In their first attempt to reach the zero-point limit, LaHaye *et al.* have provided direct measurements of the actual temperature of a mechanical beam down to temperatures as low as ~60 mK (see the figure, right panel). The temperature is inferred from the Brownian motion signal picked up by the single-electron transistor. Such direct temperature measurements are extremely important, because the mechanical beam is not necessarily at the base temperature of the refrigerator. In fact, the corresponding base temperature was about 35 mK, suggesting that the energy released by the tunneling electrons is not dissipating quickly enough, causing local heating of the beam. Work is currently under way by LaHaye *et al.* to reduce this local heating effect. Whether this will allow further cooling of the mechanical beam remains to be seen. Nevertheless, finding ways to cool nanoscale and larger mechanical resonators down to millikelvin temperatures and below is essential for unmasking their quantum zero-point motion (*9*, *10*).

It is also essential that displacement detection sensitivities be improved by at least a factor of 10. The single-electron transistor has already been demonstrated to have unparalleled sensitivity. It should be possible for LaHaye *et al.* to increase their sensitivity by positioning the mechanical beam closer to the transistor island, as was achieved in (*4*), or by increasing the coupling voltage on the mechanical beam. There is also room for reducing the noise level in the amplifier stage following the single-electron transistor. With such improvements in their device design, it should be possible for the first time to reach the quantum limit for motion of mechanical systems well outside the microscopic domain.

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PALEONTOLOGY

# From Fins to Fingers

**Jennifer A. Clack**

How do you get from fins to fingers, from an animal that swims in water to one that walks on land? This key evolutionary innovation was first made during the Devonian period, about 370 to 360 million years ago, and can be succinctly described as the "fish-tetrapod transition." In recent years, the fossil evidence for this event has increased almost exponentially in quality and quantity, stimulating fresh ideas and changing perspectives (*1*). On page 90 of this issue, Shubin *et al.* (*2*) reveal how even fragmentary finds can be used to draw inferences about the nature and sequence of changes that must have taken place during the evolution of terrestrial locomotion by tetrapods. Shubin *et al.* describe a humerus from the Devonian period that they discovered in Pennsylvania. The morphology of this limb bone proclaims it to be not only from a tetrapod, but from one predicted to be of a completely new and unusual form. From this humerus, the investigators infer some of the anatomical and functional changes that took place in the tetrapod lineage during the Devonian period, and these changes in turn suggest some possible routes by which terrestriality was attained.

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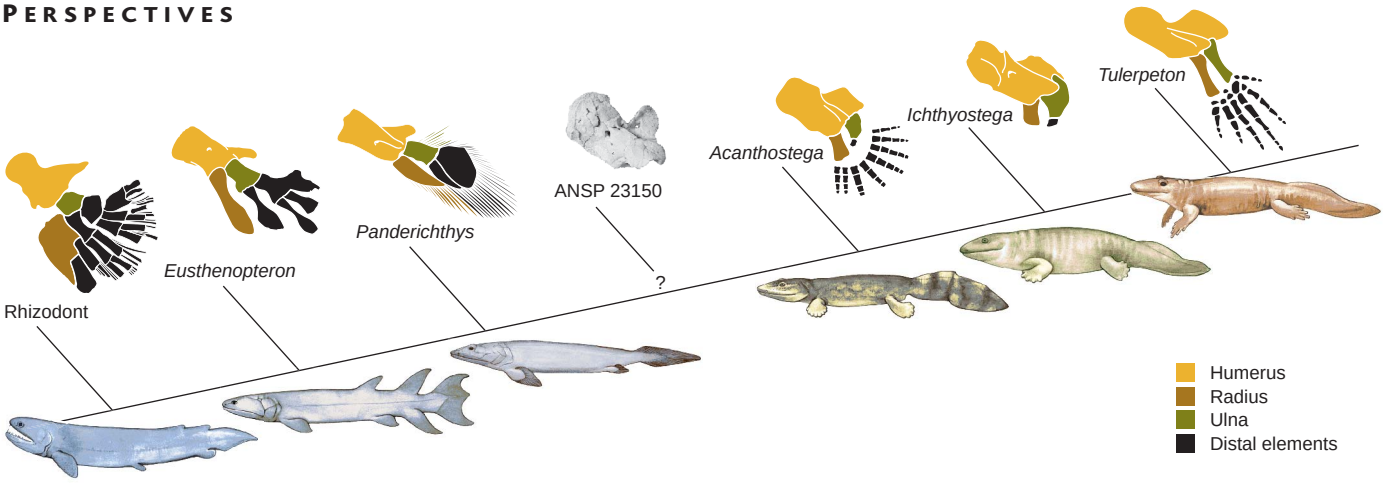
The lobe-finned relatives of early tetrapods had complex internal skeletons and a suite of muscles in their paired fins, features eventually exploited to produce weight-bearing limbs (see the figure). Among the immediate relatives of tetrapods, the most proximal three elements of their limbs can be readily identified as related to the humerus, radius, and ulna of the forelimb, and the femur, tibia, and fibula of the hindlimb. The humeri of Devonian tetrapod-like fish such as *Eusthenopteron* and *Panderichthys* bear particular resemblance to those of early tetrapods, and several key features are common to them all (see the figure). However, fins and limbs are conspicuously different with respect to orientation, range of movement, and function. The new humerus provides some clues as to the timing and sequence in which these differences arose, although it poses yet more intriguing questions.

