QUANTUM CONTROL

Squinting at quantum systems

Quantum measurements always have a back-action: they 'kick' the system in a particular way. This can be used to drive the system to any desired state using a fixed type of measurement, provided it can be 'unsharpened'.

HOWARD M. WISEMAN

For the purpose of controlling a system, two facts appear self-evident. First, the more information one can obtain about the system, the better one can control it. Second, one needs to do more than just obtain information in order to control the system. In the quantum world, however, self-evidence cannot be trusted. Writing in *Physical Review A*, Ashhab and Nori[1] refute the two 'facts' just given and show that a quantum system can be quickly driven to any desired state using a fixed type of measurement. Although various schemes have been proposed[2,3] for driving a quantum system from one state to another using only quantum measurements, this is the first time it has been shown to be achievable using repetitions of a given measurement. Crucially, the authors' proposal requires the measurement to be unsharp. That is, one must avoid obtaining too much information about the system.

Driving a system to a desired target state is a common control problem in physics and engineering. An everyday example is driving your car to a desired location. In practice, this involves observing what is happening all the time, but the observation is not what drives the car. In principle, if you knew your initial state (location), and there was no 'noise' (no other cars on the road), and you had a good theory (a perfectly memorized route map, and a knowledge of how your car responds to its controls), then you could drive your system (car) to the desired state with no observation whatsoever (with your eyes closed).

In quantum physics, observation can have a much more active role than it does in driving a car. This is related to Heisenberg's uncertainty principle, which implies that even if the system is in a pure state (that is, we know as much about the system as nature allows), some of its properties must be unpredictable. As a consequence, making a certain type of measurement of a system to reveal more about a certain property (for example, its momentum) will necessarily disturb other properties (for example, its position), making them more uncertain. This happens even if the measurement is minimally disturbing[4], so that it leaves the system in a pure state as close as possible to the initial pure state, on average[5].

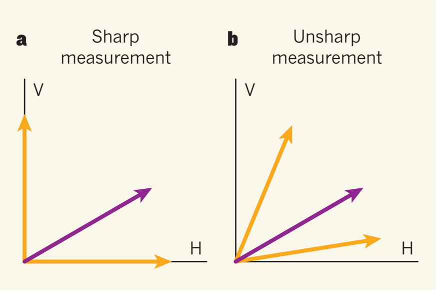

Figure 1 | Sharp and unsharp measurements. The purple arrow represents the initial pure quantum state of a two-dimensional quantum system such as the polarization of a photon. For this physical system, the direction H represents a horizontally polarized state and V represents a vertically polarized state, and the initial state is a particular superposition of these (but closer to H than V). **a**, After a sharp measurement of polarization, the photon is in either the H-polarized state or the V-polarized state (orange arrows). **b**, After an unsharp measurement ('squinting'; here with a sharpness of 50%), the photon is still in a superposition, but the 'H' result puts the state (lower orange arrow) much closer to an H-polarized state than the 'V' result puts it to a V-polarized state (upper orange arrow). Ashhab and Nori[1] show that by tweaking the sharpness of the measurement to the right value, the measurement-induced change in the state can be optimized.

The unavoidable disturbance necessitated by gaining information about a quantum system is known as quantum back-action, and the change it causes in the system's state can be used to control the system. In particular, probing a system — even in a minimally disturbing way — can replace the application of direct controls to drive it into a desired target state[1–3]. What sets the proposal of Ashhab and Nori[1] apart is its innovative use of measurement strength, or 'sharpness'[4].

In traditional quantum mechanics, one considers sharp measurements[4], in which the final pure state is determined solely by the measurement outcome (that is, it is independent of the initial state). If one could design the measurement so that the set of possible final states included the desired target, then clearly one would have the possibility of causing the system to jump straight there by a single measurement. But what if these possible final states are fixed, and do not include the desired state?

What Ashhab and Nori have shown is that for one class of measurements ('symmetric, informationally complete' measurements[6]) any target state can be attained, as long as the measurement can be repeated, and as long as one can make it unsharp[4]. As would be expected, unsharp measurements have less quantum back-action than sharp measurements (Fig. 1). They cause jumps towards — rather than directly to — the possible final states of the corresponding sharp measurement. Unsharp measurements are known to be better than sharp measurements in feedback control of quantum systems[7,8]. Ashhab and Nori[1] introduce a completely new sort of feedback, in which the degree of sharpness for each measurement depends on the outcomes of previous measurements.

To return to the analogy of driving a car, in quantum physics it is as if your car would jump to a different location every time you opened your eyes to observe it. For a sharp observation (eyes wide open), there would be only a fixed set of possible post-jump locations, so if none of these was your target location, then you would never get to where you want to go. But with an unsharp measurement (squinting), how far the car would jump towards one of those fixed locations would depend on the car's current location. By squinting just the right amount each time, you would have a good chance of reaching your target location after only three observations. This is what Ashhab and Nori have shown to be possible using unsharp measurements for a two-dimensional quantum system (such as the polarization of a photon).

