

Questions about the Cambrian Explosion, Evolution, and Intelligent Design

1. What was “Darwin’s dilemma”?

“Darwin’s dilemma” refers to Charles Darwin’s bafflement that the fossil record contradicted what his theory of evolution predicted. In his classic book *On the Origin of Species*, Darwin declared that if his theory of evolution were true “it is indisputable that before the lowest Cambrian stratum was deposited... the world swarmed with living creatures.”¹ Yet Darwin admitted that the fossil record below the Cambrian strata seemed to be bereft of such creatures. Instead “species belonging to several of the main divisions of the animal kingdom suddenly appear in the lowest known fossiliferous rocks”—without any evidence of prior ancestral forms. Darwin frankly acknowledged that this lack of ancestral forms was “a valid argument” against his theory. But he hoped that time—and more research—would provide the evidence that was lacking. Some 150 years later, the documentary *Darwin’s Dilemma* probes how Darwin’s dilemma has been aggravated—not resolved—by the last century of fossil discoveries, starting with the strange and wonderful creatures uncovered a century ago in the Burgess shale in British Columbia, Canada.

2. Has the Precambrian fossil record solved “Darwin’s dilemma”?

Those who think that papers like J. William Schopf’s 2000 *PNAS* paper, “Solution to Darwin’s dilemma: Discovery of the missing Precambrian record of life,”² actually solve the mystery of the Cambrian explosion, probably did not read past the paper’s title, or haven’t been paying close attention to this debate in recent years.

Precambrian fossils exist; this has been known for many decades, from fossil localities around the world. But no ID proponent has ever argued that there are no Precambrian fossils.

Rather, ID proponents observe that there are no *clear evolutionary precursors to the Cambrian fauna*, where nearly all of the major living animal phyla appear in an abrupt fashion without any evolutionary antecedents. **That the precursors to the Cambrian groups are indeed missing from the record is widely accepted among paleontologists**; thus, this is not the controversial aspect of the ID position. About the missing precursors at the base of the tree of the animal phyla, Valentine notes:

...many of the branches, large as well as small, are cryptogenetic (cannot be traced into ancestors). Some of these gaps are surely caused by the incompleteness of the fossil record...

but that cannot be the sole explanation for the cryptogenetic nature of some families, many invertebrate orders, all invertebrate classes, and all metazoan phyla.³

Charles Marshall concurs:

While the fossil record of the well-skeletonized animal phyla is pretty good, we have virtually no fossils that are unambiguously assignable to the most basal stem groups [putative ancestors] of these phyla, those first branches that lie between the last common ancestor of all bilaterians and the last common ancestor of the living representatives of each of the phyla...their absence is striking. Where are they?⁴

To be clear: Valentine and Marshall, leading paleontologists, oppose ID theory.

By contrast, most ID theorists argue that the ancestral fossils are missing because they never existed. The best explanation of this abrupt bioinformational explosion of new body plans, they argue, is intelligent design. This is the controversial aspect of the ID position on the Cambrian Explosion.

But let's turn to Schopf's *PNAS* paper, which discusses some of the known Precambrian fossils. Contrary to what his title suggests, however, these fossils comprise bacterial and other unicellular fossils that do not provide the "solution to Darwin's dilemma." For example, fossils cited by Schopf include:

- *Eozoon canadense*, which was found to be not a fossil but a rock produced by metamorphism. Early evolutionary biologists wrongly presumed it was a fossil because they so badly wanted to solve "Darwin's dilemma."
- *Cryptozoon*, which is thought to be a stromatolite—a bacterial mat. At best, these stromatolites only show bacteria and are *not* true multicellular fossils that would have been directly ancestral to the Cambrian fauna. Like the prior example, this turned out to be a case where, according to Schopf, "Mineralic, purely inorganic objects had been misinterpreted as fossil." Thus faulty evolutionary presumptions about Precambrian fossils led to wrong conclusions about these fossils.
- *Chuaria*, which is a single celled algae, originally wrongly thought to be a shelly invertebrate due to more misguided attempts to solve 'Darwin's Dilemma.'
- Barghoorn Gunflint microfossils, which again comprise bacterial stromatolites that do not serve as precursors to the Cambrian fauna.
- Bitter Springs Chert, which again are microbe fossils, not clear evolutionary precursors to the Cambrian fauna.