The new humerus, like those of other Devonian tetrapods and their close relative *Panderichthys*, is flattened dorsoventrally, and the shoulder joint appears to have had a greatly restricted range of movement. However, in *Panderichthys*, as in other fish, the fin and shoulder joint face posteriorly, whereas in tetrapods they are reoriented to face laterally. As a result of this reorientation, the attitude of the limb to the body is essentially horizontal rather than vertical; the operational space in which the limb acts is level with the shoulder joint rather than posterior to it; and the direction in which its muscles pull is approximately at right angles to the body rather than at an acute angle to it. Shubin *et al.* suggest that features such as the orientation of a ridge on the ventral side of this new humerus show that some of these changes had already taken place. The net result was probably a limb that was effective in the dorsoventral plane and could prop up the relatively large plated head of an early tetrapod, but whose front-to-rear movement, necessary for walking, was very limited.

Probably the most striking aspect of the new humerus is its distal end. Proximally, it is fairly similar to those of its relatives. Distally, however, the new humerus shows unique modifications such as a very short but very stout entepicondyle, a robust and distally projecting ectepicondyle, and relatively enormous articular facets for the radius and ulna. The former two features speak of elaborated muscles to the ulna and radius, respectively, whereas the radial and ulnar facets, large and tucked beneath the end of the humerus, suggest short, stout epipodials forming a permanently flexed elbow. This arrangement is similar to, although more exaggerated than, that proposed for the more widely known Devonian tetrapod *Ichthyostega* from Greenland (*3*) (see the figure). Recent work suggests that *Ichthyostega* is unlikely to have "walked" in a conventional way, and the new humerus similarly looks unlike one that works as a walking limb (*4*).

One question concerns what was attached to the end of the limb from which this humerus came. It is not clear when digits arose or when fin rays were lost in the tetrapod lineage; hence, a combination of digits with remnant fin rays is a theoretical possibility. It is now clear, contrary to some previous developmental evidence, that an extensive fin endoskeleton is not incompatible with an extensive ray-supported web. Indeed, one lobe-finned group, the rhizodonts, specialized in such a combined morphology, producing large pectoral fins that they probably used for station-holding (that is, maintaining a steady position while waiting to ambush prey) (*5*). Shubin *et al.* suggest this kind of function as a possible

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**Walking the Devonian walk.** Tetrapods exist in a range of different forms (tetrapodomorphs). Here they are arranged in a cladistic sequence, each with its left forelimb or forefin in dorsal view. The new humerus (ANSP 23150) from a Devonian tetrapod discovered in Pennsylvania by Shubin *et al.* (*2*) is shown at the node of the cladogram (question mark) suggested by the authors. Sources: rhizodont based on (*9*) and (*10*); *Eusthenopteron* compiled from (*11*); *Panderichthys* based on (*12*) and (*13*); *Acanthostega* from (*6*); *Ichthyostega* based on provisional reconstructions in (*1*) and (*4*); *Tulerpeton* from (*1*) and (*14*).

precursor to the evolution of weight-supporting limbs in tetrapods. However, the three more completely known Devonian tetrapod limbs were polydactylous (see the figure), and given the phylogenetic position proposed for the owner of this new humerus, more than five digits seem likely, together with an ulna that was shorter than the radius. There is evidence that digits arose before wrists or ankles (*6*), and polydactylous limbs with an array of digits could well have assisted in spreading the load on a prop-like appendage, before stable load-bearing joints at wrists and ankles had evolved.

Recent discoveries of Devonian tetrapods have demonstrated not only a worldwide distribution, but also a range of specializations hitherto unsuspected. These are not the conservative, clumsy creatures envisaged by popularists. Rather, they show a range of morphologies and adaptations consistent with innovators exploiting new and previously vacant niches. *Ichthyostega*, for example, had a highly specialized ear adapted for underwater audition (*7*). These animals probably did not walk efficiently, but their modes of locomotion certainly varied, as they adapted skeletons and sensory organs for the challenges posed by emergence from the water.

The new humerus comes from a site in Pennsylvania that recently has yielded two other new taxa of Devonian tetrapod. If this is really a third form, it hints at a wide diversity of tetrapods existing in close proximity, in what is emerging as one of the richest and most varied of any late Devonian vertebrate site [for a faunal and floral list, see (*8*)]. North America is relatively unexplored for Late Devonian and Early Carboniferous vertebrates, and it is to be hoped that these new discoveries will stimulate further exploration in this potentially highly rewarding area of study.

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GENOMICS AND EVOLUTION

# Shotgun Sequencing in the Sea: A Blast from the Past?

**Paul G. Falkowski and Colomban de Vargas**

Our evolutionary heritage is imprinted in the genes of microbes that live in the oceans, yet that genomic information is barely understood, let alone written in biological textbooks. A research article by Venter and colleagues (*1*) on page 66 of this issue harnesses the power of high-throughput DNA sequencing and computational genomics to produce a massive data set of large DNA fragments from total microbial genomes extracted from the subtropical North Atlantic Ocean off the Bermuda coast. Their study identifies more than 1.2 million new genes recovered from the DNA extracted from ~1500 liters of surface seawater. Such an enormous number of new genes from so few samples obtained in one of the world's most nutrient-impoverished bodies of water poses significant challenges to the emerging field of marine molecular microbial ecology and evolutionary biology.

The biological and geochemical history of Earth can be separated into two supereons (see the figure). The first, beginning ~3.8 billion years ago and lasting until ~2.3 billion years ago when oxygen in the atmosphere and oceans increased substantially (*2*), was characterized by metabolic experimentation and innovation. During this 1.5-billion-year interval, life consisted of aquatic microbes. These microbes evolved redox-based metabolic pathways, which led to nitrogen fixation, photosynthesis, sulfate reduction, methanogenesis, and numerous other processes that would ultimately alter the chemistry of our planet. The evolution of oxygen-producing photosynthesis, and the subsequent oxidation of the atmosphere and

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