
Plant Kingdom
Bryophyta
Anthocerophyta
Hepatophyta
Lycopodiophyta
Sphenophyta
Psylophyta
Pteridophyta
Cycadophyta
Gingkophyta
Coniferophyta
Chordata
Angiospermae
Arthropoda
Flowers
130 mya
Animal Kingdom
Rhyniophyte*
Zosterophyllophyta*
Tracheophyta*
Seeds
370 mya
Vascular plants
420 mya
Land plants
450 mya
Green algae
670 mya
Protist Kingdoms
Origin of Life
3.4 bya
1000 mya
500 mya
Today
Fungi Kingdom
Bacteria Domain
Archaea Domain
Artist Joana Ricou

ARTISTS' ARTICLE

The Tree, the Spiral and the Web of Life: A Visual Exploration of Biological Evolution for Public Murals

Joana Ricou and
John Archie Pollock

ABSTRACT

The authors created the *Spiral of Life* as a new, accessible symbol for the evolution of life. This novel visual interpretation of evolution challenges traditional tenets of the field in light of emerging new themes in research. The *Spiral* brings recent principles to the general public and also provides scientists with a new visual concept to support further discussion. The *Spiral* emerged from the combination of the analysis of the latest scientific research with an artistic process to create new images and icons. A resulting complementary series of artworks was installed in five cultural institutions and museums in Pittsburgh, PA.

Our science outreach work constantly reveals the growing disconnect between the current state of science and the general public's understanding of fundamental principles of science. In keeping with what C.P. Snow observed in *Two Cultures* [1] and a recent National Academy of Sciences report highlighted [2], this disconnect has had a profound, pervasive and negative impact on science education, public policy and health in the United States.

Evolution struck us as an interesting topic within which to address this divide. The coincidence of Charles Darwin's 200th birthday and the 150th anniversary of the publication of *On the Origin of Species* in 2009 was the impetus for a worldwide movement that promoted awareness of evolution and spurred our own efforts. The dialogue surrounding this topic is obfuscated by the cultural debate that still rages over the validity of the science in this area and the lack of understanding of the relevance that evolution has to everyday life. Communicating the principle of common descent and evolutionary relationship of all living things was also interesting to us because the subject is currently actively researched by scientists, who still see defining over-arching principles as a significant challenge.

Visualization is a part of evolutionary research. Different diagrams are created depending on the specific point of view, intellectual framework, data sets and other constraints. While scientific visualizations must not allow for "artistic license," they always have an aesthetic component [3]. Since the current research into evolution still has many questions to address, and the way that the data is visualized is important to data interpretation, we find that image explorations can contribute both as support for visualization and as propositions. These characteristics make evolution promising territory for a fruitful art-and-science collaboration.

The traditional split between the roles of the scientist and the artist is harder to define in our collaboration than is often the case, because Ricou is an artist trained in cellular biology and genetics and Pollock is a physicist/biology researcher with a secondary career in science visualization and education. Both artistic and scientific opinions contributed to the making of this project, with a concern for the general accessibility of the science. The decision-making process was guided by the tug-of-war between the scientific point of view that resists generalization and the artistic point of view that is traditionally more concerned with the big picture. As Goodsell and Johnson suggest [4], artistic license allows selective disclosure, purposeful distortion of scale or perspective and simplification, among other tools, to serve the goal of clarifying a bigger picture and exciting interest. The artist is willing to incorporate what is known and create a visual hypothesis of what is not certain, while the scientist in both of us reached for exacting content based on the modern molecular genetic data in the published scientific literature.

Given the pace of research on evolution, we are aware that any images committed to paper today will become outdated in a few short years. Nonetheless, there is a need for a symbol that captures and clarifies the principles currently under discussion. We needed a symbol that would be accessible to the general public and have the potential to serve as a mental framework for researchers to model, anticipate and hypothesize with.

