NEWS & VIEWS

PHYSICS

A quantum less quirky

Seth Lloyd

What physicists want for Christmas is a solution to the philosophical conundrums of quantum mechanics. They will be disappointed, but work that dissolves one aspect of quantum weirdness is some consolation.

There is a strange quantum-mechanical phenomenon. A brilliant researcher receives a Nobel prize for work on quantum physics, but then expresses scepticism about the validity of the theory. Albert Einstein started the trend in 1921, and remains its most famous exponent. He received his Nobel for the quantum-mechanical explanation of how electric current can be generated just by shining light on a surface (the photoelectric effect), but for the rest of his life expressed a deep-seated distrust of the quantum. God, as he famously said, does not play dice. Most recently, Tony Leggett, a Nobel laureate in 2003, expressed his belief that quantum physics is at the very least incomplete, and needs to be supplemented by some new physics. Writing in *Physical Review A*, Wojciech Zurek[1] now provides some balsam for these and other pained minds.

So what makes geniuses deny the source of their inspiration, and muddy the font of their fame? The answer is the intrinsic bizarreness of quantum mechanics. Waves consist of particles; particles are shadowed by waves; electrons (or anything else, for that matter) can be in two places at once.

Tests of infant cognition show that the idea that an object cannot be in two places at once is ingrained in our psyches from the age of about three months. At the same age, babies become aware that objects exist even when they cannot be seen. Playing peek-a-boo with a child aged less than three months is intensely dissatisfying: when you cover your face, they exhibit no excitement or interest. Daddy is gone: so what? After three months, everything changes. When you cover your face, the child waits with eager anticipation for the "Boo!": he or she knows you're there behind the hands.

In quantum mechanics, if you can't see an object, you mustn't assume it is there: an unmonitored electron can be, and generally is, everywhere at once. By the age of three months, children are better equipped to live in the macroscopic world, but their intuition for quantum mechanics is spoilt.

Everyone finds quantum mechanics counterintuitive, Nobel laureates included (at least,

ILLUSTRATION BY ANDY MARTIN

Nobel laureates older than three months). I find quantum mechanics counterintuitive. I am not a Nobel laureate, but I spend my research time thinking about quantum mechanics in order to build quantum computers and quantum communication systems. But so what if I find it counterintuitive? My intuition is frequently wrong anyway. As long as I can perform the calculations and get the right answers, then I should be happy.

But if ever a scientist deserved to trust his intuition, it was Einstein. For his sake, and for those like him who find quantum weirdness deeply distressing, we should delve a little further into the roots of the problem. In his paper[1], Zurek does just that, providing a simple, elegant and intuitive explanation of one of the strangest and most counterintuitive features of quantum mechanics — its peculiar mathematical shape.

Mathematically speaking, quantum mechanics is a strange beast. The states of particles such as electrons correspond to functions or vectors in a complex vector space. Physical transformations (an electron hopping from place to place, for example) correspond to linear operators or matrices acting on those functions and vectors. The act of measuring the properties of the system equates to applying the appropriate mathematical operator to the vector describing the system. On measurement, the system 'collapses' to an eigenvector of the measurement operator (that is, a vector that the operator, applied again, will simply transform into a multiple of itself), and an associated eigenvalue. The eigenvalue gives the outcome of the measurement.

Why is this so? Why does measurement leave a system described by nothing other than an eigenvector ('in an eigenstate', in the jargon) of the measurement operator? For the past 80 years, the answer to this question has been because Erwin Schrödinger and Werner Heisenberg said so: it's just one of the 'postulates' of quantum mechanics.

Zurek shows that it is in fact a consequence of an intuitively more satisfactory postulate: that if one makes a measurement twice in rapid succession, one always obtains the same result. He uses an argument based on his and William Wootters's proof[2] of the celebrated 'no-cloning' theorem (essentially, that you can't create identical copies of an unknown quantum state) to show that if a measurement were to leave a system in anything other than an eigenstate of that measurement, immediate repetition of the measurement would have a chance of yielding a different result. A quirky, mathematical postulate of quantum mechanics is thus replaced by a simple derivation from an intuitive result.

Einstein was celebrated for proclaiming that God is subtle, but not malicious. The proof that, despite His predilection for games of chance, God does not attempt to change the rules mid-game certainly would have delighted Einstein. Would it have convinced him of the validity of quantum mechanics? My intuition tells me not. ■

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1. Zurek, W. H. *Phys. Rev. A* **76,** 052110 (2007).
2. Wootters, W. K. & Zurek, W. H. *Nature* **299,** 802–803 (1982).

CANCER DIAGNOSTICS

One-stop shop

Jonathan W. Uhr

Detecting cancer early and monitoring its progress non-invasively are high on oncologists' agenda. So the design of a neat device that detects and counts cancer cells shed into the blood by tumours is a welcome advance.

A hallmark of carcinomas — malignant tumours of epithelial tissues such as breast and colon — is the invasion of neighbouring tissues at an early stage of tumour growth. This process is associated with the shedding of tumour cells into the bloodstream. So counting and characterizing such circulating tumour cells to monitor the progress of the disease might be the most viable alternative to the unacceptable process of repeated, invasive biopsies. On page 1235 of this issue, Nagrath *et al.*[1] report the development of an efficient and selective method for isolating these rare cells using microchip technology.

