

Figure 2 | Saturn's rings. Processes of accretion and fragmentation of ring particles are emphasized. The boulder in the foreground accretes smaller ring particles through an S-shaped structure very similar to the propellers. (Artist's impression by W. K. Hartmann.)

collectively, their number cannot be inferred by photometry — the study of objects' brightness. But photometry can be used to obtain an idea of the distribution of sizes of the main particle population in Saturn's rings (those with radii ranging from centimetres to a few metres). The number of particles N with a radius greater than r is found to follow approximately an inverse-square law³, $N(>r) \sim r^{-2}$. This means that for each boulder with a diameter between 5 and 15 metres, there are about 100 particles of sizes between 0.5 and 1.5 metres, and 10,000 particles between 5 and 15 centimetres.

Looking at the number of gaps in the ring system, the number of kilometre-sized objects can also be inferred. There are two known moons embedded in the rings that plough circumferential gaps through the A ring: Pan (with a diameter of around 10 kilometres) in the 325-kilometre-wide Encke gap⁵ and Daphnis (diameter around 5 kilometres) in the 42-kilometre Keeler gap. Even though diffuse ringlets within the Encke gap⁶, and clear narrow gaps in the 4,800-kilometre Cassini division between the A and B rings⁷, imply the presence of further kilometre-sized moonlets, their number would be too small by far to be consistent with an extension of the inverse-square law for the sizes of the main population to the kilometre scale.

Interpolating between the number of 10-metre particles from photometric observations to the number of known kilometre-sized moons (two) would imply a size distribution in this region that falls off very steeply⁸, approximately as $N(>r) \sim r^{-4}$. (That exponent would mean that, for each moonlet in the size range between 0.5 and 1.5 kilometres, there are about 10,000 bodies with diameters between 50 and 150 metres, and 100 million between 5 and 15 metres.) Tiscareno and colleagues' observations⁴ are, taking into account the

statistical uncertainties, consistent with such a steep distribution (Fig. 3 on page 650).

The ring system's global distribution of particle sizes — including the embedded moons, the population of intermediate-sized boulders identified by Tiscareno *et al.*, and the main population of ring particles — provides evidence for processes of particle fragmentation and reaccretion in the rings that are probably still going on (Fig. 2). Following formation in the break-up of an ice moon, the primordial size distribution of the rings may have evolved to its present form by dint of such processes. Spectra of the rings at ultraviolet wavelengths⁹

also indicate relatively fresh water-ice in certain ring regions, implying that parts of the system are younger, perhaps recreated episodically by more recent moonlet disruptions.

The images in which the propeller structures were identified were taken from the unlit side of the rings as Cassini inserted itself into orbit around Saturn. Given the viewing geometry and illumination at the time, the high contrast of the propellers in these images is difficult to square with our current understanding. Photometric modelling of dynamic simulations¹⁰ might help here to define the particle properties better. The ring images from orbit insertion had the highest possible resolution in Cassini's nominal tour of the Saturn system. However, the higher inclinations of the spacecraft scheduled for late 2006 could provide favourable conditions for a systematic survey of larger propellers induced by the much less common moonlets that exceed a few hundred metres in size. Saturn's rings, long mysterious and compelling, may yet hold more secrets. ■

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NEUROSCIENCE

Rewinding the memory record

Laura L. Colgin and Edvard I. Moser

How does the brain store sequences of experience? Clues come from brain recordings of rats running along a track. The animals' memories seem to be consolidated in an unexpected way as they rest between runs.

Memories develop in several stages. After the initial encoding of new information during learning, memories are consolidated 'off-line', seemingly while not being actively thought about, through a cascade of events that is not well understood. In humans and other mammals, such an enhancement of recent memories may occur during sleep¹. But on page 680 of this issue, Foster and Wilson² show that substantial consolidation might also happen while awake during rest periods.

