

NATURE

100 YEARS AGO

While we were taking sympathetic breaths with the insatiable shag, the latter reappeared – yet again with a 15-inch eel. Four 15-inch eels – all swallowed alive – within the space of about four minutes! ... Would he bring up another? Yes, there he was again with another 15-inch eel! A very vigorous eel – just like the others in size and appearance, and swallowed in the same manner, after about 30 seconds' resistance. This made five eels. The question now arose as to what would be the end of this bird. Was he going to die the death of King Henry I before our eyes? ... To make a long story short, we counted *twelve* eels! – all stout 15-inchers. The twelfth seemed, perhaps, rather feebler than the others, but it nearly got away. H.R.H. now seemed to reflect that this last misadventure was a warning, swallowed his twelfth, and took flight... There is, of course, only one explanation of all this; the twelve eels were one and the same eel ... The peculiar procedure of ejecting the prey under water appears very remarkable. From *Nature* 8 December 1898.

50 YEARS AGO

Since last August there have been reports in the Press of a crisis among biologists in the U.S.S.R. The crisis culminated in a decree from the Præsidium of the Academy of Sciences ... This decree dismisses a number of prominent biologists from their posts, closes two famous laboratories, and removes orthodox geneticists from committees... The Lenin Academy of Agriculture Sciences, of which body Lysenko has been president for ten years, held a Conference during July 31–August 7 of this year... Lysenko's address followed familiar lines ... It denies the chromosome theory of heredity. It arraigns several Soviet biologists because their work is inconsistent with Marxist ideology and is sterile of practical results ... The objective of Lysenko's attack on Mendelism is not so much its false ideology, but rather its impotence. By insisting on the stability of the germ plasm Mendelism "condemns practical workers to fruitless waiting". The inheritance of acquired characters is a doctrine necessary for the progress of Soviet agriculture. From *Nature* 11 December 1948.

the SO₂ flux measurements by COSPEC, allow for remote determination of HCl, HF and SiF₄, and of changes in the flux of several gas species with excellent time resolution. (Incidentally, the authors^{1,2} use different reporting units, which can be related by tons d⁻¹ × 0.012 = kg s⁻¹).

Application of these new methods will add much to our knowledge of volcano–atmosphere interactions by giving us improved data on many species, particularly the halogen compounds. For example, the study of the ratios HCl:SO₂ and HCl:HF can provide information about the rise and degassing of magma, and is thus a means of eruption monitoring and prediction². Likewise, quantitative measurements of these species can be used to constrain geochemical models of magma equilibrium and oxidation state, and of the interactions among the solid, liquid and gas phases³.

These advances^{1,2} will also challenge our understanding of volcanic gas measurements. In the case of SO₂, geochemists have had great difficulty in interpreting gas flux data in a consistent way, and many volcanoes have been reported to release 'excess' sulphur^{11,12}; that is, they release more sulphur than expected from study of the mother rock. This uncertainty can apparently now be clarified by a better appreciation of how the oxygen fugacity (effective molecular pressure) in melts influences the separation of SO₂ (ref. 13). An understanding of the pattern or

'order of release' of volcanic gases from magmas as related to their relative solubility has been a long-term guiding idea of work in this area^{14,15} — there is now hope that intrusion of fresh, gas-rich magma into magma bodies, suggested by some interpretations of volcanic gas data¹⁶, might be unambiguously detected by remote sensing and used to increase the accuracy of forecasts. □

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Molecular evolution

A hydrogen-producing mitochondrion

T. Martin Embley and William Martin

Dark, damp (and sometimes smelly) places harbour some of nature's most curious eukaryotes. The likes of swamps and intestines are swarming with mostly single-celled eukaryotes (protists) that, like all cells, must produce ATP to survive. Yet these places lack enough oxygen to sustain ATP synthesis as it occurs in textbook mitochondria like our own. Some protists possess no mitochondria, surviving from anaerobic fermentation in the cytosol. Others have quite odd mitochondria that harbour anaerobic ATP-producing pathways. On page 527 of this issue, Akhmanova *et al.*¹ report a gem of such an odd mitochondrion in the ciliate protist *Nyctotherus ovalis*.

