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THE GENES BEHIND THE CAMBRIAN EXPLOSION

Once biologists discovered the genetic tool kit, they realized that it might have made the Cambrian explosion possible 535 million years ago. The first animals to appear in the fossil records include primitive animals such as jellyfish and sponges—diploblasts whose embryos form from only two layers. Biologists have looked for master-control genes in these animals as well but have mostly been disappointed. Diploblasts have only a handful of these genes and don't seem to use them in the same tightly organized way that triploblasts do.

That's not surprising when you consider the simplicity of the jellyfish's body. It does not have a body axis with left and right sides. Instead, its body is radially symmetrical, like a bell or a sphere. Its mouth is also its anus. Its nervous system is a decentralized web, rather than branches running off a central cord. It does not have the complex organization of a lobster or a swordfish.

Only after the primitive diploblasts branched off on their own did the genetic tool kit emerge in the common ancestor of all other animals. It made more complex bodies possible in these new animals: they could set up a grid of coordinates in a developing embryo, dividing the body into more parts, more sensory organs, more cells for digesting food or making hormones, more muscles for moving through the ocean.

Exactly what kind of body that common ancestor had is difficult to say. But paleontologists shouldn't be surprised to unearth some inch-long creature that lived not long before the Cambrian explosion with a wormlike body; a mouth, a gut, and an anus; muscles and a heart; a nervous system organized around a nerve cord and a light-sensing organ; and, finally, some kind of outgrowths on its body—if not actual legs or antennae, then perhaps appendages around its mouth to help it eat. It might be the creature that left those anonymous trails among the Ediacarans.

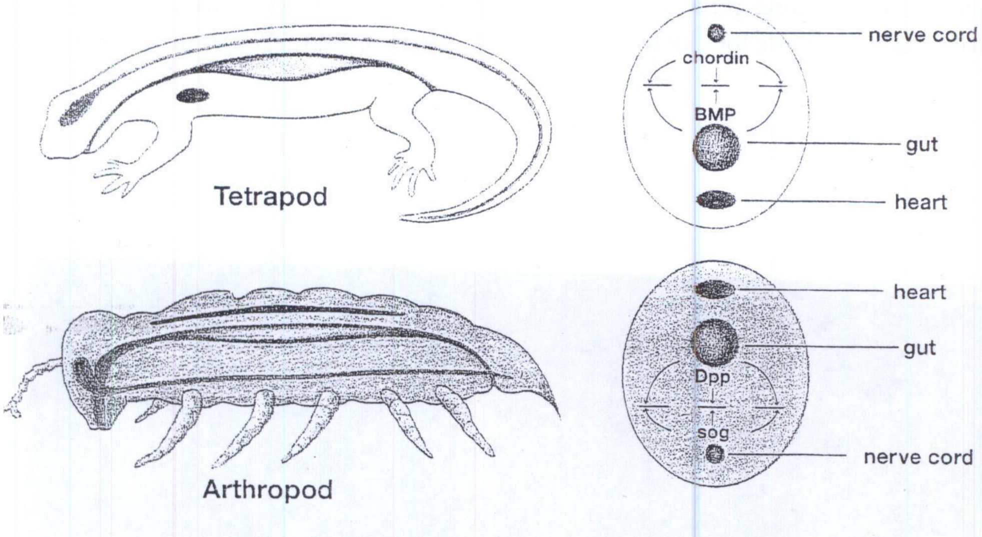
Paleontologists now believe that only after the genetic tool kit was complete could the Cambrian explosion take place. Only then was it possible for dozens of new animal body plans to emerge. Evolution did not build a new network of body-building genes from scratch in the process; it simply tinkered with the original genetic tool kit to build different kinds of legs, eyes, hearts, and other body parts. These animals took on dramatically different appearances, but they still held on to an underlying program for building bodies.

One of the most dramatic examples of this flexibility lies in the origin of our own nervous system. All vertebrates have a nerve cord running down their backs (the dorsal side, as biologists call it), while the heart and digestive tract are on the front (or ventral) side. Insects and other arthropods have an opposite arrangement: the nerve cord is on the ventral side, and the heart and gut are on the dorsal.

These mirror-image body plans inspired a fierce debate between Georges Cuvier and Geoffroy Saint-Hilaire in the 1830s. Cuvier found their anatomy so fundamentally different that he decided vertebrates and arthropods belonged in two completely distinct groups. But Geoffroy claimed that if you transformed the arthropod body plan drastically enough, you would end up with the vertebrate body plan. It turns out that Geoffroy was right, but in a way he couldn't have imagined. The nervous systems of vertebrates and arthropods are indeed starkly different. But the genes that control their development are the same.

