Quantum minds: Why we think like quarks

05 September 2011 by **Mark Buchanan**
Magazine issue 2828. **Subscribe and save**
For similar stories, visit the **The Human Brain** and **Quantum World** Topic Guides

Read more: "Quantum logic could make better robot bartenders"

The fuzziness and weird logic of the way particles behave applies surprisingly well to how humans think

When errors make sense (Image: Paul Wesley Griggs)

1 more image

THE quantum world defies the rules of ordinary logic. Particles routinely occupy two or more places at the same time and don't even have well-defined properties until they are measured. It's all strange, yet true - quantum theory is the most accurate scientific theory ever tested and its mathematics is perfectly suited to the weirdness of the atomic world.

Yet that mathematics actually stands on its own, quite independent of the theory. Indeed, much of it was invented well before quantum theory even existed, notably by German mathematician David Hilbert. Now, it's beginning to look as if it might apply to a lot more than just quantum physics, and quite possibly even to the way people think.

Human thinking, as many of us know, often fails to respect the principles of classical logic. We make systematic errors when reasoning with probabilities, for example. Physicist Diederik Aerts of the Free University of Brussels, Belgium, has shown that these errors actually make sense within a wider logic based on quantum mathematics. The same logic also seems to fit naturally with how people link concepts together, often on the basis of loose associations and blurred boundaries. That means search algorithms based on quantum logic could uncover meanings in masses of text more efficiently than classical algorithms.

It may sound preposterous to imagine that the mathematics of quantum theory has something to say about the nature of human thinking. This is not to say there is anything quantum going on in the brain, only that "quantum" mathematics really isn't owned by physics at all, and turns out to be better than classical mathematics in capturing the fuzzy and flexible ways that humans use ideas. "People often follow a different way of thinking than the one dictated by classical logic," says Aerts. "The mathematics of quantum theory turns out to describe this quite well."

It's a finding that has kicked off a burgeoning field known as "quantum interaction", which explores how quantum theory can be useful in areas having nothing to do with physics, ranging from human language and cognition to biology and economics. And it's already drawing researchers to major conferences.

One thing that distinguishes quantum from classical physics is how probabilities work. Suppose, for example, that you spray some particles towards a screen with two slits in it, and study the results on the wall behind (see diagram). Close slit B, and particles going through A will make a pattern behind it. Close A instead, and a similar pattern will form behind slit B. Keep both A and B open and the pattern you should get - ordinary physics and logic would suggest - should be the sum of these two component patterns.

But the quantum world doesn't obey. When electrons or photons in a beam pass through the two slits, they act as waves and produce an interference pattern on the wall. The pattern with A and B open just isn't the sum of the two patterns with either A or B open alone, but something entirely different - one that varies as light and dark stripes.

Such interference effects lie at the heart of many quantum phenomena, and find a natural description in Hilbert's mathematics. But the phenomenon may go well beyond physics, and one example of this is the violation of what logicians call the "sure thing" principle. This is the idea that if you prefer one action over another in one situation - coffee over tea in situation A, say, when it's before noon - and you prefer the same thing in the opposite situation - coffee over tea in situation B, when it's after noon - then you should have the same preference when you don't know the situation: that is, coffee over tea when you don't know what time it is.

Remarkably, people don't respect this rule. In the early 1990s, for example, psychologists Amos Tversky and Eldar Shafir of Princeton University tested the idea in a simple gambling experiment. Players were told they had an even chance of winning $200 or losing $100, and were then asked to choose whether or not to play the same gamble a second time. When told they had won the first gamble (situation A), 69 per cent of the participants chose to play again. If told they had lost (situation B), only 59 per cent wanted to play again. That's not surprising. But when they were not told the outcome of the first gamble (situation A or B), only 36 per cent wanted to play again.

Classical logic would demand that the third probability equal the average of the first two, yet it doesn't. As in the double slit experiment, the simultaneous presence of two parts, A and B, seems to lead to some kind of weird interference that spoils classical probabilities.

Flexible logic

Other experiments show similar oddities. Suppose you ask people to put various objects, such as an ashtray, a painting and a sink, into one of two categories: "home furnishings" and "furniture". Next, you ask if these objects belong to the combined category "home furnishings or furniture". Obviously, if "ashtray" or "painting" belongs in home furnishings, then it certainly belongs in the bigger, more inclusive combined category too. But many experiments over the past two decades document what psychologists call the disjunction effect - that people often place things in the first category, but not in the broader one. Again, two possibilities listed simultaneously lead to strange results.

These experiments demonstrate that people aren't logical, at least by classical standards. But quantum theory, Aerts argues, offers richer logical possibilities. For example, two quantum events, A and B, are described by so-called probability amplitudes, alpha and beta. To calculate the probability of A happening, you must square this amplitude alpha and likewise to work out the probability of B happening. For A or B to happen, the probability amplitude is alpha plus beta. When you square this to work out the probability, you get the probability of A (alpha squared) plus that of B (beta squared) plus an additional amount - an "interference term" which might be positive or negative.

This interference term makes quantum logic more flexible. In fact, Aerts has shown that many results demonstrating the disjunction effect fit naturally within a model in which quantum interference can play a role. The way we violate the sure thing principle can be similarly explained with quantum interference, according to economist Jerome Busemeyer of Indiana University in Bloomington and psychologist Emmanuel Pothos of the University of Wales in Swansea. "Quantum probabilities have the potential to provide a better framework for modelling human decision making," says Busemeyer.