The ciliate lives in the suffocatingly oxygen-poor confines of cockroach intestines, where it helps the insect to digest cellulose. Instead of consuming oxygen, *Nyctotherus*'s mitochondrion has the bizarre property of excreting hydrogen as a by-product of ATP synthesis. Similar hydrogen-generating organelles — hydrogenosomes — have been

studied in anaerobic eukaryotes for 25 years². Hydrogenosomes have often been suspected of stemming from the same endosymbiotic bacterium that gave rise to mitochondria. But now, Akhmanova *et al.* report a hydrogenosome that has its own genome, directly betraying its endosymbiotic past.

Cells of *Nyctotherus* (which do not grow in culture and have to be carefully micromanipulated from cockroach hindguts) contain hydrogenosomes that can be labelled by antibodies against DNA. The authors found that the cell produces a ribosomal RNA which, although not proven by *in situ* hybridization to localize to the organelle, bears all the sequence characteristics expected of ciliate mitochondria. Plus, it may look like a mitochondrion, but this DNA-bearing organelle is unquestionably a hydrogenosome because it produces hydrogen — Akhmanova and colleagues found hydrogen-consuming³ methanogenic endosymbionts inside the cells of *Nyctotherus*. Finally, *Nyctotherus* expresses a nuclear-encoded gene for a