When a vertebrate embryo begins to form, the cells on both the dorsal and the ventral sides have the potential to become neurons. Yet we do not have spinal cords running down our bellies, because the cells on the ventral side of vertebrate embryos release a protein called Bmp-4, which prevents cells from becoming neurons. Gradually Bmp-4 spreads from the ventral cells toward the dorsal side of the embryo, blocking the formation of neurons as it goes.

If Bmp-4 spreads all the way to the other side, no neurons could form at all in a vertebrate embryo. But as the embryo develops, its dorsal cells release



All vertebrates (side view at top left) have spinal cords running along their backs, and hearts and digestive systems in front. Insects and related invertebrates (bottom left) have the opposite arrangement. Yet the same kind of mechanism controls their development, as shown in the cross sections at right. A nerve-blocking protein (Bmp in vertebrates and Dpp in insects) spreads through the body until it is countered by a second protein (chordin or sog, respectively), which allows the spinal cord to develop.

a protein that blocks Bmp-4. Known as chordin, it protects the dorsal side of the embryo from Bmp-4, leaving the cells there free to turn into neurons. Eventually they give rise to the spinal cord that runs along a vertebrate's back.

Compare that sequence of events to what happens in a fruit fly. When a fruit fly embryo first forms, it can also form nerves on both its dorsal and ventral sides. But then a nerve-repressing protein called Dpp is made on its dorsal side, instead of the ventral side where Bmp-4 first appears in vertebrates. As Dpp spreads toward the ventral side of the fly, it is blocked by the protein sog. Protected from Dpp, a fly's ventral side can form a nerve cord.

These sets of genes not only perform similar jobs in insects and vertebrates, but their sequences are nearly identical. The nerve-blocking gene Dpp and the nerve-blocking gene Bmp-4 are matches, as are their antagonists, sog and chordin. They are so similar, in fact, that if a sog gene from a fly is inserted into a frog embryo, a second spinal cord will start taking form in the frog's belly. The same genes are building the same structures in insects and frogs, but they're flipped.

Such similar genes doing such similar jobs must have a common ancestry. John Gerhart at the University of California at Berkeley has proposed how this transformation took place. The first animals with the genetic tool kit grew several small nerve cords running along the sides of their bodies rather than a single big one. These ancestral animals carried a gene that was the ancestor of both chordin and sog, and it promoted the growth of neurons at all the places where a nerve cord was to form in their embryos.

This common ancestor gave rise to all the lineages that appeared during the Cambrian explosion. In the lineage that led to arthropods, the nerve cords all coalesced into a single one running on their ventral side. In vertebrates, the cords all migrated to the back. But the original genes for building nerve cords didn't disappear; the place where they became active changed. And so, over time, they became the mirror images that so impressed Geoffroy.

GENE DUPLICATION AND THE DAWN OF VERTEBRATES

Vertebrates acquired more than just spinal cords running down their back during the Cambrian explosion. With some tinkering to their genetic tool kit, they evolved eyes, complex brains, and skeletons. In the process, vertebrates became powerful swimmers and excellent hunters and have remained the dominant predators of the ocean and land ever since.

The oldest known vertebrate fossils—lamprey-like creatures found in China—date back to the midst of the Cambrian explosion, 530 million years ago. In order to understand how those first vertebrates emerged from their

