neurons (Fig. 1b). Furthermore, when the final stages of cell division are inhibited in hippocampal or cultured *Drosophila* neurons, the daughter cells contain two centrosomes. These cells form two long neurites that extend from positions directly overlying the two centrosomes (Fig. 1c). Although the experiments are carried out in different organisms, they indicate that centrosomes are required and sufficient for determining the position of axon outgrowth. Furthermore, they suggest the existence of a 'stage 0' in which cell polarity exists without any visible effect. This pre-existing polarity is used at later stages to direct neurite formation and axon specification.

These observations reveal exciting parallels between differentiating neurons and other cell types in which centrosomes initiate polarization. Shortly after fertilization, zygotes (single-celled embryos) of the nematode worm *Caenorhabditis elegans* become highly polarized along what will become the anterior–posterior axis[3]. This polarity is needed during the first cell division to segregate proteins differentially into what will become the two daughter cells, which will go on to have different fates. The axis of polarity in *C. elegans* zygotes is determined by the sperm entry-point, with polarization being initiated by an interaction between the centrosome (provided by the sperm) and the cell membrane[3].

The similarity between *C. elegans* and neurons extends to the molecular level. Both polarity processes seem to involve an evolutionarily conserved set of proteins known as Par proteins[3,4]. In *C. elegans*, Par-3 and Par-6 and the atypical protein kinase C (aPKC) localize to the anterior cell membrane, whereas Par-1 and Par-2 are concentrated posteriorly. In hippocampal neurons, Par-3 and Par-6 are found only in the axon, and if they are overexpressed, other neurites are induced to assume an axon-like morphology (see ref. 4 for a review). Moreover, vertebrate relatives of Par-1 seem to enhance neurite outgrowth. Although the distribution of Par proteins before differentiation now needs to be examined, the findings of Calderon de Anda *et al.*[1] suggest the existence of an evolutionarily conserved molecular machinery that polarizes cells and uses centrosome position as a reference point.

How does the centrosome influence the overlying cell membrane to induce neurite outgrowth at a particular position? The first morphological change during neuronal differentiation is the formation of lamellipodia. The process that creates these structures during cell migration is fairly well understood. It is driven by formation of a meshwork of actin proteins beneath the cell membrane. In fact, cell migration and neurite outgrowth might involve the same molecular machinery. It is remarkable that one of the first events in cell migration (at least in brain cells called astrocytes) is the reorientation of the centrosome to the future leading edge. This process is accompanied by a redistribution of the protein Cdc42 (a small GTPase, involved in cell signalling) and — like axon formation and *C. elegans* polarity — it requires Par-6 and aPKC (ref. 5). Although the function and distribution of these proteins during early neuronal differentiation (the hypothetical stage 0) are unknown, it is likely that they control the cross-talk between centrosomes and the cell membrane in neurons as well.

What happens downstream of the Par proteins? The protein Rac (another small GTPase) is primarily responsible for lamellipodium formation, and Par-3 interacts with the Rac activators Tiam1 and STEF (ref. 4). So Par-3 could be responsible for lamellipodium formation through localized Rac activation. Thus, by analogy to other cell-polarity events, we can already draw a molecular pathway for neurite outgrowth that can be tested in the hippocampal neuron culture model. It should be noted, however, that *Drosophila* axon outgrowth is independent of Par-6 and aPKC, and the proposed pathway must be verified experimentally before any further conclusions can be drawn.