- Saucer-sized organisms, at Ediacara, also called the Ediacaran Fauna, which are enigmatic fossils generally not thought to be ancestral to the Cambrian fauna.

Regarding this last example, the Ediacaran fauna are often cited by those who discuss Precambrian fossils. But these fossils do not solve “Darwin’s dilemma” because they are not thought to be ancestral to the modern phyla that appear explosively in the Cambrian. (In fact, the documentary *Darwin’s Dilemma* extensively discusses the Ediacaran fauna and how they do NOT explain the Cambrian Explosion.) As evolutionary paleontologist Peter Ward writes:

[L]ater study cast doubt on the affinity between these ancient remains preserved in sandstones and living creatures of today; the great German paleontologist A. Seilacher, of Tübingen University, has even gone so far as to suggest that the Ediacaran fauna has no relationship whatsoever with any currently living creatures. In this view, the Ediacaran fauna was completely annihilated before the start of the Cambrian fauna.⁵

In fact, Seilacher’s view is shared by various modern evolutionary scientists. Cooper & Fortey (1998) show in Figure 1 of their paper that the Ediacaran (called “Vendobionta”) fauna are not ancestral to the Cambrian fauna, and they write:

The beginning of the Cambrian period, some 545 million years ago, saw the sudden appearance in the fossil record of almost all the main types of animals (phyla) that still dominate the biota today. To be sure, there are fossils in older strata, but they are either very small (such as bacteria and algae), or their relationships to the living fauna are highly contentious, as is the case with the famous soft-bodied fossils from the late Precambrian Pound Quartzite, Ediacara, South Australia.⁶

Likewise, Andrew Knoll and Sean Carroll observe that “It is genuinely difficult to map the characters of Ediacaran fossils onto the body plans of living invertebrates” and thus evidence of these fossils being precursors to Cambrian fauna “remains equivocal.”⁷ A Blackwell Scientific invertebrate biology textbook concurs that the Ediacaran fauna do not solve Darwin’s dilemma:

Whether they were, in fact, early members of any phyla still living today and possible ancestral forms, or were members of phyla long since extinct, is a question of considerable current debate. At any rate, they shed little light on the question of which phyla were ancestral to other phyla, or if indeed, animals have a common ancestry.⁸

Finally, the prominent paleontologists, Valentine, Erwin, and Jablonski, are hesitant to claim these Ediacaran fossils bear any ancestral relation to Cambrian fauna, stating that “the relations of any of these fossils to Cambrian bilaterians remains uncertain and awaits further collecting and critical analysis.”⁹ Most evolutionary scientists thus do not believe that the Ediacaran fossils solve “Darwin’s dilemma.”

In fact, the lack of Precambrian fossil precursors to the Cambrian fauna is all but admitted in Schopf's aforementioned *PNAS* paper, which concedes that "Megascopic eukaryotes, the large organisms of the Phanerozoic, are now known not to have appeared until shortly before the beginning of the Cambrian—except in immediately sub-Cambrian strata, the hunt for large body fossils in Precambrian rocks was doomed from the outset." This is a striking admission: paleontologists do *not* know of fossils that serve as clear evolutionary precursors to the explosion of biodiversity that appears in the Cambrian. Schopf's statement that "those of us who wonder about life's early history can be thankful that what was once 'inexplicable' to Darwin is no longer so to us," is difficult to accept because "Darwin's dilemma" is not solved by these bacterial, unicellular, and other ambiguous fossils yielded by Precambrian rocks. The fact that essentially all of the Precambrian fossils cited by Schopf entail unicellular organisms or other enigmatic fossils, and the fact that he admits a lack Precambrian "Megascopic eukaryotes," defeats the purpose citing his paper to show a "Solution to Darwin's dilemma."