Insight into how sleep benefits memory consolidation has been gained by recording

neural activity in the hippocampus, a brain region that is crucial for mnemonic processing³. Cells that are activated in the hippocampus during certain awake behaviours fire in the same order but faster during the subsequent slow-wave phase of sleep^{4,5}. This reactivation of firing patterns occurs during 'sharp waves', excitatory waveforms that dominate hippocampal recordings throughout slow-wave sleep⁶. Sharp waves are accompanied by very fast oscillations (about 200 hertz) known as ripples, generated when multiple cells fire together within a narrow time



50 YEARS AGO

The Haunting of Borley Rectory — This account of the evidence for abnormal happenings in what the late Harry Price described as “the most haunted house in England” well maintains the tradition of the Society for Psychical Research for honest and cautious study of alleged parapsychological phenomena. A heavy task was undertaken at the invitation of the Society by three trained investigators. Their story is at times as interesting as a detective novel; it reveals queer actions of some very curious people; it leaves very little to be explained of the actual haunt itself and a good deal to be puzzled over in the motives, actions and reactions of the people principally concerned. The general conclusion is that credulity, malobservation, trickery and fraud account for the great bulk of the recorded evidence.

From *Nature* 31 March 1956.

100 YEARS AGO

The System of the Stars. By Agnes M. Clerke — There is much excellent sense in the French proverb, “Prends le premier conseil d’une femme, et non le second,” which expresses the view that the intuitive instinct of a woman is a safer guide to follow than her reasoning faculties; and although in these days it is considered ungracious to make this suggestion, evidence of its truth is not difficult to discover in most literary products of the feminine mind. It is no disparagement to Miss Clerke to say that even she shares this characteristic of her sex, so that sometimes she lets her sympathies limit her range of vision in the field of stellar research. No doubt this disposition is exercised unconsciously, but what is an attractive instinct when applied to ordinary affairs of life is derogatory when it influences the historiographic consideration of contributions to natural knowledge.

From *Nature* 29 March 1906.

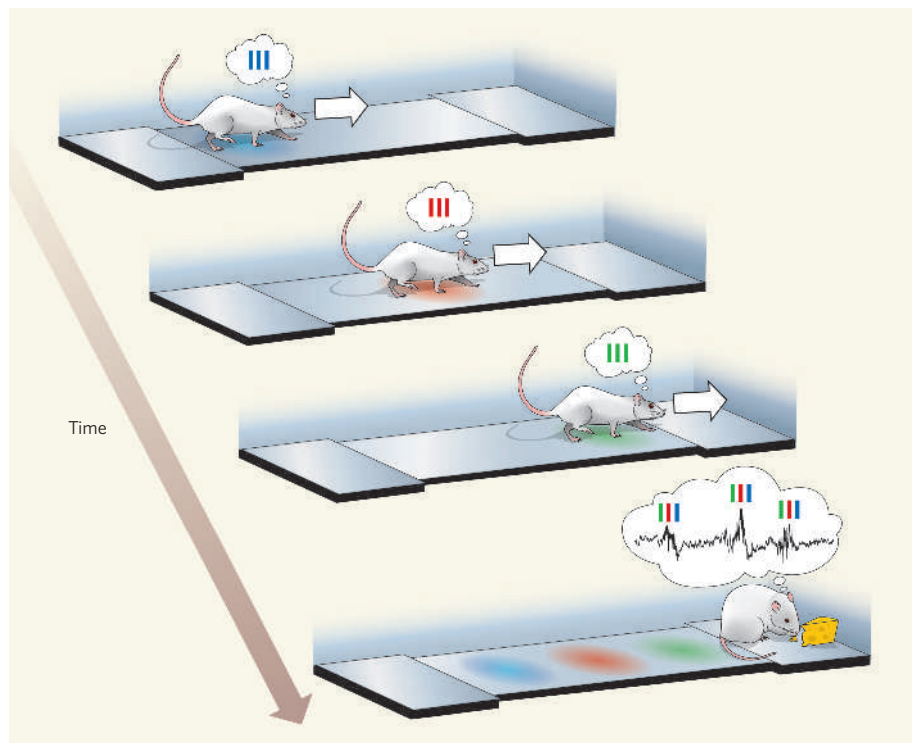


Figure 1 | Reverse replay. Three place cells (blue, red and green) in the hippocampus fire as a rat runs on a linear track. The coloured lines represent firing of place neurons. When the rat is rewarded with food at the end of the linear track, the hippocampus enters sharp-wave mode, and the firing sequences replay in reverse (that is, green, red, blue).

window⁷. Co-activation of interconnected neurons during ripples may result in long-lasting modifications of the synapses in the network (that is, the communication junctions between neurons)⁸.