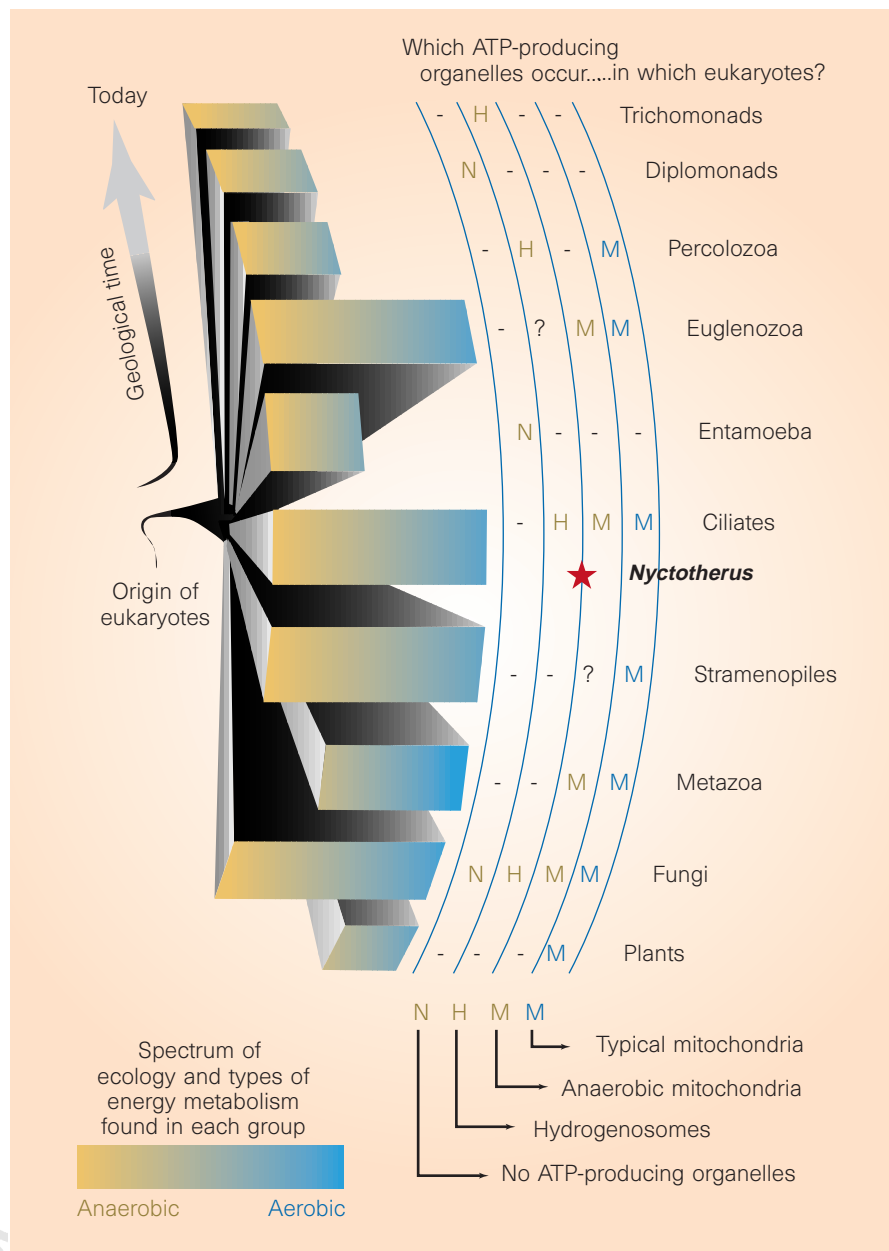


Figure 1 Summary of ATP-producing organelles across a very limited, and arbitrarily chosen, spectrum of eukaryotic taxa. The ciliate *Nyctotherus ovalis* (red star) contains hydrogenosomes, which Akhmanova *et al.*¹ now show contain their own genome. A peculiar group of eukaryotes called microsporidia are related to fungi⁶, whence the 'N' for that group. Antarctic euglenids contain organelles that may be hydrogenosomes¹⁰. Some groups designated 'N' may have organelles, but their role, if any, in energy metabolism is unclear. (Data taken from refs 4, 5 and references therein, and also refs 2, 3, 6–10.)

hydrogenase (an enzyme that makes hydrogen) that is probably imported into the hydrogenosome with a transit peptide¹, as is the case for most proteins in mitochondria.

The evolutionary significance of these findings is twofold. First, hydrogenosome-associated DNA was hitherto a genuine missing link⁴. Such discoveries are rare, and the genes in this DNA are likely to hold exciting surprises. The other, deeper, significance emerges when we remind ourselves that ciliate hydrogenosomes are just the tip of the iceberg (Fig. 1). Hydrogenosomes and the anaerobic (or micro-aerophilic⁵) lifestyle are

widespread among contemporary eukaryotes^{4,6}, including groups that are distantly related in conventional genealogies and, sometimes, arise from within otherwise aerobic groups. Although biologists do not agree which groups of eukaryotes might be the most primitive, most will find their favourite candidate somewhere in Fig. 1, and most biologists do believe that all eukaryotes share a single common ancestor.

The key to understanding hydrogenosomes, and why they produce hydrogen, is energy metabolism⁴. All known eukaryotes generate energy (ATP) by one principle —

Electron acceptor	Excreted end product	Example
O ₂	H ₂ O	Many
Fumarate	Succinate	Flatworm ⁷
NO ₃ ⁻	N ₂ O	Fungus ⁸
NO ₃ ⁻	NO ₂ ⁻	Ciliate ⁹
H ⁺	H ₂	Ciliate ¹

Figure 2 Some electron acceptors, and the corresponding reduced end-products associated with energy metabolism in mitochondria.

the oxidative breakdown of reduced carbon compounds. Electrons removed during the oxidation process must be dumped onto an electron-accepting compound (an acceptor) that can be excreted from the cell. Otherwise, ATP production — and life — comes to a halt. Our mitochondria use oxygen as the acceptor and excrete water. But the mitochondria of anaerobic eukaryotes must resort to compounds other than oxygen (Fig. 2). Some use organic acceptors such as fumarate⁷, some use nitrate^{8,9}. The mitochondria of *Nyctotherus*¹, like other hydrogenosomes^{2,4}, simply transfer the electrons onto protons, producing hydrogen.