If an evolutionary theorist's goal is to argue that the Cambrian explosion was not "abrupt" or "explosive" due to Precambrian fossils that allegedly document the evolution of the Cambrian fauna, then that evolutionary theorist is going to lose his argument. Rather, recent textbooks explain that the fossil record does not document the evolution of the phyla which appear in the Cambrian explosion:

Most of the animal phyla that are represented in the fossil record first appear, 'fully formed,' in the Cambrian some 550 million years ago...The fossil record is therefore of no help with respect to the origin and early diversification of the various animal phyla.¹⁰

Such statements are made because the fossil record genuinely records that nearly all of the major animal phyla appear abruptly and without clear evolutionary precursors. Precambrian fossils that solve this "dilemma" have been lacking since Darwin's time.

For a response to a 2009 paper making similarly wrong-headed claims about Precambrian fossils providing the "solution to Darwin's dilemma," see Jonathan Wells, "Deepening Darwin's Dilemma," (Sept. 16, 2009), available at <http://www.discovery.org/a/12471>.

3. Don't mutations to DNA, in the genes controlling development (such as Hox genes), explain how new bodyplans evolved?

No. Here is why.

Since the late 1970s, by studying species as different as fruit flies, sea urchins, and mice, biologists have learned a great deal about the genes needed for development to proceed normally from the fertilized egg to the adult. Often described as "master control genes," these DNA sequences code for proteins that regulate the expression (timing and location) of many other genes, usually by acting as switches (rather like the switches in a railroad yard). Remarkably, these developmental regulatory genes are widely shared, or conserved, among animals – even between species as different as *Drosophila* (a fruit fly),

Loligo (a squid), and *Mus* (a mouse). In these very different animals, the “same” gene, known as *eyeless* in flies and *Pax-6* in mice, helps to regulate the development of eyes: a compound eye for the fly, but camera-type eyes for squid and mice. Many other examples of such conserved regulatory genes are now known.¹¹

This raises the first problem with the DNA → development → bodyplan explanation:

- **If developmental regulatory genes are largely the same from one animal group to the next, what explains the striking differences of such groups in their large-scale body plan architecture, such as having an internal (chordate) versus an external (arthropod) skeleton?**

This puzzle has come to be known as the “paradox of conservation.” Biologist Stuart Newman notes that “it was extremely puzzling to find that the same transcription factor [gene and its protein product] would act as a master control molecule in such morphologically distinct organs [compound vs. camera eyes] in such evolutionarily distant taxa [flies, squid, and mice].”¹²

But the second problem is much more severe:

- **Animals do not tolerate mutations to genes involved in regulating bodyplan construction.**

Because these genes act early in development, as the fertilized egg begins to divide (or even earlier, as the egg itself is built by the mother), mutations affecting the expression of regulatory genes have cascading, and devastating, consequences for the embryo. These mutants are known as “embryonic lethals,” and die before birth. With mutations expressed later in development, the animal may survive to adulthood, but it is gravely crippled, and cannot mate or establish a new lineage. The famous *Antennapedia* mutant in fruit flies, for instance, has legs where its antennae should be. Outside the lab, such mutants are complete non-starters in Darwinian competition. They do not constitute novel adaptations, but dead ends.

Given the severity of developmental mutations today, some evolutionary biologists have argued that circumstances must have been different before, and during, the Cambrian Explosion. We’ll discuss this possibility under question 6, below.

4. If animals with backbones and dorsal nerve cords first appeared in the Cambrian—for instance, the fish *Haikouichthys*—and humans possess both of those features, do humans ultimately trace their evolutionary ancestry to the Cambrian fish?

Not necessarily. A **phylum** (plural, *phyla*), such as “Chordata” (i.e., the chordates), to which both fish and humans belong, is an *abstract category*, defined by the presence of diagnostic anatomical features. What is real—that is, actually out there in nature—are the organisms, within species, which embody these different bodyplans or phylum architectures.

But, unless one begs the question, there is no more reason to think that all chordates descended from the first fossil chordate, than there is to think that all airplanes trace their causal history to the Wright brothers' flying machine. The concept "airplane" includes many different actual representatives, or real-world instances, but those particular machines may (and indeed do) have independent causal histories. They do not share common ancestry, but represent *a distinctive kind of system* with diagnostic features: an airfoil wing, powered thrust, three-axis control, and so on. Those diagnostic features capture a wide range of different real-world examples, of course, from a single-engine Piper Cub to a Boeing 777.