The first step in our creative process was to review the current scientific literature, news articles, imagery and web resources. In this process we considered over 84 different primary sources, texts and web projects [5]. The primary research data we collected had unsettled, changing and/or contradictory aspects. We resolved individual conflicts by consulting a panel of experts (listed in this paper's acknowledgments). For example, opinions on the branching pattern and the dates of the branching in bacteria are not settled. Different evidence points lead to conflicting answers. We based our project on the dates provided in Madigan and Martinko's 11th edition of *Brock Microbiology of Microorganisms* [6], with guidance from John Stolz of Duquesne University. We collected data simultaneously with spreadsheets and diagrams and subjected both to feedback from our scientific advisors.

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Article Frontispiece. ***Spiral of Life III: Animal Evolution*, digital art on vinyl, 18 × 10 ft, 2009, Pittsburgh Zoo & PPG Aquarium. This piece focuses on the animal kingdom. (© Joana Ricou and John Pollock)**

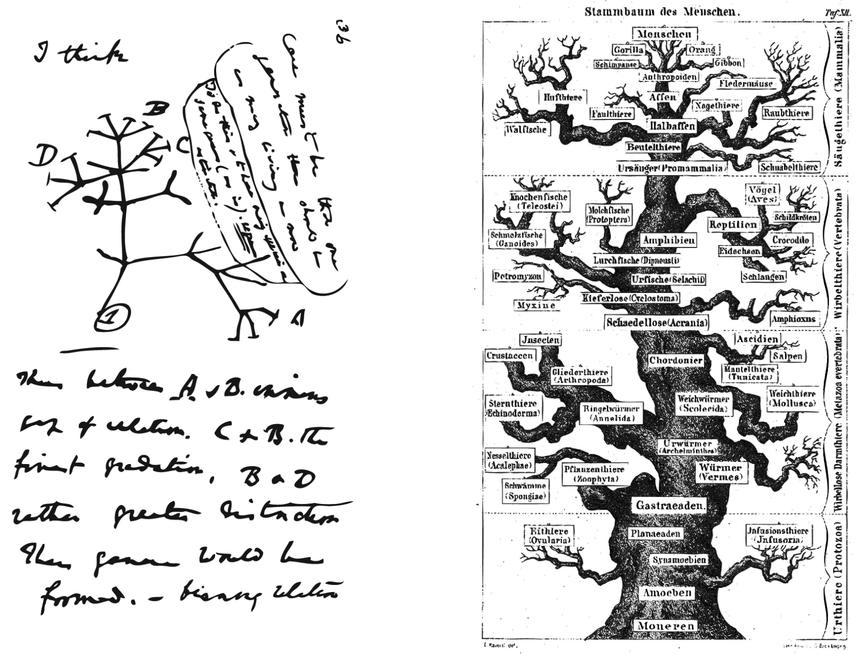


Fig. 1. (digitally enhanced) (a, left) First evolutionary tree drawn by Charles Darwin in his Notebook B in 1837 (public domain). For Darwin, the tree described the relationships between groups of organisms, revealing that all species are related through common ancestry and that they change over time. (b, right) *Evolution of Man—Pedigree of Man* Plate XV by Haeckel, 1879 (public domain). Within a decade of Darwin's publication of *The Origin of Species*, Ernst Haeckel had drafted multiple views of evolutionary trees, which typically placed humans as the most evolved species.

The Tree

While Charles Darwin was not the first to use a tree structure to organize living organisms, the "tree of life" he drew in 1837 became an icon and cognitive model for evolution (Fig. 1a) and is recognizable in modern cladograms. His model established that all species are related by common descent (common root) and that they diversified (ramification). The length of the branches can signify time or evolutionary difference. As decades passed by, the popularized interpretation of this revolutionary image accumulated misconceptions: for example, that evolution is a linear, vertical process and that all of life descends from a single common ancestor and culminated in the human species (as shown in Fig. 1b, a Haeckel illustration [7]). Another is that evolution has direction or is a progression [8], which has ended in modern times. While within the scientific community there is consensus regarding the fundamental principle of evolution, emerging research wrestles with the constraints of this iconic framework, in particular regarding the role of horizontal gene transfer processes, which we discuss later. Most modern imagery and visual tools, such as the Tree of Life web project [9], continue to use the tree icon as a framework.

