QUANTUM INFORMATION

Good causes

Classically, it is impossible to infer causal dependencies from the correlations between two variables alone, but in the quantum world causal relationships exist that can be completely characterized by observing the correlations between two systems.

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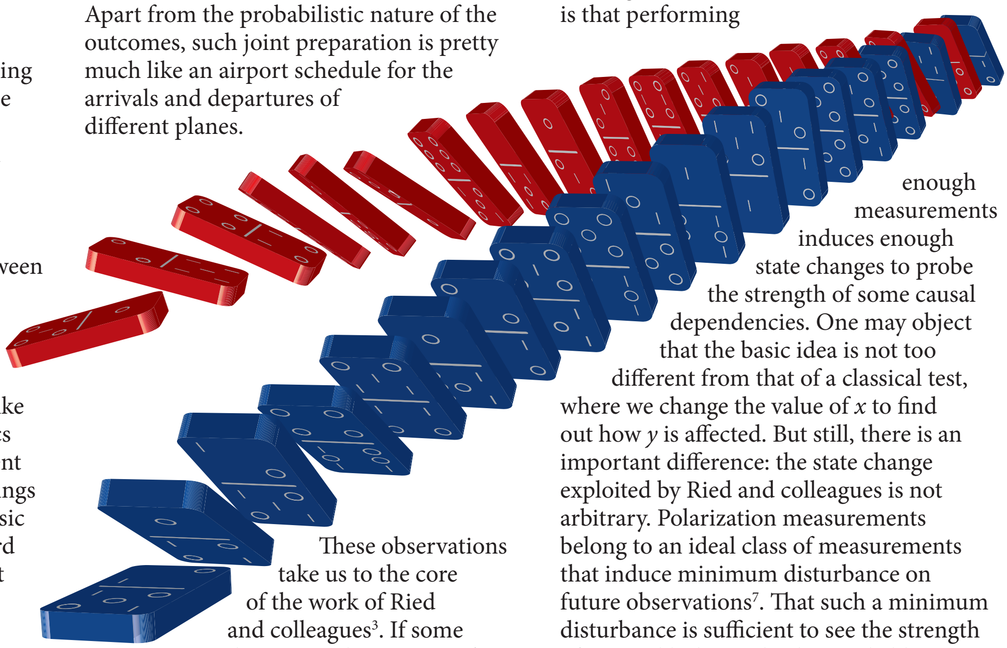
Discovering causal links has countless applications in medicine, genetics, climatology and economics[1,2]. And it is a tricky business, too. In classical statistics, everyone is familiar with the maxim 'correlation does not imply causation' — knowing that two variables are correlated is not enough to conclude that one influences the other. A plane to Milan may take-off regularly a few hours after the landing of a plane from Beijing, not because the arrival of the latter causes the departure of the former, but simply because of the airport schedule. This is an example of a common cause, which can account for the correlations between two variables, *x* and *y*. Lacking other clues about how the correlations arise, the only way to establish that *x* has a causal influence on *y* is by freely changing the value of *x* and checking whether the probability of *y* is affected.

The situation is different in quantum mechanics. Writing in *Nature Physics*, Katja Ried and colleagues[3] show that quantum correlations can completely characterize the causal relationship between two systems. When and why this is possible turn out to be deep and stimulating questions.

Causality in quantum mechanics has recently come into the limelight[4]. Like classical mechanics, quantum mechanics is a causal theory — meaning that present experiments are not affected by the settings of future experiments[5]. This is a very basic property, without which it would be hard to even talk about causal inferences. But the similarities between quantum and classical causality seem to end here: when it comes to the 'correlation versus causation' business, quantum mechanics has a genuinely new story to tell.

Imagine that we observe the correlations between two measurements of single-photon polarization, obtained by repeating the experiment in different settings — for instance, with polarizers oriented along different directions. Can we tell whether the outcome of the first measurement influences the outcome of the second? The surprising answer is yes — sometimes. Suppose that we choose the same setting for both measurements and the two polarizations turn out to be the same, no matter what that setting is. Then, we can safely conclude that the second measurement has been performed on the output of the first, and therefore is causally affected by its outcome[6]. Conversely, suppose that the polarizations are always anti-correlated. Then, Ried and colleagues[3] observe that the two measurements must have been performed in parallel on an entangled quantum state. The correlations now imply a common cause: the joint preparation of two photons prior to our measurements. Apart from the probabilistic nature of the outcomes, such joint preparation is pretty much like an airport schedule for the arrivals and departures of different planes.