Thus, while we recognize airplanes as belonging to a definable class of objects, we do not require that the actual members of that class share a material (or historical) lineage. The same may well be true for the members of the animal phyla. What we see in the Cambrian Explosion, then, are the early representatives of distinct kinds of biological forms, and ways of living, but not ancestral groups. Other representatives of those forms will appear later in Earth history.

To be sure, some ID theorists, such as Lehigh biochemist Michael Behe, think all animals share common ancestry. For them, all chordates (or members of other phyla) are linked in an evolutionary tree. Other ID theorists (such as Stephen Meyer and Jonathan Wells) disagree, and favor the interpretation sketched in the paragraph above. This is a topic of ongoing discussion within the intelligent design research community.

5. Don't all biologists think that DNA provides the blueprint for animal development, and thus, for different animal bodyplans?

Again, the answer is no. While DNA may be *required* for bodyplan formation, evidence shows it is not *sufficient* to specify the disparate architectures of different animals.

To understand why, imagine visiting a construction site. You see piles of lumber, stacks of bricks, coiled wire, and so forth—but no building activity. The work crew is sitting under a tree, drinking coffee. What's up? you ask them. No blueprint, they answer—and we can't do anything without that plan.

The orderly construction of any building requires more than the raw materials. Concrete, lumber, wire, and other materials may be combined in any number of ways, but constructing a *particular* habitable building requires a *global*, or comprehensive, plan. The plan must be comprehensive in three *spatial* dimensions, specifying the form of the final product, but also *temporally*: each step in the construction process must occur in the right order (the foundation being laid before the walls and roof are added, for instance). The materials themselves, while necessary, do not provide this global plan.

In a parallel sense, DNA provides the necessary building materials: transcribed into RNA, the information in DNA specifies the assembly of proteins. But any cell, or any animal, exists as a three-dimensional form. Proteins must be localized to specific "addresses" in the cell, or organism, to do their jobs. DNA and its protein products thus *presuppose* a global cellular or organismal context, within which this

information-bearing molecule, and proteins, will play their role. Without that context, DNA is as biologically inert as a string of pebbles.

Harvard geneticist Richard Lewontin expresses the point eloquently:

No living molecule is self-reproducing. Only whole cells may contain all the necessary machinery for “self”-reproduction.... Not only is DNA incapable of making copies of itself, aided or unaided, but it is incapable of “making” anything else...The proteins of the cell are made by other proteins, and without that protein-forming machinery nothing can be made. There is an appearance here of infinite regress (What makes the proteins that are necessary to make the protein?), but this appearance is an artifact of another error of vulgar biology, that it is only the genes that are passed from parent to offspring. In fact, an egg, before fertilization, contains a complete apparatus of production deposited there in the course of its cellular development. We inherit not only genes made of DNA by an intricate structure of cellular machinery made up of proteins.¹³

In animal development, DNA plays its role within the pre-existing cellular context of the egg. And an egg cell needs Mom -- that is, the maternal environment -- to construct it. The egg cell, which when fertilized will become the developing embryo, is not however simply a passive bag for DNA. Rather, the egg carries precise three-dimensional information in its cytoskeleton, membranes, and other structures -- information that will determine the global form of the embryo, and adult, to come.

Cambridge University developmental biologist Adam Wilkins recently expressed the point as follows:

Genomes [DNA and genes] are not really blueprints and, in themselves, do not contain the information for development, which flows in particular and complicated ways, via whole series of molecular and cellular interactions, starting from unique gene-product-gene interactions in the egg. Despite the long-standing appeal of the metaphor, there is no “genetic programme” for development written in the genome.¹⁴

In all animals that we know, the three-dimensional information stored in the global arrangement of the egg *is always co-present* with DNA. Both are needed for normal development.

There is thus no biological reason to assume that DNA, while necessary for development, is alone sufficient to direct the process. If you want to construct a building, you need a blueprint. If you want to construct a developing embryo, you need (at least) an egg, and for that, you need Mom.

6. (a) How long was the Cambrian Explosion? (b) Can any event that took millions of years to occur really be called an “explosion?”