This work raises a number of obvious questions. Can one prove analytically what Ashhab and Nori have shown by numerical calculations? How does it generalize to higher-dimensional systems? Is having an informationally complete[6] measurement sufficient? Squinting at a quantum system may not be the easiest way to drive it to a target state, but answering these questions will continue to reveal more about the fascinating and non-self-evident field of quantum measurement and control. ■

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ANIMAL BEHAVIOUR

The nexus of sex and violence

In mice, brain neurons that respond during either mating or aggression exhibit spatial overlap, and some even respond during both. This may help to explain the relationship between sex and violence in human behaviour. SEE ARTICLE P.221

CLIFFORD B. SAPER

The close relationship between sex and violence has been an enduring theme in literature, theatre and music since the dawn of 'civilized' culture. A particularly graphic depiction of the connection can be found in Anthony Burgess's book *A Clockwork Orange*, which famously mixes the two in a mélange of 'ultraviolence'. Although fascinating, the intertwined nature of these two opposites of social interaction and the underlying neurobiological basis have remained a puzzle. On page 221 of this issue, Lin and colleagues[1] identify some of the basic circuitry for these behaviours in the hypothalamus — a primitive part of the brain that has been highly conserved throughout mammalian evolution.

It has long been known[2] that, in cats, electrical stimulation in certain regions of the hypothalamus elicits attack behaviour. Studies[3,4] in rats have also identified a network of brain sites in which stimulation can produce aggression, including the ventromedial nucleus of the hypothalamus (VMH).

Meanwhile, investigators have identified[5] VMH neurons that express receptors for sex hormones, and have shown[6] that electrical stimulation of the VMH can produce sexual behaviours in rats. Moreover, after mating or aggression, neurons in the ventrolateral VMH (VMHvl) and several other brain areas, including parts of the amygdala, express cFos — a protein that is expressed by many brain neurons that have recently undergone activation[7]. It remained unclear, however, whether both behaviours activate the same neurons, or separate cell populations that overlap spatially. Lin and co-workers[1] attempted to sort this out.

The authors sequentially exposed male mice to another male and, 15–20 minutes later, to a female — situations that would trigger first aggression and then sexual behaviour. They then analysed neurons for two types of cFos messenger RNA: heteronuclear mRNA, which would have been produced more recently, while the female mouse was present; and cytoplasmic mRNA, which would have matured from heteronuclear mRNA generated earlier while the male mouse was present. Although neurons expressing both types of mRNA spatially overlapped in the VMHvl, they largely belonged to distinct populations. However, a proportion (20–30%) of these cells showed cFos expression during both encounters.

To better define the time course of the neuronal response, Lin *et al.* recorded the firing of individual VMHvl neurons in male mice during encounters with both sexes. Whereas some 40% of the VMHvl neurons were excited by male intruders, about half of these were activated only during close encounter and attack. By contrast, roughly one-third of the VMHvl cells were excited by a female intruder, but the level of excitement in around two-thirds of these neurons tended to decrease as the sexual encounter progressed.

About half of all recorded neurons in the VMHvl responded initially to both a male and a female intruder, but many of these ultimately continued firing during only one of the two behaviour patterns. The dual activation of some neurons during the earliest stages of both encounters indicates that they share some types of input; in other words, the interaction of the two outcomes is deeply rooted in the basic architecture of the brain.

Lin *et al.*[1] provide another line of evidence for the interaction between sexual behaviour

50 Years Ago

The Tobacco Manufacturers' Standing Committee has as a declared aim the assistance of research into questions concerned with the relationship between smoking and health. That this object is being fulfilled is evident from its report for the year ended May 31, 1960, which summarizes investigations carried out during the year under the auspices of the Committee or with its financial support ... Fractions of cigarette smoke condensate prepared in the laboratories of the Committee have been found by several workers to have carcinogenic or tumour-promoting properties, but as the report points out, these results, obtained by application of smoke fractions to animal tissues, are not necessarily reliable guides to the possible response of human lung tissue to tobacco smoke.
From *Nature* 11 February 1961

100 Years Ago

The terrible intensity of the outbreak of pneumonic plague now raging in Manchuria, and the presence of plague-infested animals within our own borders, have called forth recently a number of communications on plague in the daily press. A special correspondent in *The Times*, in two well-informed articles … summarises the situation, and gives an admirable sketch of the principal facts concerning the modes of spread of plague. Dr. L. W. Sambon has also contributed two letters on the subject … He remarks, for example, that in his belief transmission from man to man is probably more frequent than from rat to man. If Dr. Sambon bases this statement upon personal experience of epidemics of bubonic plague, it must be said that his observations are directly opposed to the experience of many competent plague workers.
From *Nature* 9 February 1911