frequencies are unoccupied, actively transmit during this period, and cease transmission when the passive signal returns.

Spectrum-sensing methods include techniques for detecting the energy or special features of a signal; those that match the signal to a known template; and those that detect the degree to which two signals are in step with each other[6]. The outcome of these methods is evaluated by calculating the detection probability (the probability that an occupied spectrum is correctly detected) and the false-alarm probability (the probability that an idle spectrum is incorrectly identified as being occupied). In cooperative spectrum sensing, multiple users make independent sensing measurements that are then collected and processed at a single node to better calculate these probabilities using the increased information.

However, although such techniques are well established, implementing the hardware for spectrum-sharing systems isn't easy. Furthermore, few researchers have attempted this at subterahertz frequencies. Polese *et al.* tackled this problem by performing spectrum-sharing experiments between a passive scientific user, the Aura satellite, and an active 6G user transmitting and receiving data at frequencies above 100 GHz. They achieved this by tracking Aura's orbits and assuming that the 6G-network activity would interfere with the satellite when the orbit was within the line of sight of the 6G user on the ground. Line-of-sight alignment therefore precluded active use, but non-alignment indicated that the spectrum was unoccupied and available. The authors obtained a licence from the FCC to implement the hardware for this scheme, and performed their experiments in an urban environment, with a transmitter and a receiver on the rooftops of adjacent buildings in Boston, Massachusetts.

Their approach involves a dual-band system, in which the 6G user's activity is dynamically switched between a lower band, at frequencies of 123.5–140 GHz, and an upper band, at frequencies of 210–225 GHz (Fig. 1b). The team integrated the hardware with programmable controls that switch the 6G active user between bands automatically and rapidly, to avoid interfering with the passive signal.

The method proved successful in tracking a single satellite with known orbital patterns. However, scaling it up to many passive and active users might be difficult. Line-of-sight tracking for multiple satellites is more complex than it is for one satellite, which complicates the task of determining when and where on the spectrum active 6G transmission can be safely undertaken.

The challenge of making new lanes for the ever-expanding wireless-network traffic remains a moving target. But Polese and colleagues have shown that spectrum sharing is a viable solution to the problem of active users interfering with passive signals — a welcome and timely development now that spectrum allocations above 100 GHz are being released. The approach will no doubt be further strengthened by emerging sensing techniques based on cooperative strategies and machine learning. These provide high detection accuracy using low-complexity algorithms, and can be tailored to suit different situations and users[7,8].

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The author declares no competing interests.
This article was published online on 26 May 2022.

Palaeontology

The fossil riddle of *Palaeospondylus*

Jorge Mondéjar Fernández & Philippe Janvier

For more than a century, scientists have pondered over mysterious fossils of an aquatic vertebrate, and argued about the type of creature this species represents. Newly analysed specimens might help to solve this puzzle. **See p.109**

If you look for fossils at the celebrated Achanarras Quarry in the Highlands of Scotland, you might stumble upon a small, fish-like animal, no more than a few centimetres long and suggestive of a tadpole, called *Palaeospondylus gunni*. This creature, which is the most common fossil vertebrate in the lake deposits there, dates to about 385 million years ago (the Middle Devonian period). It is found hardly anywhere else, and is probably one of the most mysterious fossil vertebrates ever uncovered. Since its discovery[1] in 1890, because of its unusual mix of characteristics in terms of its shape, small size, elongated body and apparent lack of paired fins, *Palaeospondylus* has been interpreted in various ways and provoked many heated debates. On page 109, Hirasawa *et al.*[2] report compelling evidence that might be useful in efforts to solve the *Palaeospondylus* riddle.

Palaeospondylus was initially interpreted as being some kind of jawless fish (belonging in a grouping called agnathans, which includes living lampreys and hagfishes)[1], possibly one foreshadowing the origin of jawed vertebrates (termed gnathostomes). As the palaeontologist Adolphe Kemna[3] put it: "it is a real monster. It is merely an intermediate animal, that still and already displays the characters of the two groups [the agnathans and gnathostomes], which it links … it is the '*Archaeopteryx*' of the gnathostomes!" (The *Archaeopteryx* fossil shed light on bird evolution from non-avian dinosaurs.) Indeed, the jawless interpretation of *Palaeospondylus* had many supporters, although others saw resemblances with gnathostomes, such as chondrichthyans (cartilaginous fishes, including sharks), placoderms (extinct armoured jawed vertebrates) or even dipnoans (lungfishes)[4].