The results of Calderon de Anda *et al.*[1] imply that the orientation of the final neuronal division is essential for correct wiring of the developing brain. Although such orientation is undoubtedly vital in invertebrates, its relevance in vertebrates is unclear[6]. The mechanisms responsible for the orientation of cell division have only recently begun to emerge in invertebrates[3]. Identification of those mechanisms in vertebrates will allow us to manipulate the orientation of cell division and test the effects on axon outgrowth — an experiment ultimately required to confirm the mechanism proposed by Calderon de Anda and colleagues. ■

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1. Calderon de Anda, F. *et al. Nature* **436,** 704–708 (2005).
2. Dotti, C. G. *et al. J. Neurosci.* **8,** 1454–1468 (1988).
3. Cowan, C. R. & Hyman, A. A. *Annu. Rev. Cell Dev. Biol.* **20,** 427–453 (2004).
4. Wiggin, G. R., Fawcett, J. P. & Pawson, T. *Dev. Cell* **8,** 803–816 (2005).
5. Etienne-Manneville, S. & Hall, A. *Cell* **106,** 489–498 (2001).
6. Wodarz, A. & Huttner, W. B. *Mech. Dev.* **120,** 1297–1309 (2003).

QUANTUM INFORMATION

Putting certainty in the bank

Patrick Hayden

A new way to manipulate quantum states resolves a long-standing conundrum about who knows what, and when and how, in the quantum world. The result is, as one has come to expect, startling and counterintuitive.

Claude Shannon's landmark 1948 theory of communication[1] tackles a nuts-and-bolts question: how do we find the best way to communicate using a given resource, such as a telegraph line or a satellite antenna? To answer that question, Shannon first took a detour into more philosophical territory by working out how to quantify the elusive concepts 'uncertainty' and 'information'. More than half a century on, quantum-information theorists have in many ways taken the opposite approach. Inspired by Shannon, but working with the notoriously counterintuitive theory of quantum mechanics, they seek to understand uncertainty and information in the quantum world by analysing the practical questions first, in the hope that the answers might then illuminate more fundamental conceptual issues.

On page 673 of this issue[2], Horodecki, Oppenheim and Winter demonstrate how effective this approach can be by justifying, in operational terms, a definition of conditional uncertainty that had previously been widely rejected owing to its strange and apparently nonsensical properties. In their formulation, what had been pathological becomes profound: with quantum information, it is possible not just to be certain, but to be more than certain.

To understand what such a statement could mean requires first absorbing how information theorists think about uncertainty. Most readers will be able to decipher the following English sentence:

D r _ p / e _ e r _ / t h _ r d / _ e t _ e r.

As the omitted letters can be inferred with near-certainty from the others, they don't contribute to the uncertainty about the sentence and can therefore be compressed away. In general, the 'uncertainty' of a data source is the amount of space in bits required to transmit its output reliably.

Now consider another sentence, this time with more than three out of every four letters deleted:

T _ _ _ / _ _ / _ a _ _ _ r / _ _ / _ _ a _.

It is no longer possible to decipher the sentence uniquely because there are many grammatically correct options. If some extra letters are provided, however, the task becomes feasible:

T _ _ s / i _ / _ a _ d _ r / t _ / r _ a d.

50 & 100 YEARS AGO

50 YEARS AGO

Recent investigations have shown that some of the free amino-acids in amphibian embryos change in concentration during early development. These changes are of interest because they may be related to the synthesis of new, specific proteins...it is possible to carry out analyses of the free amino acids not only in whole embryos but also in different regions representing different tissue primordia. Any regional differences in free amino-acid content which might be related to the early synthesis of tissue-specific proteins can in this way be detected. The results already quoted indicate that at least dorsoventral regional differences do exist.

From *Nature* 6 August 1955.

100 YEARS AGO

It is sometimes said that natural selection has ceased as regards civilised man; but very clearly this is an error. All civilised and most savage races are very stringently selected by various forms of zymotic disease. Thus in England practically everyone is brought into contact with the organisms which give rise to tuberculosis, measles and whooping-cough. Abroad, malaria, dysentery, and many other complaints play a similar *rôle*...The result of all this elimination by diseases demonstrates natural selection very beautifully. Every race is resistant to every disease strictly in proportion to its past experience of it...These facts appear to establish conclusively two truths, first that evolution is due solely to natural selection, and second that variations, except, perhaps, in rare instance, are not due to the direct action of the environment on the germ-plasm, but are "spontaneous." The Lamarckian doctrine is quite out of court. If ever acquirements are transmitted, it should be in the case of the profound and lasting changes affecting the whole body which result from disease; but in no instance is the effect produced by any disease on the race similar to that produced by it on the individual.