Why are anaerobic ATP-producing pathways so widespread in eukaryotes^{2-4,7-10}? There are two popular hypotheses for their origin which, in principle, can be tested through gene-by-gene phylogenetic analysis. One view is that the genes were acquired by eukaryotes through horizontal gene transfer from one or more prokaryotic donors, other than the antecedent of mitochondria. If this were the case, the genes for these pathways in anaerobic eukaryotes should trace to different prokaryotic (eubacterial or archaeobacterial) sources. An alternative view is that the eukaryotic genes involved in anaerobic ATP synthesis were inherited from a single common ancestor of mitochondria and hydrogenosomes. These genes are thought to have been transferred to the host's chromosomes, because they are not found in any known mitochondrial genome. In this case, the common ancestor of contemporary eukaryotes would have acquired, from a facultatively anaerobic protomitochondrion, a genome's worth of genes for all-purpose survival. These genes were then left to the workings of selection and common descent. From this we can predict that, across the anaerobic eukaryotes in Fig. 1, each gene should ultimately trace to a single eubacterial source.

We know that the antecedent of mitochondria brought with it the ability to respire oxygen — much of the respiratory chain is still encoded in mitochondrial DNA¹¹. But we don't know what else was in that symbiont's biochemical repertoire. It

probably existed two billion years ago¹² but, because it's no longer around, we cannot sequence its genome to find out. However, molecular fossils of its lifestyle might be preserved in nuclear chromosomes, including our own, allowing us to piece together the bacterial part of our heritage.

Is anaerobic energy metabolism in eukaryotes a telling relict of our history, or an oddity with little significance? Eukaryotes now regarded as primitive tend to be anaerobes, so these are important questions. The road to answers leads straight to the genomes of eukaryotes from the anoxic world. For scientists studying oxygen-shunning eukaryotes with unconventional mitochondria, with hydrogen-producing mitochondria or with no mitochondria at all, these are exciting times. □

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Nonlinear physics

Universality of turbulence

Victor S. L'vov

Elsewhere in this issue (*Nature* **396**, 552–554; 1998) Bramwell *et al.* describe the discovery of a new type of universality in turbulence. It connects this strongly non-equilibrium phenomenon of classical fluid mechanics with critical phenomena in the thermodynamic equilibrium of solids (magnetically ordered crystals).

Intuitively, hydrodynamic turbulence is understood as the chaotic motion of fluids — be it of interstellar dust in spiral galaxies, of gaseous planetary atmospheres or of water flowing from a tap (Fig. 1). The length-scales vary from galactic distances of 10¹⁶–10¹⁸ km, through planetary distances of 1,000–10,000 km down to the human scales of 1 mm–10 m (in the atmosphere and rivers, as well as in the kitchen sink).

Euler's basic mathematical description of fluid dynamics (1741) was corrected to account for viscous friction by Navier (1827)

and Stokes (1945). The Navier–Stokes equation for the velocity $\mathbf{u}(\mathbf{r}, t)$ of fluid at point \mathbf{r} and time t is simply Newton's second law for the fluid particle:

$$\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \nu \nabla^2 \mathbf{u} \quad (1)$$

This equates a particle acceleration (the left-hand side) with the forcing due to the gradient of the pressure $p(\mathbf{r}, t)$ and to the viscous friction (the term proportional to the kinematic viscosity of a fluid ν).

In principle, one has to solve this equation to fully understand all turbulent phenomena, but it is a mathematical nightmare. If one ignores the nasty nonlinear term, $(\mathbf{u} \cdot \nabla) \mathbf{u}$, the mean velocity of typical rivers turns out to be about 10⁶ km hr⁻¹, and a maximum car velocity is found to be 2,000 km hr⁻¹, both of which are clearly nonsense. The reason is that the nonlinear term is usu-

ally much larger than the linear one. Their ratio is the Reynolds number Re and, for large Re , equation (1) is impossible to solve. Moreover, no one in their right mind wants the full solution of the turbulent velocity field at all points in space-time. It is the statistical properties of the flow, such as probability distribution functions of velocity or the rate of energy consumption, that are important. So, what can we do to understand turbulence?