The Circle

Historically, a circular design has also been used to represent the organization of the natural world and has inspired more recent evolutionary diagrams that are radial or circular [10] (Fig. 2). The radial diagrams include the branching pattern but place the origin of the diagram at the center, unequivocally connoting a common origin. An example of this type is the interactive Tree of Life [11]. However, this type of geometry is the least represented in sites to which the general public has ready access, such as in museums (less than 10% in a sample of 112) [12].

. . . and the Spiral

The most important message that we seek to impart with the *Spiral* is that all life is connected by evolution and all life is evolutionarily equal. To this end, we used the circle theme, with time as the radial axis, labeled explicitly like rings in a tree. In this way, all branches of organisms living today have the same radial length, stretching from the origin to the "today" ring, to emphasize the equality of evolutionary paths. An organism at a different scale represents each group of organisms; this "purposeful distortion" [13] made microscopic and macroscopic organisms appear similar in size, to further communicate their evolutionary equality. A "future" ring tantalizes the imagination and serves as a reminder that evolution is ongoing. Through an iterative process, we combined a logical organization of the visual space with the constraints of multiple discrete branches and enormous time (see "Collapsing Time" below). In this way, a spiral shape emerged at the center of our image, emphasizing the connection between the evolution of all major taxa. This shape became the heart of our reconceptualization of evolution as the *Spiral of Life* (Color Plate A).

From Spiral to Web

The idea that many natural and human processes are best represented as a collection of linked entities or network has achieved significant prominence in the cultural and scientific zeitgeist in recent years. It should come as no surprise that evolutionary biology is also participating in this conceptual revolution. Scientists now recognize that "horizontal transfer," processes that violate the strictly tree-like flow of genetic information proposed by Darwin, have been contributing to evolution over the millennia [14] (Fig. 3).

Traditional cladograms represent "vertical" processes and refer to the passage of genetic material from a parent generation to an offspring generation. We found that there is another type of process, "horizontal," that plays an important role in evolution. Horizontal transfer occurs when genetic information gets passed from one individual to another not through reproduction but by a virus, transposable elements [15] or other means, and this information is passed on to progeny. The existence of horizontal processes means that evolution can occur during the lifetime of an organism, which is an idea closer to Lamarck's theories than Darwin's. There is a consensus that these processes, while rare, have happened and continue to happen and are crucial in evolution [16–19]. However, horizontal gene transfer (HGT) is not included in most representations of the tree of life in museums [20]. The added concentric links between branches signify the "horizontal" molecular and cellular processes that transfer genetic material between species. The idea of the evolution of life as a net was originally suggested in 1993 [21], and a visualization of pervasive HGT was published in 2005 [22] (Fig. 3).

The fusion of bacteria and archaea

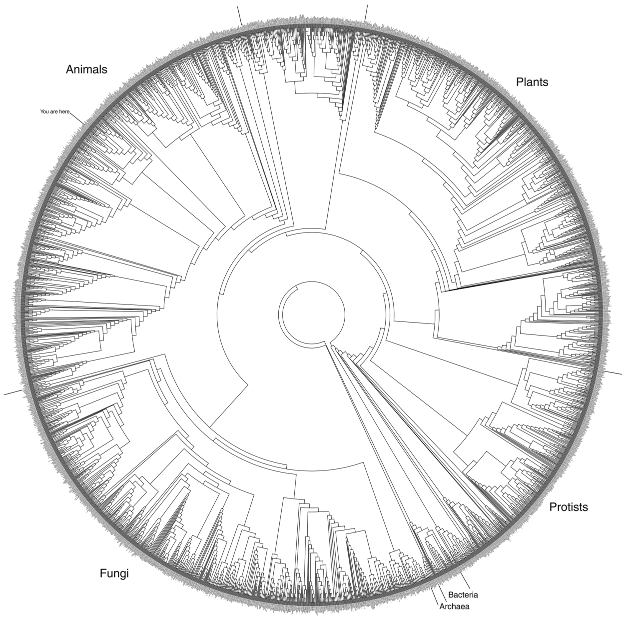


Fig. 2. David M. Hillis, Derrick Zwickl and Robin Gutell of the University of Texas created this circular diagram based on DNA sequence analysis of small unit ribosomal RNA sampled from about 3,000 species [43]. Originally intending a long banner, Hillis et al. found that a circle allowed them to pack in more species [44]. (© David Hillis)

