For songbirds, singing is a complex behaviour that must be learned. It has stimulated rapidly advancing research in various disciplines, notably neurobiology and behavioural ecology[1], yet we still do not understand in detail how sound is produced by the birds' vocal organ, the syrinx. The main reason for this is that the syrinx is located at the base of the trachea (windpipe), making it relatively inaccessible to direct physiological studies[2] — the powerful, direct methods that have been successfully used to study sound production in the human voice box cannot easily be adapted to investigate the avian syrinx. So our ideas about sound generation in birds are based on indirect approaches, such as analysis of vocalizations and of the morphology of the syrinx, and theoretical models.

A report by Fee *et al.*[3] on page 67 of this issue shows that a combination of indirect and direct approaches can help to overcome these difficulties. Their careful analysis of zebra finch (*Taeniopygia guttata*) song revealed linear and nonlinear phenomena, including switches from periodic to aperiodic or chaotic oscillations and period doubling (see box). Transitions from linear to nonlinear dynamics occurred rapidly (within 1 ms), without silent intervals between the two states, suggesting that the transitions arise from intrinsic properties of the vibrating components of the syrinx rather than from complex neural control.

Until now, it was assumed that the central nervous system directly controls the often intricate temporal pattern of song[4]. In birds, singing involves the expiratory muscles that line the body wall and generate pulses of increased air pressure by compressing the posterior air sacs (Fig. 1). These pulses define the coarse temporal pattern, which can be modified by activity of the syringeal muscles. These muscles are attached to the syrinx, and they turn sound production on and off by opening and closing the airways through the syrinx. The respiratory and syringeal muscles also control the acoustic structure of song, such as sound frequency and amplitude, and frequency modulation[5]. An elaborate network of brain areas controls the respiratory and syringeal muscles during song production[6]. But we now learn that intrinsic mechanical properties of the syrinx can contribute to temporal and acoustic song patterns. These patterns are independent of complex central control, requiring a minimal contribution (in the form of slowly changing pressure) from the respiratory and vocal muscles.

Fee *et al.*[3] discovered this by studying the vibratory behaviour of the zebra finch syrinx in an *in vitro* preparation. Sounds induced by drawing air through the excised syrinx showed linear and nonlinear acoustic phenomena, similar to those observed in

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sender. In some species of bird, for example, acoustic versatility of song is an indicator of male reproductive fitness[7]. So, this may be important for choice of mate and encounters between members of the same sex. If peripherally generated acoustic structure requires a less precise motor control than complex sound modulation controlled by the action of muscles, is it also weighed differently by a listener who is trying to work out the 'quality' of the singer?

The findings are also of practical importance for researchers trying to quantify the quality of birdsong. Our assessment of song complexity is tightly linked to our knowledge of sound-producing mechanisms, and now that peripheral contributions to song structure must be added to the picture, the task has become even more challenging.

Finally, there remains the question of whether nonlinear dynamics might also be involved in singing by other species of bird. I suspect that, as the news spreads, more examples of nonlinear effects contributing to the temporal and acoustic pattern in bird vocalizations will be described. Nonlinearity is also well recognized in the physiology of the human vocal organ, albeit often in connection with voice disorders[8]. But to those who suffer from a roughness of voice, it must be of little comfort to know that nonlinearity can also be a mechanism to enhance vocal properties. ☐

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Quantum mechanics

Where the weirdness comes from

Peter Knight

More than 60 years after the famous debate between Niels Bohr and Albert Einstein on the nature of quantum reality, a question central to their debate — the nature of quantum interference — has resurfaced. Dürr, Nonn and Rempe, reporting on page 33 of this issue[1], have used an atom interferometer to show that Schrödinger's concept of 'entanglement' between the states of particles is the key to wave–particle duality, and to understanding much that is weird about quantum mechanics. This is quite different from the usual textbook explanation of duality in terms of unavoidable 'measurement disturbances'. It confirms that entanglement is essential in establishing quantum weirdness and in the emergence of classical behaviour at larger scales.