These observations take us to the core of the work of Ried and colleagues[3]. If some correlations imply a cause–effect relationship and others imply a common cause, then it should be possible to characterize every probabilistic mixture of the two extremes. This intuition is indeed correct. Ried *et al.* show it both theoretically and experimentally in an optical network containing a random switch that controls the causal dependence between two polarization measurements. With probability p, the measurements are performed in cascade (cause–effect relationship), whereas with probability $1 - p$ they are performed in parallel on an entangled state (common cause). In this scenario, the striking conclusion is that the correlations in just a few measurement settings are enough to measure p, completely characterizing the strength of the causal dependencies hidden in the network. Such a task would have been impossible in the classical world.

How can we make sense of the sharp difference between quantum and classical? Recall that in the quantum world the observation of a system generally induces a change of its state. What Ried *et al.*[3] show is that performing enough measurements induces enough state changes to probe the strength of some causal dependencies. One may object that the basic idea is not too different from that of a classical test, where we change the value of *x* to find out how *y* is affected. But still, there is an important difference: the state change exploited by Ried and colleagues is not arbitrary. Polarization measurements belong to an ideal class of measurements that induce minimum disturbance on future observations[7]. That such a minimum disturbance is sufficient to see the strength of a causal link is indeed remarkable.

Curiously, part of the advantage fades away if we alter quantum theory by replacing complex numbers with real numbers. In a fictional world described by real-number quantum mechanics, photons could have only linear polarizations and the correlations between polarization measurements would not suffice to detect the causal dependencies in the network used by Ried and colleagues[3]. An intriguing open question is whether ordinary quantum mechanics is the only physical theory that allows us to discover such dependencies through ideal measurements. Luckily, the tools to tackle this question are already in place: both the framework of causal networks[8] and the notion of ideal measurement[9,10] have been recently extended from quantum mechanics to arbitrary physical theories.

Another natural question is: what is special about those causal dependencies that can be characterized just in terms of ideal measurements? In quantum mechanics, Ried and colleagues[3] provide the answer when the causal dependence is a probabilistic mixture of common cause and cause–effect relationships, showing that quantum coherence and entanglement are necessary features. The case of more general causal dependencies, as well as correlations in quantum networks containing more than two measurements, remains a subject of future research. Even more broadly, the ideas introduced by Ried *et al.*[3] could find applications in the study of exotic quantum gravity scenarios featuring a non-fixed causal structure[11–13]. In all of these cases, the abundance of open questions, as well as the rapid emergence of new counterintuitive results, reveals that causality in quantum mechanics is a much richer and more surprising area than previously thought. ❐

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FLUID DYNAMICS

Sticky stitches

Drizzle syrup over your pancakes and you may notice a coil developing where the fluid thread hits the surface. This well-known phenomenon — the 'liquid rope-coil effect' — results from the interplay between the syrup's viscosity and gravitational and inertial forces.

Similarly, a viscous liquid rope falling onto a moving surface (or from a moving nozzle) can produce a pattern that deviates from a straight line. In fact, several different patterns have been observed for such systems — nicknamed fluid-mechanical sewing machines because the generated motifs resemble common stitch patterns. Pierre-Thomas Brun and colleagues have now come up with a model that reproduces the experimentally obtained patterns and predicts additional features (P-T. Brun *et al.*, *Phys. Rev. Lett.*, in the press; preprint at http://arxiv.org/abs/1410.5382).

The typical paths traced out by a viscous liquid thread on a moving belt are loops (translated coils), alternating loops, meanders and straight lines. Their periodicities come from the intrinsic frequencies of the tracing processes, which have been found to be multiples of the coiling frequency for the static (non-moving surface) case. Brun *et al.* performed numerical simulations of the sewing machine, taking viscosity and gravitation into account, but with inertia artificially switched off. Remarkably, the resulting phase diagram (with


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dimensionless nozzle height and surface speed as phase variables) contained all possible types of pattern, suggesting that inertial forces weren't playing a significant role.

This conclusion prompted the authors to devise a geometrical model in which the path drawn by the falling liquid rope was described by a set of equations for the position of the contact point and the local curvature of the path. The equations arise from considering the shape of the pendant thread (dictated by gravity and viscosity) and the coupling between the fluid and the moving surface.

The solutions of the geometrical model matched the outcomes of the full simulations very well. In addition, the authors discovered a new pattern with coils wide apart from one another (the 'W-pattern'), as well as hysteretic effects: the transitions between different regimes when changing the surface velocity occurred at different speeds for acceleration and deceleration.

Apart from uncovering the physical processes underlying fluid-mechanical sewing machines, the findings of Brun *et al.* are relevant to a variety of industrial applications like the manufacture of non-woven fabrics or the automated production of cake decorations. They also enable an understanding — or even simulation — of the drip painting technique used by Jackson Pollock.

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