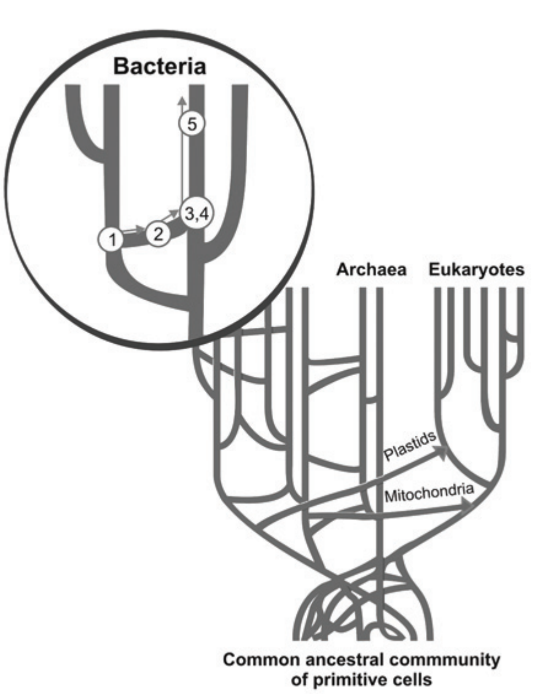
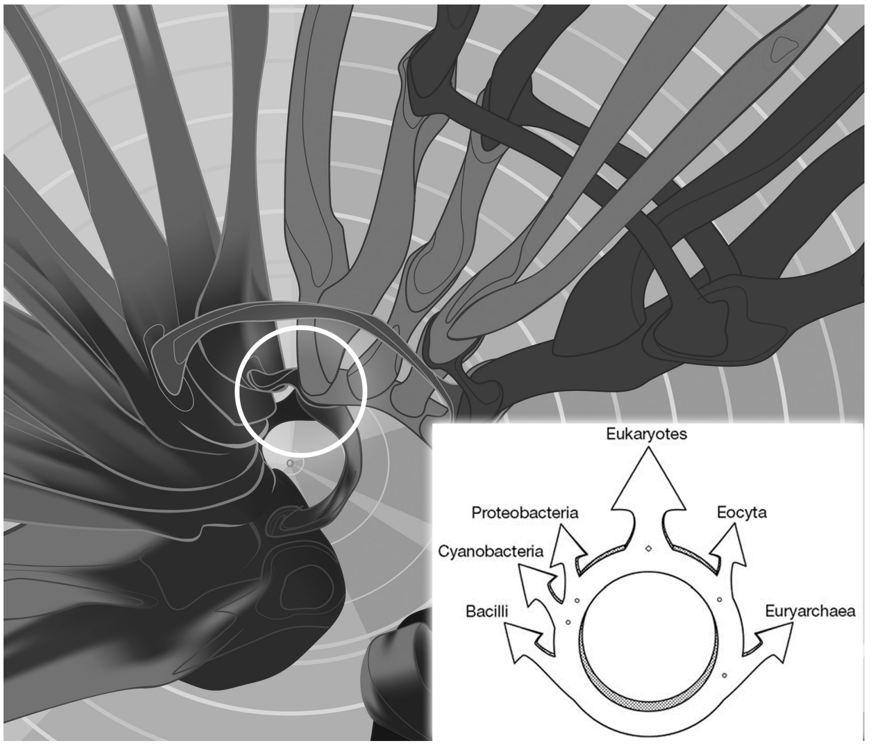


Fig. 3. Barth Smets proposes this image to capture the role of horizontal gene transfer in evolution [45]. The image also represents the origin of life as a complex web instead of a single line. Reprinted by permission from Macmillan Publishers Ltd: Nature (doi:10.1038/nrmicro1253), © 2005.