From *Nature* 3 August 1905.

The gap between what was provided at first (four letters), and what allowed us to decipher the sentence (no more than ten letters) illustrates the notion of 'conditional uncertainty' — the amount of extra information required to decipher a message.

One of Shannon's seminal results[1] was to find a simple formula for the uncertainty of a data source X. This function, usually written $H(X)$, is known as the Shannon entropy of X. Conditional uncertainty can be represented in similarly simple terms. If Y is used to represent the information already given to the receiver — the analogue of the indecipherable four letters in our example — the amount of extra information that must be provided is $H(X,Y) - H(Y)$, a quantity known as the conditional entropy of X given Y (ref. 3).

This second formula is easy to interpret: the extra information required is equal to the uncertainty in the total message, consisting of both X and Y, minus the uncertainty owing to Y alone, which should be subtracted, as Y is already known.

Among its many intuitive features, the conditional-entropy function is always greater than or equal to zero. That's because there is potentially more to be ignorant of in two messages X and Y together than in Y alone, so the inequality $H(X,Y) \geq H(Y)$ holds. For example, X and Y could represent future issues of the *Financial Times* and *The Wall Street Journal*, respectively: readers who take the time to follow both newspapers will be intimately familiar with the practical meaning of the inequality! In the context of conditional uncertainty, the interpretation is again highly intuitive: the amount of extra information required to decipher a message cannot be less than zero bits or, equivalently, it is impossible to be more than certain about the outcome of an event.

Intuitive indeed, but alas no longer true in quantum information theory. Horodecki, Oppenheim and Winter analyse[2] a quantum-mechanical version of the message-completion problem and find that the amount of extra information required can sometimes be less than zero qubits (a qubit is simply the quantum version of a bit). In their version of the problem, there are three participants: call them the sender, the receiver and the referee. The referee prepares a quantity of quantum information consisting of many particles, some of which he distributes to the sender and the receiver, and the rest he keeps for himself. The sender's job is to find an encoding that allows her to transfer her share of the information to the receiver using as few qubits as possible. To further isolate the quantum-mechanical features of the problem, the sender is also allowed to send old-fashioned messages consisting of bits at zero cost.

The authors show[2] that the number of qubits that the sender needs to transmit is precisely $S(A,B) - S(B)$, where A now refers to the sender's particles, B to the receiver's particles and S is the von Neumann entropy, a direct quantum-mechanical generalization of Shannon's entropy. This formula is identical in form to the solution of the non-quantum version. With quantum particles, however, it is possible for A and B to be correlated in ways that are impossible in the classical situation[4]. In such cases, the systems A and B are said to be entangled (for a popular account of this phenomenon, see ref. 5). One consequence of entanglement is that conditional uncertainty, $S(A,B) - S(B)$, can sometimes be less than zero. In other words, the receiver can be more than certain!

In practice, if the receiver is more than certain, the sender doesn't need to transmit any qubits at all for the receiver to be able to decipher the message. So the receiver can put some certainty in the bank for a rainy day, in the form of extra entanglement with the sender that could be used to reduce the receiver's uncertainty about future messages. Entanglement is such a strong form of correlation that it can actually be used to send qubits from the sender to the receiver using a procedure known as quantum teleportation[6]. On the accounting ledger, therefore, having stored entanglement is almost as good as being able to communicate.

This neat and satisfyingly bizarre resolution disposes of a long-standing puzzle in quantum information theory: put simply, how to quantify who knows what. In more technical language, the puzzle was how to quantify conditional uncertainty. The formula $S(A,B) - S(B)$ had been proposed[7], but was widely rejected because of its pathological tendency to become negative. Until now, no one had succeeded in finding a setting in which the formula's full range of positive and negative values would have a meaningful interpretation. (It was a quantum-information theorist's version of the famous conundrum from *The Hitchhiker's Guide to the Galaxy*: if 42 is the answer to Life, the Universe and Everything, what is the question?)