Represented by thousands of specimens, *Palaeospondylus* has been the subject of numerous studies using different, and sometimes groundbreaking, methods[5–7], which have confirmed or refuted the various proposed placements of this species on the evolutionary tree over the years. As such, *Palaeospondylus* has been attributed to almost every major vertebrate group, and was even considered to belong to its own new group[5]. How can we explain these disparate attributions for such a relatively well-characterized fossil?

The difficulty in interpreting *Palaeospondylus* lies in its peculiar preservation pattern. Its delicate skeleton was assumed to be made entirely of cartilage, thus constituting a true internal skeleton (termed an endoskeleton). However, there are no indications of dermal bones, which form an exoskeleton, and thus no ornamentation or teeth, which are generally used to assign fossil fishes on the evolutionary tree. This unusual absence of an exoskeleton suggested that *Palaeospondylus* might be a kind of larva or juvenile of any of the aforementioned fish groups, preserved early in development, before the exoskeleton formed[4].

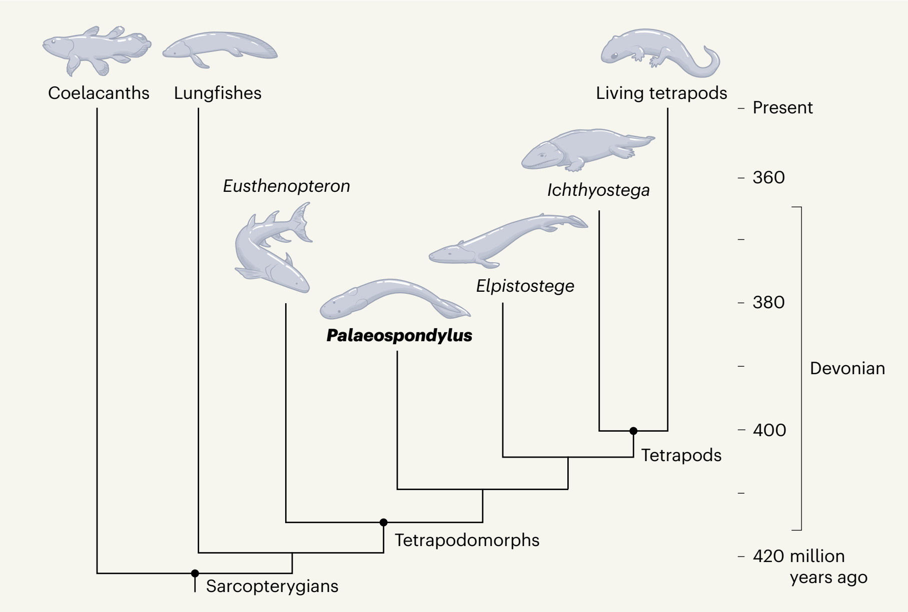

Figure 1 | A mysterious fossil. The fishy-looking fossils of *Palaeospondylus gunni*, found in 385-million-year-old lake sediments, have puzzled palaeontologists for more than a century. The skeleton, mainly formed of cartilage, and the unusual lack of dermal bones, scales, teeth and paired fins, make it hard to determine what sort of creature it was. Hirasawa *et al.*[2] reconstructed the cranial anatomy of *Palaeospondylus*, and attribute it to bony fishes called sarcopterygians (lobe-finned fishes). Sarcopterygians diversified during the Devonian period, and they include living examples such as the coelacanths and lungfishes. Sarcopterygians also gave rise to the tetrapodomorph fishes, such as *Eusthenopteron*. Tetrapodomorphs were the forerunners of the tetrapods (four-limbed land vertebrates that include *Ichthyostega*, and ourselves). The authors suggest that *Palaeospondylus* is a larval form of a tetrapodomorph, similar to *Elpistostege*. They propose that the lack of teeth and dermal bones in *Palaeospondylus* specimens might be because the braincase and the backbone formed before other skeletal components arose.

