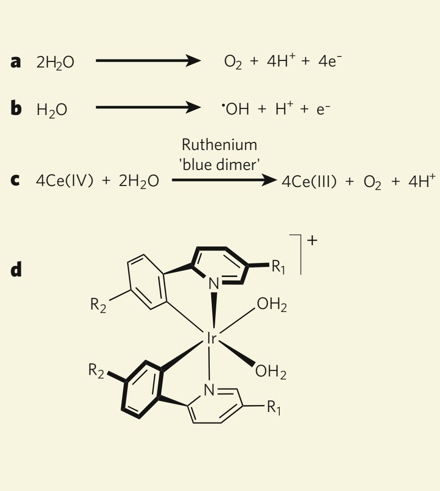

Figure 1 | Catalytic water oxidation. Photosynthesis is fuelled by the conversion of water into oxygen and hydrogen. **a**, In the first part of this process, known as water oxidation, water is converted into oxygen, four protons (H$^+$) and four electrons (e$^-$). **b**, Oxidation by the removal of one electron at a time is slow because it creates an energetically unfavourable intermediate, a hydroxyl radical ($^\bullet$OH). **c**, One of the few artificial catalysts for water oxidation is the ruthenium 'blue dimer', which is activated by a cerium salt (shown here as Ce(IV), reduced in the reaction to a lower oxidation state, Ce(III)). **d**, Bernhard and colleagues[1] describe a new family of iridium (Ir) catalysts for water oxidation, shown here. Their activity can be tuned by changing the organic molecules bound to the metal. R$_1$ and R$_2$ represent general chemical groups.

elsewhere in the photosystem. Electron-deficient molecules (oxidants) are thus created that can accept electrons from neighbours.

The source of these electrons is a part of the reaction centre known as the oxygen-evolving complex, or OEC. The OEC makes up its lost electrons by stealing some from water molecules, producing oxygen in the process[2–4]. Even plants find this task difficult: under ambient sunlight in the chloroplast, the OEC must be resynthesized every half an hour or so owing to the oxidation damage it suffers from the oxygen that it has produced.

A synthetic, non-protein catalyst that can oxidize water as effectively as the OEC does exist. This is the ruthenium 'blue dimer'[5,6], a complex that must be activated electrochemically or by a strong oxidizing agent (usually a cerium salt; Fig. 1c). The blue dimer is a well-defined molecule that undergoes the stepwise loss of four electrons and four protons, producing a fleeting intermediate that rapidly oxidizes water. But although initially effective, the blue dimer can lose its catalytic efficiency after just a few cycles.

Compared with earlier catalysts such as the blue dimer, Bernhard and colleagues' iridium-based catalysts[1] (Fig. 1d) are simple to make. Their oxidizing ability is tuned by changing the ligand molecules that bind to the iridium metal. As with the blue dimer, they need to be activated by a cerium oxidizing agent. The details of this mechanism are still lacking, but proton-coupled electron transfer is likely to be essential. This trick of the trade is used by both the OEC and the ruthenium blue dimer, and involves simultaneous transfers of both electrons and protons as the catalyst is activated. This allows many oxidative equivalents to accumulate at one site, one step at a time, without a catastrophic build-up of charge[7].

Barring serendipitous discoveries, further progress in designing catalysts for water oxidation will require detailed knowledge of the mechanism by which these reactions occur. Bernard and colleagues' iridium compounds[1] are promising. But we have limited understanding of how they work, and their catalysed reactions are slow — more than 100 million times slower than those in the OEC. Nevertheless, catalysts for water oxidation are so rare that the discovery of a new family is cause for celebration. Once the essential design details that govern their behaviour have been thrashed out, and their stability is improved, they offer real prospects as tunable catalysts for the essential process of water oxidation. ■

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EVOLUTIONARY BIOLOGY

Darwin in the fossils

Andrew P. Hendry

Adaptation by natural selection is thought to drive evolution. Although it has been difficult to confirm this process in the fossil record, evidence has been there all along: we just haven't been looking properly.