that gave rise to the eukaryotic cell, called eukaryogenesis (see Fig. 3), is a well-established horizontal step [23]. In the *Spiral,* this fusion is represented by the literal fusion of branches from both groups, arriving at an image similar to the "ring of life" suggested by Rivera and Lake [24] (Fig. 4, inset). We chose to include a third branch in the fusion step stemming directly from the origin. This third branch establishes the likely contributions of genetic material from unknown sources like plasmids or viruses [25,26]. In our original art, the branches are colored according to their domain and outlined to distinguish their start and end points. Fusions are indicated with knots to clarify what branches are involved. The third stem disappears after eukaryogenesis, indicating that the different successful combinations of building blocks that make up the archaea, bacteria and eukarya domains increased in stability and eventually out-competed all others. Those that disappeared are forgotten to the modern world, except for the ghosts left behind, hidden as fossils in the DNA record [27].

Other accepted "horizontal" examples are the initial and subsequent endosymbiosis of cyanobacteria and particular eukaryotes that evolved into the modern chloroplast—the foundation of all green plants. We represented these processes also as concentric lines (Fig. 4). The perpendicular branches were nudged

Fig. 4. The white circle indicates the evolution of eukaryotes. This step resulted from the fusion of the archaea and bacteria branches and a third background branch. Horizontal connections (depicted above, outside the circle) represent later endosymbiosis events: the engulfment of cyanobacteria that led to the modern chloroplast and the subsequent endosymbiosis of the latter. (© Joana Ricou and John Pollock) (inset) The "ring of life" as proposed by Rivera and Lake [46]. In this paper, the authors provide evidence for the fusion of bacterial and archaea genomes in the evolution of the eukaryotic genome and suggest that the tree is really a ring at this stage. Reprinted by permission from Macmillan Publishers Ltd: Nature (doi:10.1038/nature02848), © 2004.



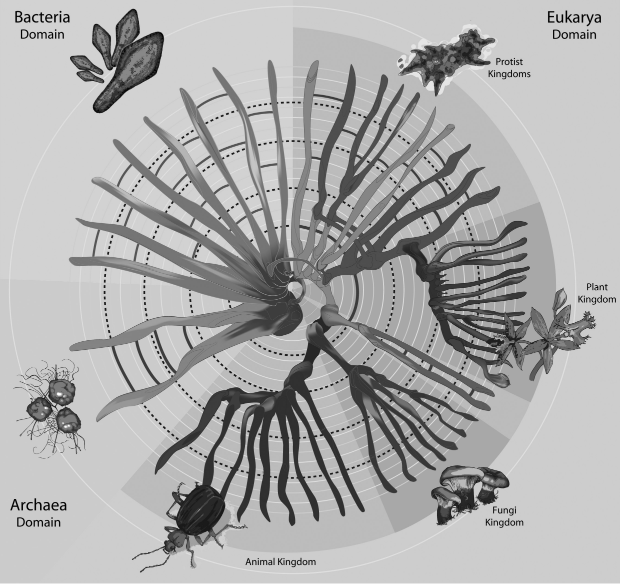


Fig. 5. Horizontal processes (solid concentric lines) are known to be common across unicellular life. Emerging research suggests that they may also be more common than previously thought in multicellular organisms (dashed concentric lines). Adding these concepts converts the spiral into a web. (© Joana Ricou and John Pollock)