Although reactivation during sleep may provide a mechanism for consolidation of recent memories, the mystery remains as to how memories can be maintained as distinct entities for hours or days in sleep-deprived subjects, considering that the participating neurons are probably involved in myriad events before the subject is finally allowed to take a nap. One clue comes from the observation that sharp waves occur also during waking states; for example, during resting, eating, drinking and brief breaks in exploration^{6,9}. Such ‘interleaved’ sharp waves may strengthen associations between recently activated cells only seconds after an event⁷.

Foster and Wilson² provide fascinating evidence for a mechanism that could generate such associations. They studied rats running back and forth on a narrow track, and they recorded neural activity from so-called place cells¹⁰. These hippocampal cells have spatial receptive fields, so each cell responds when the animal is in a particular location. Food was placed at the ends of the track, and the animals stopped after every lap to eat. When the rat paused, sharp waves emerged in its hippocampus. During these sharp waves, the place cells from the running period were reactivated, but their order of firing was reversed with respect to their earlier order of activation on the track (Fig. 1).

But how do neurons reverse firing sequences that were just stored in forward order? This might happen in at least two ways, one depending on the rat’s recent history and one reflecting its location in the environment. In the first possibility, the cells responding to place fields closest to the rest location are the first to reach the threshold for firing during the sharp wave because their synapses are still in a ‘facilitated’ state. Cells with fields that are farther away are less facilitated, so they take longer to reach the threshold. In the second option, cells fire in reverse order merely because firing probabilities of place cells increase with decreasing distance from the centre of their place fields, regardless of whether or not the rat has just passed through the fields. The latter possibility is partly ruled out because Foster and Wilson did not observe reverse replay in sharp waves recorded at the start of the session, before the rat began moving. This suggests that reverse reactivation is determined by the preceding sequence of events.

The million-dollar question, however, is what the brain gains by rewinding its neural record. At present, we do not know why sharp-wave-associated replay is forward in some circumstances (during sleep, say) and reversed in others. Foster and Wilson speculate that reverse replay has a role in reward-directed sequence learning during spatial navigation. Rewards (reinforcers) such as the food received at the ends of the track strengthen the preceding behavioural responses in a time-dependent manner such that the longer between the response and the reward, the less

the behaviour is strengthened^{11,12}. This mechanism is adaptive in evolutionary terms as it normally causes a fairly selective enhancement of those responses that generate the reward.

The authors hypothesize that the formation of associations between a reward and the representation of elements of a rat's trajectory in the immediate past is boosted during sharp-wave-associated replay by a neuromodulatory signal such as dopamine. Dopamine is a chemical released in the forebrain (in the striatum and cortex, and presumably the hippocampus) at the time of reward, especially when reward is not expected by the animal^{13–15}. Because ripple trains are variable in length, the effects of the boosting signal would be most reliable if it occurred at the beginning of the sharp wave; however, an early boost could be linked to the key later elements of the preceding firing sequence only if the sequence were reactivated in reverse order, as in Foster and Wilson's study. It remains to be seen

whether these speculations will stand up to experimental testing. At the moment, we do not know whether dopamine-releasing neurons fire in synchrony with hippocampal sharp waves.