The strange links go beyond probability, Aerts argues, to the realm of quantum uncertainty. One aspect of this is that the properties of particles such as electrons do not exist until they are measured. The experiment doing the measuring determines what properties an electron might have.

Hilbert's mathematics includes this effect by representing the quantum state of an electron by a so-called "state vector" - a kind of arrow existing in an abstract, high-dimensional space known as Hilbert space. An experiment can change the state vector arrow, projecting it in just one direction in the space. This is known as contextuality and it represents how the context of a specific experiment changes the possible properties of the electron being measured.

The meaning of words, too, changes according to their context, giving language a "quantum" feel. For instance, you would think that if a thing, X, is also a Y, then a "tall X" would also be a "tall Y" - a tall oak is a tall tree, for example. But that's not always the case. A chihuahua is a dog, but a tall chihuahua is not a tall dog; "tall" changes meaning by virtue of the word next to it. Likewise, the way "red" is defined depends on whether you are talking about "red wine", "red hair", "red eyes" or "red soil". "The structure of human conceptual knowledge is quantum-like because context plays a fundamental role," says Aerts.

These peculiar similarities also apply to how search engines retrieve information. Around a decade ago, computer scientists Dominic Widdows, now at Google Research in Pittsburgh, Pennsylvania, and Keith van Rijsbergen of the University of Glasgow, UK, realised that the mathematics they had been building into search engines was essentially the same as that of quantum theory.

Quantum leaps

It didn't take long for them to find they were on to something. An urgent challenge is to get computers to find meaning in data in much the same way people do, says Widdows. If you want to research a topic such as the "story of rock" with geophysics and rock formation in mind, you don't want a search engine to give you millions of pages on rock music. One approach would be to include "-songs" in your search terms in order to remove any pages that mention "songs". This is called negation and is based on classical logic. While it would be an improvement, you would still find lots of pages about rock music that just don't happen to mention the word songs.

Widdows has found that a negation based on quantum logic works much better. Interpreting "not" in the quantum sense means taking "songs" as an arrow in a multidimensional Hilbert space called semantic space, where words with the same meaning are grouped together. Negation means removing from the search pages that shares any component in common with this vector, which would include pages with words like music, guitar, Hendrix and so on. As a result, the search becomes much more specific to what the user wants.

"It seems to work because it corresponds more closely to the vague reasoning people often use when searching for information," says Widdows. "We often rely on hunches, and traditionally, computers are very bad at hunches. This is just where the quantum-inspired models give fresh insights."

That work is now being used to create entirely new ways of retrieving information. Widdows, working with Trevor Cohen at the University of Texas in Houston, and others, has shown that quantum operations in semantic Hilbert spaces are a powerful means of finding previously unrecognised associations between concepts. This may even offer a route towards computers being truly able to discover things for themselves.

To demonstrate how it might work, the researchers started with 20 million sets of terms called "object-relation-object triplets", which Thomas Rindflesch of the National Institutes of Health in Bethesda, Maryland, had earlier extracted from a database of biomedical journal citations. These triplets are formed from pairs of medical terms that frequently appear in scientific papers, such as "amyloid beta-protein" and "Alzheimer's disease", linked by any verb that means "associated with".

The researchers then create a multi-dimensional Hilbert space with state vectors representing the triplets and applied quantum mathematics to find other state vectors that, loosely speaking, point in the same direction. These new state vectors represent potentially meaningful triplets not actually present in the original list. Their approach makes "logical leaps" or informed hypotheses about pairs of terms, which are outside the realms of classic logic but seem likely promising avenues for further study. "We're aiming to augment scientists' own mental associations with associations that have been learned automatically from the biomedical literature," says Cohen.

He and his colleagues then asked medical researchers to use the approach to generate hypotheses and associations beyond what they could come up with on their own. One of them, molecular biologist Graham Kerr Whitfield of the University of Arizona in Phoenix, used it to explore the biology of the vitamin D receptor and its role in the pathogenesis of cancer. It suggested a possible link between a gene called *ncor-1* and the vitamin D receptor, something totally unexpected to Kerr Whitfield, but now the focus of experiments in his lab.

Yet one big question remains: why should quantum logic fit human behaviour? Peter Bruza at Queensland University of Technology in Brisbane, Australia, suggests the reason is to do with our finite brain being overwhelmed by the complexity of the environment yet having to take action long before it can calculate its way to the certainty demanded by classical logic. Quantum logic may be more suitable to making decisions that work well enough, even if they're not logically faultless. "The constraints we face are often the natural enemy of getting completely accurate and justified answers," says Bruza.

This idea fits with the views of some psychologists, who argue that strict classical logic only plays a small part in the human mind. Cognitive psychologist Peter Gardenfors of Lund University in Sweden, for example, argues that much of our thinking operates on a largely unconscious level, where thought follows a less restrictive logic and forms loose associations between concepts.

Aerts agrees. "It seems that we're really on to something deep we don't yet fully understand." This is not to say that the human brain or consciousness have anything to do with quantum physics, only that the mathematical language of quantum theory happens to match the description of human decision-making.

Perhaps only humans, with our seemingly illogical minds, are uniquely capable of discovering and understanding quantum theory. To be human is to be quantum.

Mark Buchanan *is a science writer based in the UK*