It might be considered too late to diagnose and characterize carcinomas if tumour cells have already entered the circulation, but this is not always the case. For example, although the presence of circulating tumour cells in patients with breast cancer usually indicates a poor prognosis, it does not necessarily indicate cancer metastasis. This is because only a small fraction of these cells have metastatic potential[2], and soon after entering the bloodstream, many tumour cells become committed to a suicide programme[3]. Also, circulating tumour cells are found in a significant proportion of breast-cancer patients long after such patients have undergone a mastectomy, despite being clinically disease-free and at a very low risk of their cancer recurring[4].

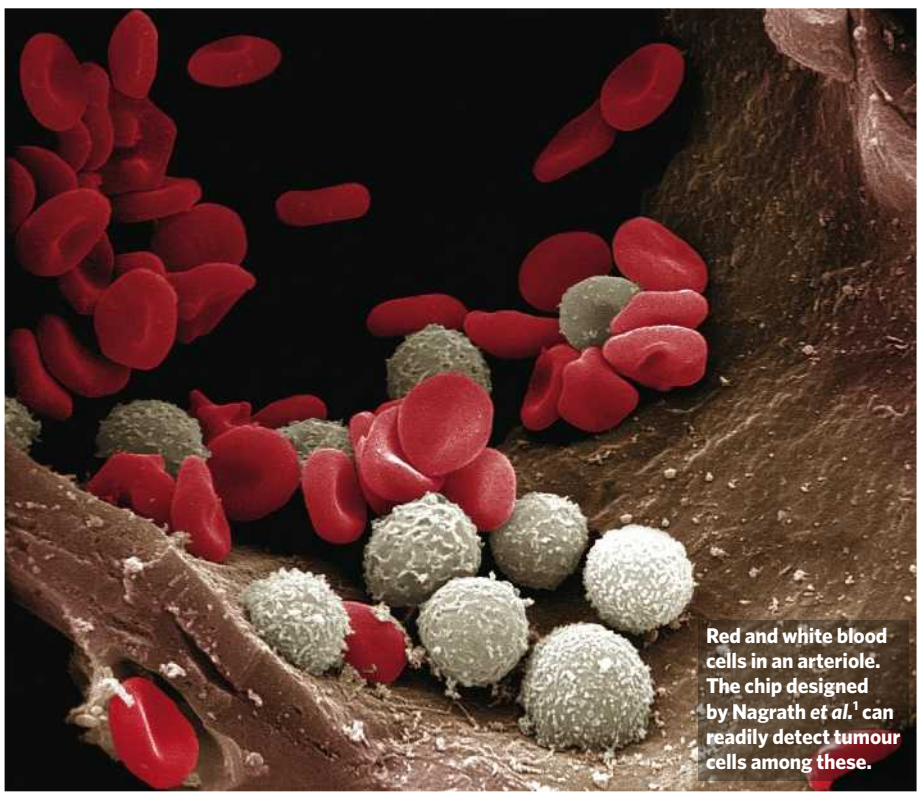
Identifying and counting these cells can also be useful for monitoring carcinomas. For example, patients who have more than a certain level of circulating tumour cells have a poorer prognosis and so require more aggressive therapy[5]. Counting the cells after a course of treatment has been started can show whether it is effective, thereby allowing the treatment regimen to be modified much earlier than if physicians had to rely solely on changes in tumour size[5]. Furthermore, analysis of particular genes or proteins in tumour cells has revealed that they are continually altering genetically. So genetic changes in themselves could be a reason for modifying a patient's course of treatment[6], and could be useful for selecting drugs that target particular cellular pathways involved in the malignancy. Indeed, such patient-specific approaches are deemed the therapies of the future.

The usual criteria for identifying circulating tumour cells are their microscopic appearance (they are larger than most white blood cells, with a large nucleus and little cytoplasm), a characteristic expression profile of the cytokeratin protein, and the absence of a protein marker for normal blood cells. Although not definitive, these criteria are probably sufficient identification if there are large numbers of tumour cells in the patient's blood.

Various techniques have been used to capture these rare cells, and advances include the development of an automated instrument for counting them known as CellSearch, which is currently in clinical use[7]. The detection unit of this instrument uses metal particles coated with an antibody to the EpCAM protein, which is present on virtually all carcinoma cells[8]. A magnetic field is then used to capture antibody-bound tumour cells. However, such techniques generally detect circulating tumour cells in only 20–60% of patients with metastatic disease[9].

The work of Nagrath *et al.*[1] is the latest advance. The authors have developed a microfluidic ('lab-on-a-chip') device that can separate circulating tumour cells from whole-blood samples. The surface of this chip houses 78,000 microposts, each coated with antibodies to EpCAM. Fresh, unprocessed blood is pumped across the chip under controlled flow conditions to avoid damaging the fragile tumour cells. (This is a great improvement on conventional immunomagnetic enrichment procedures, which often damage the cells.) The cells bind to the microposts and are identified by a camera that can detect their morphology, viability and the presence of tumour markers on their surface (see Fig. 1 on page 1235). Different tumour markers can be identified by staining the cells with specific antibody–dye conjugates.

The chip seems to be highly sensitive. The authors could detect circulating tumour cells in almost all of the patients they examined who had recurrent carcinomas, regardless of the tumour's organ of origin, and in all of seven patients with early-stage tumours. Moreover, the purity of the cells obtained with this device was far higher



Red and white blood cells in an arteriole. The chip designed by Nagrath *et al.*[1] can readily detect tumour cells among these.

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