(a) Opinions among paleontologists differ about the length of the Cambrian Explosion. Robert Carroll of McGill University estimates that the radiation took a “very short” interval of time, “in the order of 5 to 10

million years,” somewhere between 545-530 mya.¹⁵ Charles Marshall of Harvard University, allowing for different starting and ending points in the fossil record, posits a longer interval. “From the first appearance of heavily skeletonized animals to the first body fossils of trilobites,” argues Marshall, “the radiation took some 20 million years.”¹⁶ Samuel Bowring of MIT and colleagues, however, estimate that the most explosive phase of the radiation “lasted only 5 to 6 m.y. In any event it is unlikely to have exceeded 10 m.y. Numbers of phyla, classes, orders, families, and genera all reached or approached their Cambrian peaks during [this short interval].”¹⁷

(b) The term “explosion” is not a misnomer. As Marshall observes:

There are five major components of the Cambrian “explosion” that need to be explained: (a) the spectacular increase in animal disparity [i.e., in different *types* of animals], (b) the rise in animal diversity [i.e., in numbers of species within the different types], (c) why the time of onset of the explosion was some 543-542 mya, (d) why the duration of the explosion was some tens of millions of years long, and (e) why the event appears unique.¹⁸

Paleontologist James Valentine of UC-Berkeley stresses that the uniqueness of the Cambrian Explosion is not “an artifact” of an incomplete fossil record, or the peculiarities of preservation:

...some workers have supposed that the explosion is not real, but is an artifact of the preservation of fossils, representing an increase in preservability rather than representing the origins of new groups. There is considerable evidence that the explosion was real, however....For example, some of the groups that appear during the explosion require durable skeletons as part of their early bodyplans, so their origins can be no earlier than the origins of their durable skeletons.¹⁹

7. Couldn't circumstances have been different in the past, to allow for the rapid evolution of novel bodyplans from a common ancestor?

Well, maybe. But why think this? What is the evidence?

Here is the problem. Faced with the uniqueness of the Cambrian Explosion, and also with the known devastating consequences of mutations to animal development, some evolutionary biologists have argued that things must have been (very) different half a billion years ago. Paleontologist Douglas Erwin of the Smithsonian Institution notes that “the simple, empirical fact is that the establishment of new bodyplans is not a frequent event....There is every indication that the range of morphological innovation possible in the early Cambrian is simply not possible today.”²⁰

If new animal bodyplans evolved rapidly from an (unknown) common ancestor, therefore, mutations that today would destroy or cripple embryos must somehow have been tolerated. Furthermore, the genetics of such mutations must have been very different from what we see today in the well-studied model systems of developmental biology. As Campbell and Marshall argue,

There seems to be no alternative but to seek some unusual feature of the primitive genome that would allow it to change in such a way that large coordinated viable morphological changes could take place over short periods of geological time.²¹

Now, **notice that this hypothesis *assumes* that the disparate Cambrian bodyplans stem from a common ancestor, by unknown evolutionary pathways.** In short, the hypothesis assumes what needs to be demonstrated.

Without that assumption, however, there are no observational grounds for postulating “unusual features” of Cambrian genomes or developmental programs.

Seen another way, we have every reason to think that a Cambrian arthropod *would need* a stable (not mysteriously labile) genome and development, to exist and reproduce at all. “One cannot ignore the fact,” argues evolutionary biologist Jeffrey Levinton, a critic of this “unusual features” hypothesis, “that a stable developmental program was just as necessary for survival in the Cambrian as it is today.”²²

8. Cambridge University paleontologist Simon Conway Morris is featured in *Darwin's Dilemma*. What is his explanation for the Cambrian explosion?