If reverse replay is a mechanism for strengthening hippocampal sequence memories during goal-directed behaviour, several questions arise. For example, is the firing sequence stored as an ordered memory or as a unitary representation with a stronger representation of the later than of the earlier elements? Moreover, is reverse replay specific to sharp waves that coincide with reward? Sharp waves are observed during breaks without rewards. Do these sharp waves also exhibit reverse replay and, if so, are these associated with memory storage? Finally, can memories of events be stored without interleaved sharp waves? Whatever the answers may be, the discovery of reverse replay is bound to pave the way for more surprises. ■

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QUANTUM METROLOGY

Size isn't everything

Samuel L. Braunstein

From probing living cells under a microscope to scanning the heavens for gravity waves, the limitations of precision measurements constrain our capacity to discover more about the world. But what exactly are those limits?

Just how accurate can measurements get? Whereas classical physics places no fundamental limits on how well we can do, in the quantum world it's a different story. Writing in *Physical Review Letters*, Giovannetti, Lloyd and Maccone¹ derive general limits for the precision with which a single variable can be measured quantum mechanically.

But is this new? After all, Heisenberg's uncertainty principle — one of the earliest results in quantum mechanics — already places a fundamental limitation on the precision with which we can make a measurement. In its simplest form, the uncertainty principle identifies so-called complementary observables, pairs of quantities for which knowing one quantity precisely means that the other can only be poorly known. This fundamental principle makes it impossible to learn everything about a quantum-mechanical system.

If we monitor only one quantity, however, there is no such in-principle limitation. In fact, this is exactly the strategy exploited in interferometric measurements, in which light travels down a pair of distinct paths and the difference between the two path lengths leads to an observable change in the output of the device. This path difference can be measured to an arbitrary accuracy. But what if we are given some constraint, such as a total energy budget or total light intensity? We all know

that it is easier to see in a well-lit room than in a dim one. Similarly, the higher the energy or light intensity in an interferometer, the higher its resolution. One may therefore ask, for a fixed budget, how small a path difference can be discerned?

Our intuition from everyday experience tells us that the most promising strategy for measuring a distance is to choose a measuring stick with marked intervals of length comparable to the distance we wish to measure. We would not, for example, choose a metre stick to measure a molecule. Following similar logic, we might choose the wavelength of light for our interferometer to be comparable to the path difference we want to measure. Surprisingly, Giovannetti and colleagues' latest result¹ can be used to show that, for optimal quantum strategies, there is no such bias to the size of our measuring stick or the separation of its tick marks.

An optimal strategy refers to a measurement procedure that minimizes the effects of noise on a signal. Ultimately, any measurement is limited by the amount of noise in the system: to discern a signal, the signal-to-noise ratio should be around one or larger. This premise underpins all parameter-estimation theory, both classical and quantum. Classically, statistical averaging over N repeated but independent measurements will lead to a \sqrt{N} reduction in the noise. This improvement is known to

be optimal because it achieves the bound, known as the Cramér–Rao lower bound², that expresses the best accuracy that can be accomplished in the statistical estimation of a parameter. When this classical bound is generalized to repeated quantum measurements, the analogous quantum bound provides a tighter form of the uncertainty principle recast in the language of parameter estimation³. However, quantum theory allows much more freedom in choosing measurement strategies than is possible in the classical world.

One of the most bizarre features of the quantum world is quantum 'entanglement', which allows systems to exhibit stronger correlations than are possible classically. Using entanglement and other tricks, quantum mechanics has led us to devise sophisticated information-processing algorithms that one day may lie at the heart of the enormous speed-ups promised by quantum computation. For example, searching for a needle in a haystack would be much faster — in principle — on a quantum computer than a classical one. The possibility of using entangled systems and/or entangled measurements, and sophisticated algorithms built into measurement devices, raises questions about the ultimate (most general) quantum bounds to measurement.

Giovannetti and colleagues' key insight¹ into this question is to recast the measurement process in terms of quantum circuits, analogous to electrical circuits, with various quantum gates, similar to logic gates, representing different quantum-mechanical 'operators'. They then introduce black-box operators that perturb the quantum state in a known fashion, but by an unknown amount. Such an operation might, for instance, be adding a phase delay along one arm of an interferometer: the unknown parameter associated with the black box thus corresponds to the parameter we