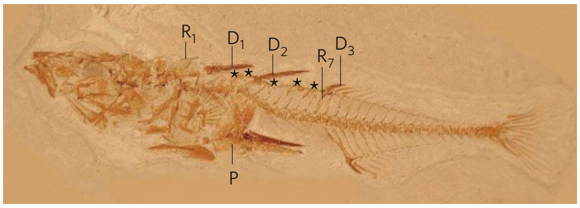
Most biologists accept that morphological evolution reflects the darwinian process of natural selection, with evidence coming from numerous studies of contemporary populations[1] and from classic interpretations of the fossil record[2]. Some palaeontologists, however, see a fly in this darwinian ointment. In particular, statistical analyses of fossil data generally fail to confirm that natural selection strongly influences morphological evolution[3–5]. Partly for this reason, a cadre of scientists is convinced that natural selection is less prevalent and important than typically assumed. The latest work from Gene Hunt and colleagues[6,7] may lessen this dissent.

A standard approach to analysing fossil sequences is to infer evolutionary mechanisms from temporal patterns in phenotypic traits — average body size, for example. One such pattern is a reasonably consistent directional trend. For example, body size might increase through time because larger body size is favoured most of the time ('directional selection'). Another pattern is constancy, or 'stasis'. For example, body size might remain the same through time because the optimal — that is, best adapted — body size does not change much through time ('stabilizing selection'). The third pattern is randomness. For example, body size might change unpredictably through time because the optimal body size is changing unpredictably ('variable selection'), or because there is no optimum at all and so body size drifts according to the arbitrary success of different individuals.

Although natural selection can cause all three patterns (directional trends, stasis or randomness), the tradition has been to invoke selection only when models of randomness fit the data very poorly. Up to now, few studies have been able to reject randomness; and those that have point to stabilizing selection, rather than directional selection. Taken at face value, these results might suggest that organisms have evolved their distinctive phenotypes without much aid from directional selection. If so, darwinian mechanisms might not be particularly important in generating the diversity of life.

The question to be addressed is whether directional selection really is absent in the fossil record, or whether the standard methods of analysis are simply biased against its detection. To address this question, one might first apply the standard battery of methods to an exemplary fossil sequence where directional selection is almost certain to be important. A good candidate is Mike Bell's 21,500-year record[4] of defensive armament in fossil sticklebacks from an ancient Nevada lake (Box 1, overleaf). This data set includes more than 5,000 stickleback specimens grouped into 250-year intervals, a remarkable level of resolution and replication. At one point in the time sequence, heavily armoured sticklebacks colonized the lake and

BOX 1 | Defensive armament of threespine sticklebacks



Threespine sticklebacks (*Gasterosteus* spp.) are most notable to evolutionary biologists for their diverse adaptations to specific freshwater environments[8]. Remarkably, most of this adaptive radiation took place after the last glaciation, a period of about 10,000 years, or 5,000 stickleback generations.

Of particular interest here, sticklebacks at sites with predatory fishes retain defensive armament, including spines along the back and on the pelvis. In contrast, sticklebacks at sites with few predatory fishes evolve much reduced armament.

Hunt *et al.*[7] studied fossils of a heavily armoured population of *Gasterosteus doryssus* that colonized a lake with few predatory fishes. The traits studied were the number of dorsal spines (D in the figure here), the size and structure of the pelvis (P), and the number of overlapping bones that help support the dorsal spines ('touching pterygiophores', asterisks between R_1 and R_7). Each of these traits is expected to decrease when an armoured population colonizes a site with few predatory fishes. **A.H.**

then showed a steady reduction in armament (Fig. 1). This evolutionary change almost certainly reflects natural selection because, in addition to other reasons, predatory fishes are rare in this ancient lake, and modern sticklebacks evolve reduced armour in the absence of fish predation[8].

If the standard methods were ever to diagnose directional selection in the fossil record, then surely it would be for these little fishes from Nevada. But not so — Bell and colleagues[4] found that the existing methods inferred randomness almost every time. It is often said that when a pattern is not visible without statistics, then that pattern isn't worth discussing. But here we have a pattern that is logical and manifestly obvious (Fig. 1) but cannot be confirmed by statistics. With more than a hint of resignation, Bell *et al.*[4] concluded that "current methods to study rates or patterns of phenotypic evolution in the fossil record are strongly biased against detecting directional selection". Taking up this challenge, Hunt[5–7] refined the existing methods and, with Bell and Mike Travis[7], used these methods to provide strong support for directional selection in the stickleback fossils.