Morris agrees that the Cambrian explosion is real. In his most recent paper on the topic, he writes, “My main conclusion is that the Cambrian explosion is a real event” and “the massive burst of diversification we see in the Cambrian itself is a real event.”²³ The causal details of Morris’s own explanation for the Cambrian Explosion, however, are hard to discern (see below). Morris indicates that he does not think the Cambrian Explosion fundamentally challenges standard evolutionary theory:

Does this course of events [i.e., the Cambrian Explosion] create a problem for Darwinism, even for evolution? I do not think so.²⁴

However, Morris is not content with any of the many evolutionary hypotheses on the table. Rather, he argues that the appearance of novel animal body plans is “natural and inevitable” on a planet like Earth:

In particular, the search for any sort of trigger may be to misunderstand the problem. Rather than invoking an almost endless litany of possibilities, among which some of the more popular include the invention of a *Hox* gene, eyes, cell signaling, extracellular matrix, nerve cells, armour, guts and so on, **it may be more useful to regard this event as the natural and inevitable result of the continuing evolution of a planetary system that shows cumulative and irreversible biogeochemical changes.**²⁵

In other words, when the time is right, 30 or so animal phyla will appear. As Morris continues:

As and when the conditions are appropriate, the opportunism and flexibility of the evolutionary process will exert itself.²⁶

9. (a) Were paleontologists Simon Conway Morris and James Valentine misled into appearing in *Darwin's Dilemma*? (b) Are they misrepresented in the film as intelligent design proponents?

(a) Morris and Valentine were not misled. Both agreed to interviews with Illustra Media (previous producers of *Unlocking the Mystery of Life* and *The Privileged Planet*) for a film on the Cambrian Explosion. Both knew at the time that they were giving interviews to Illustra Media. Both signed release forms to Illustra Media for the interviews, and both were paid for their interviews by Illustra.

(b) Morris and Valentine are not portrayed as intelligent design proponents in the film, nor are they intelligent design proponents. Rather, they appear in *Darwin's Dilemma* as leading authorities on the fossil evidence relating to the Cambrian era.

References

1. Charles Darwin, *On the Origin of Species*, fifth edition (1869), Chapter IX, "On the Imperfection of the Geological Record," pp. 378-381.
2. J. William Schopf, "Solution to Darwin's dilemma: Discovery of the missing Precambrian record of life," *Proceedings of the National Academy of Sciences U.S.A.*, Vol. 97(13):6947-6953 (June 20, 2000).
3. James Valentine, *On the Origin of Phyla*, p. 35.
4. Charles Marshall, "Explaining the Cambrian 'Explosion,'" pp. 362-3.
5. Peter Douglas Ward, *On Methuselah's Trail: Living Fossils and the Great Extinctions*, p. 36 (W. H. Freeman, 1992).
6. Alan Cooper and Richard Fortey, "Evolutionary explosions and the phylogenetic fuse," *Trends in Ecology and Evolution*, Vol. 13(4):151-156 (April, 1998).
7. Andrew H. Knoll, and Sean B. Carroll, "Early animal Evolution: Emerging Views from Comparative Biology and Geology," *Science*, Vol 284:2129-2136 (June 25, 1999) (internal citations omitted).
8. Vicki Pearse, John Pearse, Mildred Buchsbaum, and Ralph Buchsbaum. *Living Invertebrates*, p. 764 (Blackwell Scientific Publications, 1987).
9. James W. Valentine, D. Jablonski, Doug H. Erwin, "Fossils, molecules and embryos: new perspectives on the Cambrian Explosion," *Development*, Vol. 126:851-859 (1999) (internal citations omitted).
10. R.S.K. Barnes, P. Calow & P.J.W. Olive, *The Invertebrates: A New Synthesis*, pp. 9-10 (3rd ed., Blackwell Sci. Publications, 2001).