Quantum entities can behave like particles or waves, depending on how they are observed. They can be diffracted and produce interference patterns (wave behaviour) when they are allowed to take different paths from some source to a detector — in the usual example, electrons or photons go through two slits and form an interference pattern on the screen behind. On the other hand, with an appropriate detector put along one of the paths (at a slit, say), the quantum entities can be detected at a particular place and time, as if they are point-like particles. But any attempt to determine which path is taken by a quantum object destroys the interference pattern. Richard Feynman described this as the central mystery of quantum physics.

Bohr called this vague principle 'complementarity', and explained it in terms of the uncertainty principle, put forward by Werner Heisenberg, his postdoc at the time. In an attempt to persuade Einstein that wave–particle duality is an essential part of quantum mechanics, Bohr constructed models of quantum measurements that showed the futility of trying to determine which path was taken by a quantum object in an interference experiment. As soon as enough information is acquired for this determination, the quantum interferences must vanish, said Bohr, because any act of observing will impart uncontrollable momentum kicks to the quantum object. This is quantified by Heisenberg's uncertainty principle, which relates uncertainty in positional information to uncertainty in momentum — when the position of an entity is constrained, the momentum must be randomized to a certain degree.

This explanation in terms of the uncertainty principle has become a talisman for some, but it has left others uneasy, as it views the measurement and momentum kicks as 'locally realistic' — in other words, as idealized classical measurements, rather than quantum mechanical phenomena themselves. This is a dangerous position, and it has led to debate in this journal between a group centred on the Max-Planck Institute for Quantum Optics[2] and one in Auckland[3], on whether momentum kicks are necessary to explain the two-slit experiment. Obviously, momentum is involved, because a diffraction pattern is a map of the momentum distribution in the experiment. But *how* is it involved? Is it everything, as Bohr would have claimed?

This is the question addressed by Dürr *et al.*[1], who have studied the interference fringes produced when a beam of cold atoms is diffracted by standing waves of light. Their interferometer displays fringes of high contrast — but when they encode within the atoms information as to which path is taken, the fringes disappear entirely. The internal labelling of paths does not even need to be read out to destroy the interferences: all you need is the option of being able to read it out.

The key to this new experiment is that

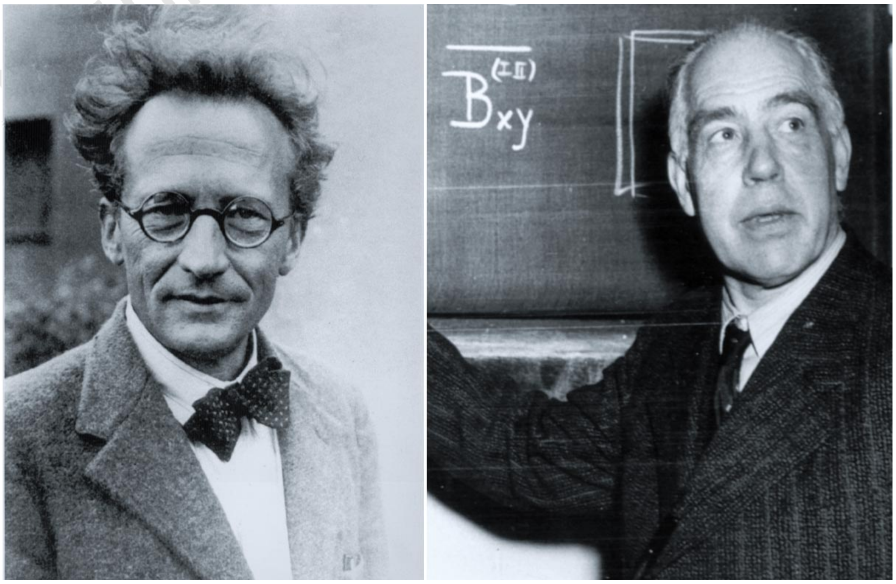

Figure 1 **Erwin Schrödinger (left) and Niels Bohr. Bohr claimed that a momentum kick, imparted by any measurement of particle position, could explain the disappearance of quantum interference in 'two-slit' experiments. A new experiment[1] shows that this effect is too small, and the disappearance must instead be explained using Schrödinger's 'entanglement' between quantum states.**

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