The palaeontologist Erik Jarvik was impressed by the resemblance between *Palaeospondylus* and metamorphosing frog tadpoles, and proposed that it might be a kind of amphibian larva[8]. This was quite different from the view of his mentor Erik Stensiö[9], who interpreted *Palaeospondylus* as being some kind of hagfish relative, consistent with an earlier study[10]. However, Jarvik's guess was difficult to reconcile with the fact that the metamorphosis observed in present-day amphibians such as frogs arose only in the Permian period, at least 100 million years after the time of *Palaeospondylus*.

Hirasawa and colleagues' findings add a new piece to the puzzle. The authors' great advance is to provide high-resolution imaging of the tissue structure of *Palaeospondylus* and to demonstrate the exceptional post-mortem preservation of the skeleton, with a particular focus on the skull. The authors reveal that the cartilage was lined by a thin layer of perichondral bone, a tissue that contrasts with the exclusively cartilaginous skeleton observed in present-day jawless fishes. Moreover, the occurrence of perichondral bone associated with a previously recognized early stage of development of endochondral bone[6] suggests that *Palaeospondylus* might be a larval form of some type of bony vertebrate (osteichthyan), caught in the process of mineralization (ossification) of its endoskeleton — a process that strengthens the endoskeleton and turns it into bone. The singular preservation characteristics of *Palaeospondylus* of an endoskeleton without traces of an exoskeleton, together with other features such as the lack of paired appendages, might thus reveal a pattern of development that occurred in two waves, in which the braincase and the vertebral column formed and started to ossify before the rest of the skeleton.

The peculiar paired posterior rod-like elements of the skull are identified as being a hyomandibula, a structure characteristic of jawed vertebrates, and the paired triangular elements in the specimen, previously thought to be paired fins, are instead interpreted as being gill coverings, possibly plate-like structures known as opercular cartilages. Assessing the typical forms of various osteichthyans that existed around the time of *Palaeospondylus*, Hirasawa *et al.* propose that the fossil is a lobe-finned vertebrate (a sarcopterygian), and, more specifically, a piscine stem tetrapod (an ancestral early aquatic forerunner of terrestrial vertebrates), intermediate on the evolutionary tree between *Eusthenopteron* and the 'elpistostegalians' such as *Elpistostege* and *Tiktaalik* (Fig. 1).

The authors' anatomical observations are supported by a phylogenetic analysis they used to generate an evolutionary tree that nested *Palaeospondylus* within the tetrapodomorph fishes — the closest relatives of limbed vertebrates. However, if the *Palaeospondylus* specimen was a larva with a different form from that of the adult, as is the case for frogs, this contrasts with the situation for the large, rather heavily built, early four-legged amphibious tetrapods, such as the iconic *Acanthostega* or *Ichthyostega* species. These are thought to have undergone a direct developmental process in which the newly hatched young looked like miniature versions of their parents and did not have a larval stage that looked different from the adults[11]. The classic tetrapod-bearing sites of Greenland (from the Late Devonian period, around 360 million years ago) yield some rare, small tetrapods[12].

The sarcopterygian nature of *Palaeospondylus* seems to be well supported. The specimen's braincase, poorly preserved as the skull is, has a zone of fragility in its mid part that implies the presence of the characteristic intracranial articulation connections of sarcopterygians. Nevertheless, it is astonishing that none of the partly disarticulated specimens shows a complete separation between the anterior and posterior halves of the braincase, as frequently occurs in fossil specimens of other sarcopterygians.

The proposed stem tetrapod assignation and time frame of *Palaeospondylus* are consistent with contemporaneous tetrapod tracks found in Poland, which represent the oldest-known indirect evidence of four-legged vertebrates[13]. However, some problems must be grappled with before this new view of *Palaeospondylus* can be accepted undisputedly as being a stem tetrapod larva. The Achanarras site yields osteichthyans represented by articulated specimens, but none displays intermediate developmental stages that might link them to *Palaeospondylus*. No sarcopterygian fish found in Achanarras can be connected to the elpistostegalians, which appear slightly later in the fossil record than the specimens at Achanarras. If small specimens of other species are uncovered at Achanarras with characteristics intermediate between those of *Palaeospondylus* and other fishes, such evidence might provide the definitive clue needed to assign *Palaeospondylus*.