11. Douglas Erwin and Eric Davidson, "The last common bilaterian ancestor," *Development* 129 (2002):3021-3032. In their Table 1 (p. 3026), Erwin and Davidson list examples of regulatory genes conserved across the animal phyla.
12. Stuart Newman, "The Developmental Genetic Toolkit and the Molecular Homology-Analogy Paradox," *Biological Theory* 1 (2006):12-16; p. 12.
13. Richard Lewontin, "The Dream of the Human Genome," *New York Review of Books*, May 28, 1992, p. 33.
14. Adam Wilkins, "Waddington's Unfinished Critique of Neo-Darwinian Genetics: Then and Now," *Biological Theory* 3 (2008):224-232.
15. Robert Carroll, "Limits to knowledge of the fossil record," *Zoology* 100 (1998):221-231; p. 228.
16. Charles Marshall, "Explaining the Cambrian 'Explosion' of Animals," *Annual Review of Earth and Planetary Sciences* 34 (2006):355-84; p. 362.
17. S.A. Bowring et al., "Calibrating rates of Early Cambrian evolution," *Science* 261 (1993):1293-98; p. 1297.
18. Charles Marshall, "Explaining the Cambrian 'Explosion,'" p. 361.
19. James Valentine, *On the Origin of Phyla* (University of Chicago Press, 2004), p. 179.
20. Douglas Erwin, "The Origin of Bodyplans," *American Zoologist* 39 (1999):617-29; p. 626.
21. K. Campbell and C. Marshall, "Rates of Evolution in Paleozoic Echinoderms," in *Rates of Evolution*, eds. K. Campbell and M. Day (London: Allen & Unwin, 1987), p. 97.
22. Jeffrey Levinton, "The Cambrian Explosion: was the one-eyed man king?" *BioEssays* 23 (2001):856-7.
23. Simon Conway Morris, "Darwin's dilemma: the realities of the Cambrian 'explosion'," *Philosophical Transactions of the Royal Society of London B* 361 (2006):1069-83; pp. 1077-8.
24. *Ibid.*, p. 1078.
25. *Ibid.*, emphasis added.
26. *Ibid.*

Resources on the Cambrian Explosion

Simon Conway Morris & H.B. Whittington, "The Animals of the Burgess Shale," *Scientific American* 241 (July, 1979): 122-133.

Harry B. Whittington, *The Burgess Shale* (New Haven, CT: Yale University Press, 1985). Stephen Jay Gould, *Wonderful Life* (New York: W. W. Norton, 1989).

James W. Valentine, S.M. Awramik, P.W. Signor & P.M. Sadler, "The Biological Explosion at the Precambrian-Cambrian Boundary," *Evolutionary Biology* 25 (1991): 279-356.

Jeffrey S. Levinton, "The Big Bang of Animal Evolution," *Scientific American* 267 (November, 1992): 84-91.

Samuel A. Bowring, J.P. Grotzinger, C.E. Isachsen, A.H. Knoll, S.M. Pelechaty & P. Kolosov, "Calibrating Rates of Early Cambrian Evolution," *Science* 261 (1993): 1293-1298.

John P. Grotzinger, "The Terminal Proterozoic Time Scale: Constraints on Global Correlations and Rates of Early Animal Evolution," *American Association of Petroleum Geologists Bulletin* 81 (1997): 1954.

Stephen C. Meyer, Marcus Ross, Paul Nelson, and Paul Chien, "The Cambrian Explosion: Biology's Big Bang," in J. Campbell and S. Meyer, eds., *Darwinism, Design and Public Education* (Michigan State University Press, 2003), pp. 323-402.

Simon Conway Morris, *The Crucible of Creation* (Oxford: Oxford University Press, 1998).

Simon Conway Morris, "Early Metazoan Evolution: Reconciling Paleontology and Molecular Biology," *American Zoologist* 38 (1998): 867-877.

D-G. Shu, H-L. Luo, S. Conway Morris, X-L. Zhang, S-X. Hu, L. Chen, J. Han, M. Zhu, Y. Li & L-Z. Chen, "Lower Cambrian vertebrates from south China," *Nature* 402 (1999): 42-46.

Jun-Yuan Chen, D.-Y. Huang & C.-W. Li, "An early Cambrian craniate-like chordate," *Nature* 402 (1999): 518-522.

James W. Valentine, D. Jablonski & D.H. Erwin, "Fossils, molecules and embryos: new perspectives on the Cambrian explosion," *Development* 126 (1999): 851-859.

Simon Conway Morris, "The Cambrian 'explosion': Slow-fuse or megatonnage?" *Proceedings of the National Academy of Sciences USA* 97 (2000): 4426-4429.

Simon Conway Morris, *Life's Solution* (Cambridge: Cambridge University Press, 2003). James W. Valentine, *On the Origin of Phyla* (Chicago: University of Chicago Press, 2004).



Center for Science & Culture at Discovery Institute
208 Columbia St. ❖❖ Seattle, WA ❖❖ 98106
(206) 292-0401 ❖❖ www.discovery.org/csc/