However, in my opinion, an intact human embryo is created by the fertilization of an egg by a sperm cell and by the resulting formation of embryonic and embryo-surrounding cell lineages, which these sac-like structures were not.

Furthermore, the 14-day rule was created to help safeguard against development of embryos to a stage at which they could become sentient or feel pain — and neither could occur in this model because anterior and posterior cells were not specified at the same time and, although untested, it is likely that no sensory neuronal cells would have formed. Therefore, Zheng and colleagues' microfluidic model might technically be exempt from the 14-day rule because it does not represent an intact embryo in the way that we consider an embryo donated for research from an *in vitro* fertilization clinic to be intact. However, the ethics of running experiments using human embryonic-like sacs for longer than 14 days should be evaluated, with particular focus on whether the structure should at any point be considered a human being.

Finally, I urge policymakers to consider this device to be a useful addition to the human-stem-cell toolbox, as it can be used to examine a period of human embryonic development that is currently inaccessible for *in vivo* research. The model can be scaled up to become high throughput, and thus could be invaluable to environmental toxicologists. The length of time for which these structures can be studied in the device is relatively short; currently, most of them collapse within a few days. In future, if these embryonic-like sacs could be cultured for longer, they could provide crucial extra information about embryonic development. In turn, we might be able to use this information to help millions of women around the world to better understand or even avoid early pregnancy loss. ■

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COMPUTING

Stochastic magnetic bits rival quantum bits

Circuits based on the stochastic evolution of nanoscale magnets have been used to split large numbers into prime-number factors — a problem that only quantum computers were previously expected to solve efficiently. SEE LETTER P.390

DMITRI E. NIKONOV

Data encryption typically relies on the practical difficulty of a process called prime factorization. In this process, a huge number (represented by 1,024 or more bits) is decomposed into a product of prime numbers. Such a task is notoriously time-consuming for conventional computers and is estimated[1] to be much more efficient for a future quantum computer — assuming that such a machine is built and uses a method called Shor's algorithm[2]. On page 390, Borders *et al.*[3] demonstrate that an integrated circuit (a computer chip) containing nanoscale magnets can split numbers up to 945 into prime factors efficiently. Such a nanomagnet chip is much easier to make than a quantum computer and, if improved, could threaten data encryption.

If you are reading this article on a computer, you are probably using electronic bits in the machine's processor and magnetic bits in its hard drive. Electronic bits are based on semiconducting devices called transistors. Such a bit has a definite state (0 or 1) that depends on whether a net negative or net positive charge of thousands of electrons is stored in the gate (a terminal of the transistor) (Fig. 1a). By contrast, a magnetic bit is based on hundreds of thousands of electron spins (magnetic moments) in a magnet. The state of this bit can also be either 0 or 1, depending on whether the net spin of the electrons points down or up (Fig. 1b).

For these two types of computing bit, a large energy barrier needs to be overcome to switch between the 0 and 1 states. As a result, the states persist despite random 'relaxation' forces caused by thermal fluctuations in the environment. Borders and colleagues' chip uses nanomagnets in which the barrier between the 0 and 1 states is small. Consequently, random relaxation forces cause the nanomagnets to randomly fluctuate between the two states, with a certain probability that the net spin points up or down (Fig. 1c). Such bits are therefore called probabilistic bits (p-bits). Borders *et al.* used their chip to perform prime factorization on numbers as large as 945.

A further type of bit, which is used in quantum computers, is known as a quantum

NATURE

50 Years Ago

During two seasons of geological and palaeontological study in the lower Omo Basin, Ethiopia, a series of remains of Hominidae were recovered from deposits of Pliocene/Pleistocene age … The hominids are from a series of horizons rich in fossil vertebrates, especially mammals, and are of particular interest as they antedate those recovered from Olduvai Gorge, Tanzania. … Remains of Hominidae from a range of time hitherto largely unknown have now been recovered from a succession of fossiliferous horizons within this series of beds. … If these attributions are confirmed, then the hominid samples from the Omo Beds would indicate the co-existence of (at least) two australopithecine taxa through much of the range of Pliocene/Pleistocene time.

From *Nature* 20 September 1969

100 Years Ago

Prof. McIntosh's expressed views are, broadly speaking, as follows:—(1) The fecundity of sea-fishes is so great … that the idea of exterminating any species of food-fish—or even of seriously diminishing its total numbers—by intensive fishing is chimerical; (2) so long as man fails to make any serious impression upon the multitudes of young fishes, there is no need for anxiety; (3) no serious inroad upon the numbers of young fishes has hitherto been made; (4) therefore all is well, the fears of the pessimists are pointless, the claims of the optimists are established.