Hirasawa and colleagues have made the surprising suggestion that *Palaeospondylus* might not be a scrappy representative of an obscure group of extinct vertebrate, placing it instead as an early member of the ancestral lineage that eventually led to land-dwelling vertebrates and, therefore, to us. This research partly solves the *Palaeospondylus* enigma, but evidence of dermal bones, such as those covering the head, or traces of scales or, even better, teeth, must be discovered to ensure that we are dealing with a tetrapod forerunner. Until then, the true nature of *Palaeospondylus* will remain a mystery, hidden in the mists of the Scottish Highlands.

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The authors declare no competing interests.
This article was published online on 25 May 2022.

Electronics

A 2D insulator for the post-silicon generation

Soo Ho Choi & Soo Min Kim

A method has been developed for fabricating thin films of the 2D insulator hexagonal boron nitride with a uniform crystal orientation. The advance makes this material a key contender for replacing silica substrates in future electronics. **See p.88**

As the electronics industry looks beyond silicon as its material of choice, many 2D materials are being investigated as candidates for the next generation of transparent and stretchable devices[1,2]. The electrical insulator hexagonal boron nitride is a popular choice as a substrate for transistors in these devices, because thin films of the material are transparent and stable — both mechanically and chemically. But obtaining 2D hexagonal boron nitride samples that have a uniform crystal-lattice structure (in other words, a single crystal) is challenging. And building them into multilayered structures that are compatible with common industry practices is even more difficult. On page 88, Ma *et al.*[3] report the synthesis of five stacked layers of single-crystal hexagonal boron nitride using a technique called chemical-vapour deposition.

Thin films of hexagonal boron nitride have already been shown to be excellent substrates for field-effect transistors, the central component of a silicon microchip. For example, when a hexagonal boron nitride film is used as a substrate for a molybdenum disulfide field-effect transistor, the mobility of electric charge carriers is four times greater than that of the same device on a standard silica substrate[4,5]. But to become truly useful for electronics, these films need to be fabricated on a sufficiently large scale for use as a wafer — the substrate on which a chip sits.

Single-crystal hexagonal boron nitride monolayers (of single-atom thickness) have previously been synthesized on a wafer scale through a technique known as surface-mediated growth, using chemical-vapour deposition with liquid-gold and single-crystal copper substrates[6–8]. However, monolayer films have fewer applications than do multilayer ones. For example, when used as an insulator between two layers of the 2D material graphene, a monolayer might not be enough to fully suppress the transport of electrons between the two graphene layers — instead, stacks of layers are needed.

Multilayer hexagonal boron nitride films are typically grown by the precipitation of boron and nitrogen solutes from nickel and iron substrates. However, these substrates are polycrystalline, meaning that they have regions with locally perfect crystal structure, separated by boundaries at which the lattices do not always match up[9,10]. Precipitation occurs at different rates at these boundaries, causing the hexagonal boron nitride films to be polycrystalline, too, and to have varying thicknesses. Such polycrystalline structure degrades the mechanical and chemical stability of the film. And the varying

From the archive

A step forward for international efforts to curb pollution, and a warning about the perils of broadcasting.

50 years ago

The principle that the polluter must pay to clean up the environment has finally been accepted by the OECD ... The effect of companies having to pay to clean up their pollution will be to raise the price of goods whose production would otherwise greatly damage the environment. The ministers also resolved that subsidies should not be provided to offset this effect. The ministers also agreed that more stringent anti-pollution controls are needed, but that care must be taken not to create barriers to trade. Where such controls will affect products that are traded internationally, governments should seek common standards ... In the guiding principles that accompany the agreement, the ministers state that national pollution policies are bound to differ because of different social priorities and different levels of industrialization.

From *Nature* 2 June 1972

100 years ago

It is obvious that anything like secrecy in conversation over the radio-telephone, as it is now often called, is out of the question, as any one in possession of a half-guinea licence and a receiving set, which can be tuned to the wave-length employed, can "listen in" and pick up the message irrespective of the station for which it was primarily intended. On account of the publicity which thus attends the utterances of the wireless telephone, its field, except in such special cases as aeroplane work, is practically limited to the dissemination of public information, news, music, and other entertainment items, or as it is now commonly called, "broadcasting." Unless, however, these broadcasting stations are rigorously controlled, they will not only defeat their own ends by drowning each other's messages in a confused babel of sounds, but will interfere with other forms of radio-communication, as already happens to a considerable extent in America.

From *Nature* 3 June 1922