In addition to finally placing the quantification of uncertainty in quantum mechanics on a solid footing, the new result[2] opens the door to solving many previously intractable problems in quantum information theory. The authors provide a sampling of these applications in their paper, including an easy solution to a quantum version of the problem of many cellphones trying to communicate simultaneously to a single base station[8]. This astonishing solution shows that one sender's quantum information can, despite its fragility, be used to help decode the other senders' transmissions at higher rates than would otherwise be possible. Once again, quantum information has proved to be more versatile and more surprising than anyone expected. ■

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1. Shannon, C. E. *Bell Syst. Tech. J.* **27,** 379–423, 623–656 (1948).
2. Horodecki, M., Oppenheim, J. & Winter, A. *Nature* **436,** 673–676 (2005).
3. Slepian, D. & Wolf, J. K. *IEEE Trans. Inform. Theory* **19,** 461–480 (1971).
4. Bell, J. S. *Physics* **1,** 195–200 (1964); reprinted in Bell, J. S. *Speakable and Unspeakable in Quantum Mechanics* (Cambridge Univ. Press, 1987).
5. Aczel, A. D. *Entanglement: The Greatest Mystery in Physics* (Wiley, London, 2002).
6. Bennett, C. H. *et al. Phys. Rev. Lett.* **70,** 1895–1899 (1993).
7. Cerf, N. J. & Adami, C. *Phys. Rev. Lett.* **79,** 5194–5197 (1997).
8. Yard, J., Devetak, I. & Hayden, P. preprint at http://arxiv.org/abs/quant-ph/0501045 (2005).

ECOLOGY

Neutral theory tested by birds

Annette Ostling

A continental-scale analysis of habitat and bird distribution in South America provides the latest challenge for neutral theory — a controversial idea in ecology about what determines the make-up of communities.

How do different species end up living together in communities? Do they coexist only when each finds a different niche, or simply when they happen to disperse to the same habitable region? Debate over these questions intensified not long ago with the introduction of 'neutral theory'[1], a stochastic theory of community properties whose predictions have proven stubbornly robust, despite its disregard of the niches that many ecologists hold dear. Writing in *Proceedings of the National Academy of Sciences*, however, Graves and Rahbek[2] point out continental-scale patterns in the bird communities of South America that neutral theory may not be able to explain.

The dominant view in ecology is that species live together in communities only when they differ from one another. Species competing for the same nutrient or food source cannot coexist because one species will always be more efficient than the others and will quickly drive the rest to extinction[3]. Species that coexist must differ from one another in the resource they use most efficiently or in the environmental conditions to which they are best adapted — that is, they must have different niches. This view is often called 'niche-assembly'.

The contrary viewpoint is that communities are primarily shaped by historical accidents that influence where species disperse (a beetle floating to a distant island on flotsam, for example, or the uplift of a mountain range that blocks the flight of seeds between nearby forests). This view has deeper roots in evolutionary biology, where history is at centre stage, than in ecology, which concentrates on short-term interactions between species. The idea behind it is that, rather than being quickly outcompeted, species that are less efficient at using a resource evolve to be as efficient as their competitors. The main criterion for coexistence is dispersal to the same habitable region. This view is sometimes called 'dispersal-assembly'.

The neutral theory tested by Graves and Rahbek[2] is the modern synthesis of dispersal-assembly into a mathematical framework. It models a community as a finite collection of individuals that have identical probabilities of reproduction, death and dispersal. This yields predictions for community properties in terms of parameters that govern the stochastic changes that the community undergoes — for example the immigration or dispersal rate, the speciation rate, and the size of the community. Despite its simplicity, neutral theory's predictions have proven robust. Claims that it has been falsified[4] have been followed by persuasive counter-arguments[5].