One of Hunt's refinements was to overturn the usual burden of proof, wherein randomness has been assumed by default and retained as the evolutionary inference unless overwhelmingly rejected in statistical tests. But there is no biological reason for this *a priori* ascendancy of randomness, and randomness is extremely difficult to reject with the existing methods[3]. Instead, we should be comparing, on equal footing, the fit of different evolutionary models (such as directional selection, stabilizing selection or randomness) to the observed data[5–7]. That is, we should stop striving to reject the null hypothesis of randomness, and instead weigh the level of statistical support for alternative models.

Hunt's other refinement was to test a more realistic model of selection. Previous tests have tended to treat directional selection as a reasonably consistent force driving average phenotypes in a given direction. This model is obviously unrealistic in the absence of any force expected to sustain selection in a particular direction over such long time frames. Instead, adaptation should often involve the asymptotic approach of phenotypes towards a particular optimum, near which the average should then remain until the optimum is perturbed[1,9,10]. That is, environmental change should cause initially strong directional selection that should gradually grade into stabilizing selection, a 'hybrid' selection model if you will. This particular process is what would be expected for heavily armoured sticklebacks colonizing a lake where predatory fishes are rare, and the hybrid model provided an excellent fit to the fossil stickleback data (Fig. 1).

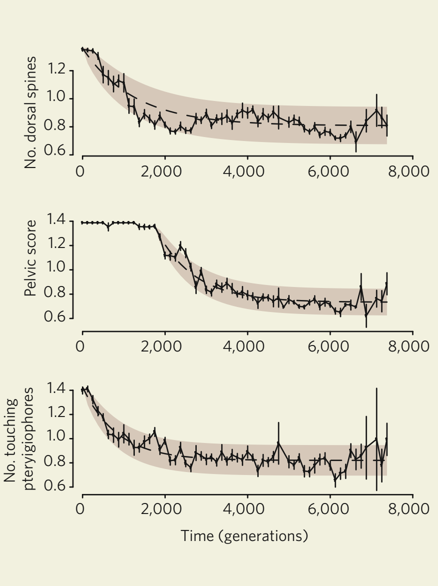


Figure 1 | Evolutionary change in the defensive armament of fossil sticklebacks. The features concerned (the number of dorsal spines, the size and structure of the pelvis and the number of 'touching pterygiophores') are indicated in Box 1. The *x*-axis shows the number of stickleback generations; data points are the average trait size for each 250-year time interval; vertical bars are standard errors. The dotted line is the best-fit relationship for the hybrid model of selection tested by Hunt *et al.*[7], and the grey envelope shows the 95% confidence interval for the model fit. (Figure modified from ref. 7.)

Several potential criticisms need to be addressed. First, Hunt *et al.*[7] start their analysis at exactly the point in time when each armour trait begins to decrease, which favours a model of initially strong directional selection. But this choice does not undermine their general conclusion, because the standard methods could not reject randomness even when started at these same times[4]. Second, the analysis[7] of the stickleback data formally examined only one model of selection — the hybrid directional–stabilizing model they expected beforehand. The authors are here again stacking the deck for success in confirming selection. But then this is the point. Their analysis is akin to a positive control in showing that a new statistical method can infer the correct evolutionary process when that process is almost certain to be acting.

The obvious next step is to apply similar thinking[5–7] to a much larger array of fossil data and evolutionary models. Doing so will justifiably accelerate the retreat from a 'one model to rule them all' vision. This work will almost certainly generate additional support from fossil sequences for the action of natural selection. Perhaps more importantly, it will become easier for biologists to accept randomness when random models still receive the most support. This acceptance, however, needs to be tempered by the realization that selection can certainly generate patterns that look random. Particularly valuable for all this work will be more fossil data with fine temporal resolution such as that seen in the stickleback samples, because selection can cause noteworthy changes in less than a hundred years[11]. Ultimately, we might hope for the emergence of general conclusions about the role of natural selection in generating the diversity of life. ■

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