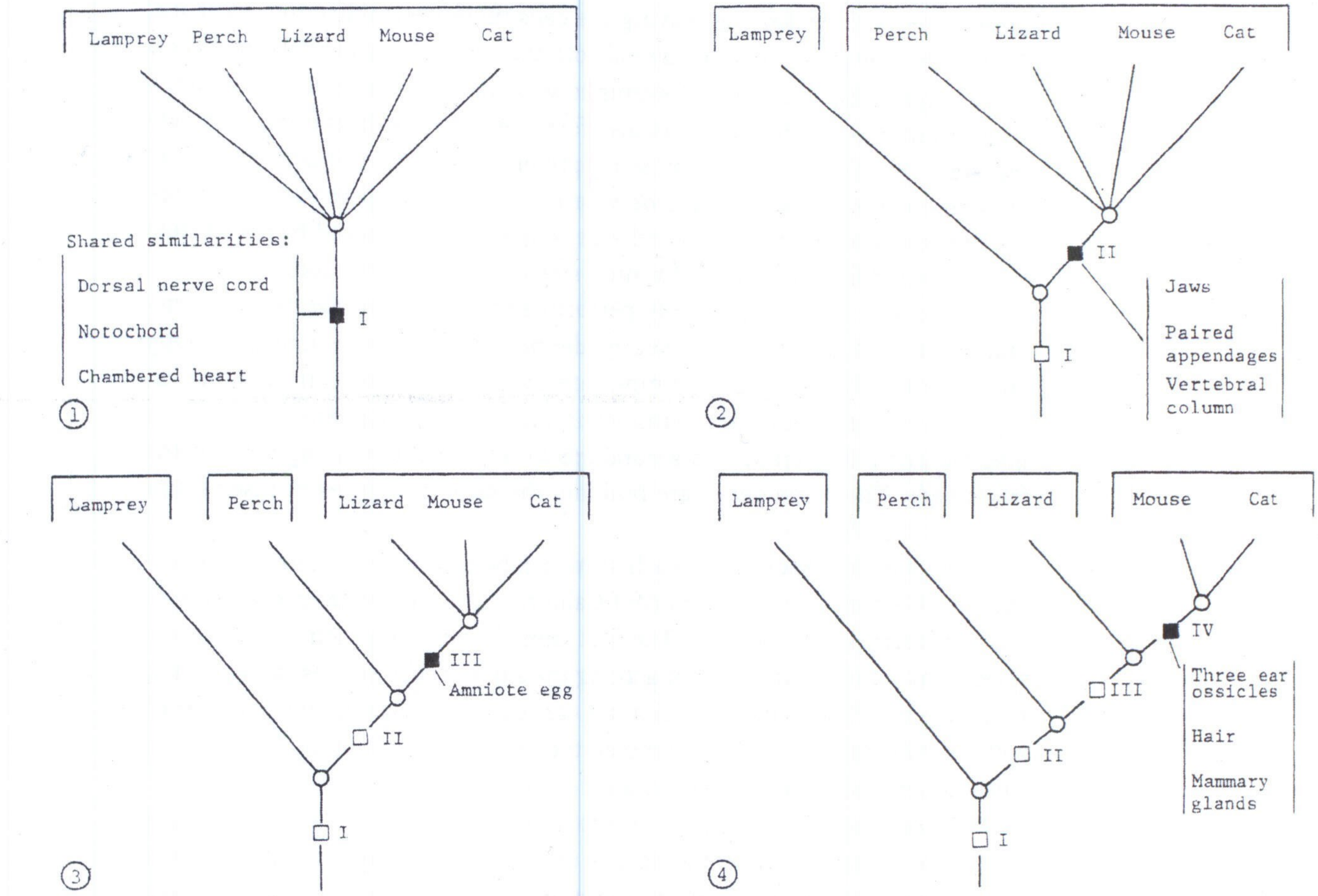


Figure 33.4 Cladograms based on shared anatomical characteristics. (Modified from Joel Cracraft, p. 171, Figure 1, in L. R. Godfrey, ed., Scientists Confront Creationism, W. W. Norton & Company, Inc., New York Copyright © 1983 by Laurie R. Godfrey. Used by permission.)

From Strahler, Arthur N., *Science and Earth History - The Evolution/Creation Controversy*. 1987, Prometheus Books, Buffalo, N.Y. page328.

Anatomical features present:

Rank:	I			II			III	IV			
Highest	x	x	x	x	x	x	x	x	x	x	Mouse, cat
	x	x	x	x	x	x	x				Lizard
	x	x	x	x	x	x					Perch
Lowest	x	x	x								Lamprey

Figure 33.5 Hierarchical structure derived from cladogram analysis of shared similarities shown in Figure 33.4. (A. N. Strahler.)

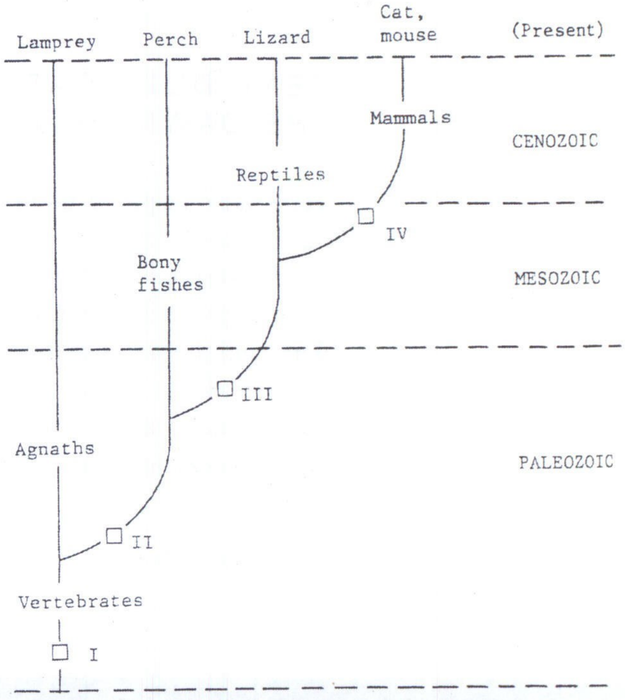


Figure 33.6 Cladogram number four of Figure 33.4, adjusted to the fossil record of Phanerozoic time. (A. N. Strahler.)