He ignores the evidence that the rate of growth of these little fishes and their rate of emigration to the offshore grounds no longer keep pace with the rate of capture … does "vigilance" consist in ignoring the plainest evidence accumulated by other people, while we sing hymns of praise to Pan or Poseidon?

From *Nature* 18 September 1919

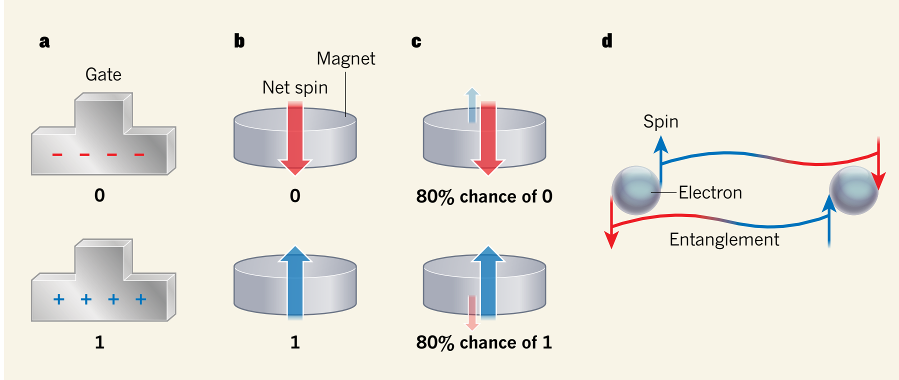

Figure 1 | Four types of computing bit. **a**, Electronic bits are based on tiny switches called transistors. The state of such a bit can be 0 or 1, depending on whether the gate — a terminal of the transistor — is negatively or positively charged. **b**, A typical magnetic bit also has a state of 0 or 1, depending on whether the net spin (magnetic moment) of electrons in a magnet points down or up. **c**, Borders *et al.*[3] report experiments on stochastic magnetic bits, which randomly fluctuate between the 0 and 1 states with a certain probability (represented by arrow size) of being in each state. **d**, Quantum bits are based on spins of single electrons and are simultaneously in the 0 and 1 states. Two such bits can be entangled, which means that the first bit is in the 1 state and the second is in the 0 state, and vice versa, simultaneously.

bit (qubit) and is based on the spin of a single electron (Fig. 1d). To understand how qubits work, a good start is to consider Schrödinger's cat. In this famous thought experiment, a cat in a closed box can be considered to be both dead and alive, until the box is opened and the cat's status is revealed. Note that, when the box is closed, the cat does not simply have a certain probability of being dead and a certain probability of being alive, as in usual (classical) probabilities. Instead, it exists in a quantum-correlated state, in which it is simultaneously dead and alive.

For Shor's algorithm, an even more intricate state of two qubits, called an entangled state, is required (Fig. 1d). The analogue would be a quantum-correlated state in which one cat is alive and a second cat is dead, and vice versa, simultaneously. Random relaxation forces are the main headache for quantum computers, because they destroy entanglement. There is a type of quantum computing, termed adiabatic, that does not need entanglement. But no theoretical work has claimed that this approach is more efficient than conventional computing.

By contrast, for p-bits, random relaxation forces are turned into a mechanism of operation, in the spirit of the theory of inventive problem solving[4] (commonly referred to by its Russian acronym TRIZ). These differences between p-bits and qubits hopefully convince you that, even conceptually, p-bits are much simpler to operate than are qubits.

There are two other advantages of the authors' approach over quantum computing. First, the nanomagnet chip is fabricated using a process that has already been developed for magnetic memories, whereas a suitable quantum computer would call for a new and highly sophisticated manufacturing process. Second, the nanomagnet chip works at room temperature, whereas the quantum computer would need refrigeration to keep it well under 1 kelvin. In addition to being a nuisance, such refrigeration would require about a kilowatt of power for every watt consumed by the computer[5], and would increase the difficulty in developing and operating this technology.

I should mention another example of an experimental proof of prime factorization that did not require quantum computing. In 2016, a Russian–US collaboration[6] carried out such factorization using spin waves, which are propagating precessions of spins in nanomagnets. Unfortunately, that work did not receive as much attention as perhaps it should have.

The nanomagnet methods of prime factorization are still in their infancy. Many developments are needed to turn these nanomagnet chips into practical computing engines: the ability to connect thousands of p-bits to each other; a demonstration of combining p-bits and transistors in an integrated circuit; and a calculation of the time and energy needed to achieve prime factorization of huge numbers using these methods.

However, owing to the aforementioned advantages, there is a high chance that these requirements will be fulfilled more quickly and more easily than for quantum computing. Given Borders and colleagues' results, the attention of research groups and the funding from many agencies might be diverted from quantum computing to nanomagnet chips. ■

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