In 1922, looking at the evolution of turbulent atmospheric conditions, Lewis Fry Richardson suggested the 'cascade picture of turbulence'. In this, the largest eddies in a system are created by instabilities of the mean streamline flow, as in hurricanes. These decay giving rise to eddies of roughly half their size which decay in turn, creating even smaller third-generation eddies — and so on, until the smallest stable eddies lose their energy because of viscous friction that turns it into heat. In high- Re turbulence, eddies exist at various scales, from the largest ones at the scale of the system size down to the smallest ones at the viscous scale. This situation is called 'developed turbulence'.

In 1941 Andrei Kolmogorov estimated the energy $E(R)$ of eddies of scale R in a unit volume of developed turbulence to be $\rho(\bar{\epsilon}R)^{2/3}$. The assumption here is that the only relevant parameter (besides the obvious length scale R and density ρ) is a rate of energy consumption $\bar{\epsilon}$. Kolmogorov's crucial idea was the assumption of universality of small-scale motions (on scales $R \ll L$) in developed turbulence. Here, universality means an independence of the statistical properties of small eddies from the nature of the fluid (be it interstellar dust or water), independence from the mechanism stirring the flow and independence from the particular geometrical form of the container.

But what about the statistics of large-scale motions? Most of us used to believe these were non-universal and would depend on factors such as the geometry of the system. As Bramwell *et al.* now show, however, there is a class of turbulent flows for which at least some characteristics of large-scale turbulent statistics are universal.

The authors demonstrate the rate of power consumption $P(t)$ in turbulent flow in an enclosed air gap between two counter-rotating disks. For very large Re the probability distribution function Q_p is Re -independent when properly rescaled. Their Fig. 1a on page 553 shows plots of $\sigma_p Q_p$ versus $(P-P)/\sigma_p$ where \bar{P} is the mean value of P and σ_p is the standard deviation of P (a characteristic width of the distribution Q_p). The normalized distributions $\sigma_p Q_p$ for different Re collapse onto the same curve even though they strongly deviate from Gaussian form for $P < \bar{P}$. Bramwell *et al.* argue that just two factors are important: that the integral Re is fixed at a constant value and that flow is

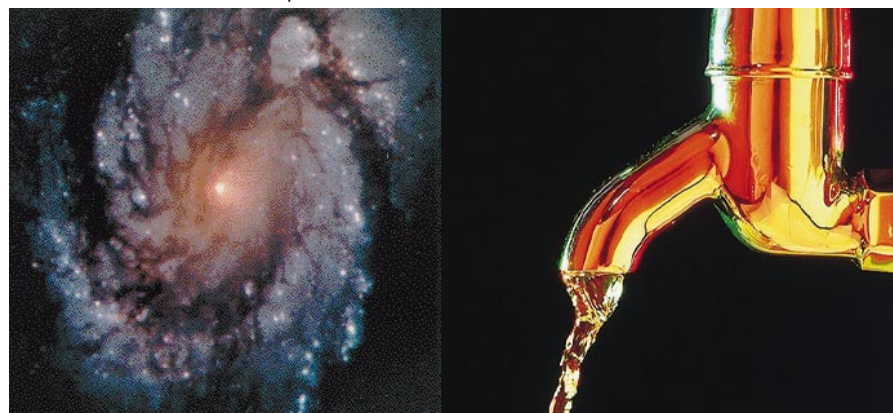


Figure 1 From interstellar space to the kitchen sink. The extreme scales of turbulence range from the motion of interstellar dust in the M100 spiral galaxy to water flowing from a tap.