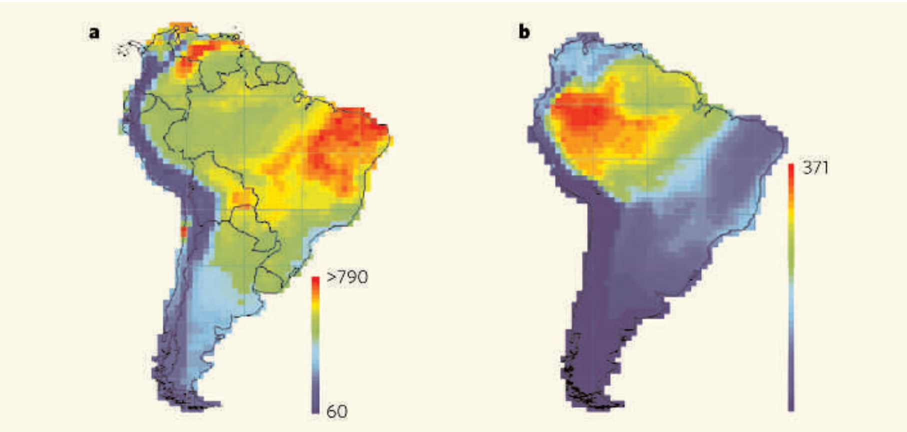
Graves and Rahbek mount a new line of attack on neutral theory by testing it at the scale of an entire continent. Armed with an impressive bird-distribution database amassed from the collections of over 30 museums in 20 countries, as well as a global land-cover map created from satellite data, they quantify the correlation between the distribution of habitat (or land-cover type) and the distribution of birds across South America at the resolution of 1° latitude by 1° longitude grid cells.

Put simply, Graves and Rahbek find that birds in more widespread habitats tend to be more wide-ranging. In particular, birds present in the lowland regions of the continent to the east of the Andes, where elevation changes slowly and habitats are widespread, are on average an order of magnitude more wide-ranging than those on the western side of the Andes, where topographic relief is at a maximum and habitat changes quickly in space (Fig. 1a). Furthermore, as one looks outwards from various locations on the continent, the change in bird-community composition is asymmetric and mimics the underlying changes in habitat (Fig. 1b).

Graves and Rahbek conclude that there is a strong causal influence of birds' habitat requirements on their spatial distribution across South America. They argue that this influence contradicts neutral theory, which ignores species differences in habitat requirements.

It is worth pointing out that the first of Graves and Rahbek's results, a correlation between habitat extent and species' spatial extents, could arise from a source other than habitat influence, a source that is instead consistent with neutral theory. The Andes act as a physical barrier to the dispersal of both birds and the flora that cover the landscape. This barrier, combined with the very different land areas available to dispersing species to the west and east of it, could alone explain the observed correlation.

But there are no dispersal barriers to explain the relationship between community composition and the distribution of riverside habitat evident in Fig. 1b. And further study of the



NATL ACAD. SCI.

Figure 1 | Summary of Graves and Rahbek's results[2]. **a,** Bird species in the lowland regions of South America, where habitat types are more widespread, are more wide-ranging than those on the western edge of the continent, where the Andes create quick changes in elevation and habitat type. Colours indicate median range-size in units of 1° latitude × 1° longitude cells. **b,** The composition of bird communities changes asymmetrically as one looks outwards from a location in the Amazon basin (here 1–2° S, 69–70° W), mimicking the underlying distribution of riverside habitat. Colours indicate the number of species in common with the focal location whose coordinates are listed. Neutral theory may be consistent with **a** but Graves and Rahbek are correct that it cannot predict the ecological importance of habitat evident in **b**. The theory may still be relevant at smaller scales, however, and species differences in habitat requirements can evolve under dispersal-assembly on a heterogeneous landscape. (Figures reproduced from ref. 2.)