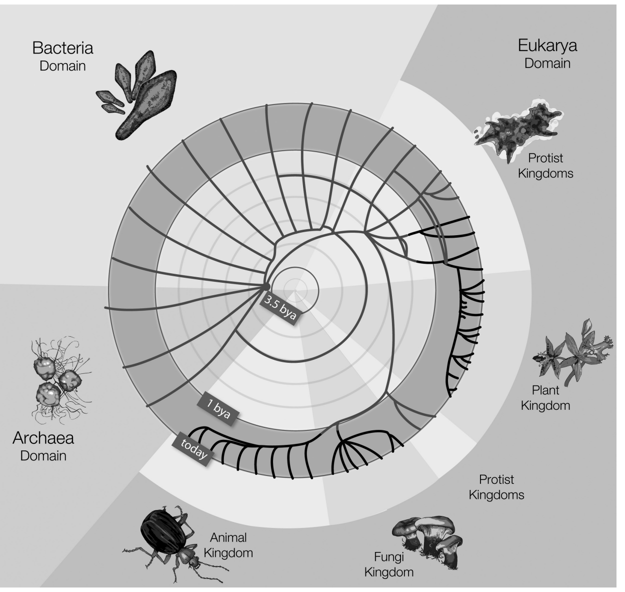
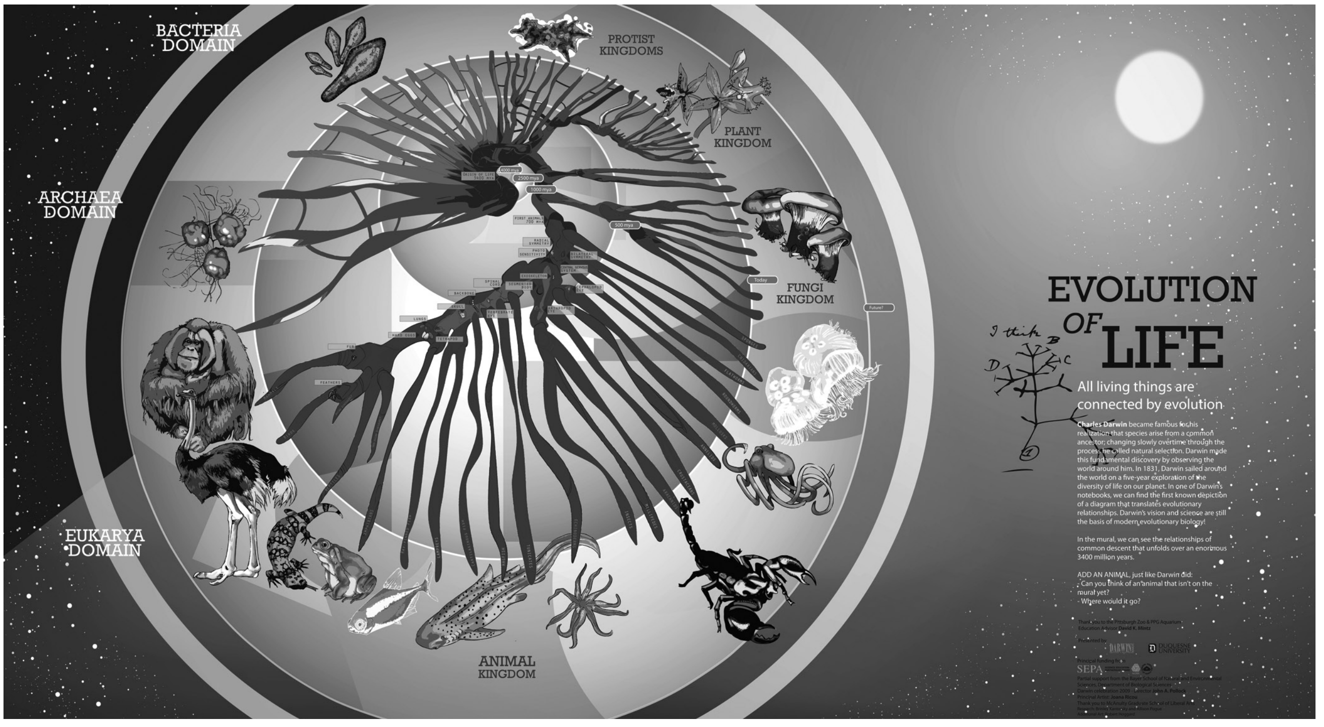


Fig. 6. *Spiral of Life diagram—linear time*, digital art, 2010. This diagram's linear timescale shows how multicellular life (black branches) emerged significantly later than unicellular life (grey branches), around 1 billion years ago. Major evolutionary events for multicellular organisms have occurred, then, from 1 bya to today (range indicated by shaded ring). (© Joana Ricou and John Pollock)

Fig. 7. *Spiral of Life II: Plant and Animal Co-Evolution*, digital art on canvas, 30 × 40 in, 2009. This piece was installed at Phipps Conservatory & Botanical Gardens and identifies major steps in the evolution of plants and their co-evolution with vertebrates and arthropods. In this piece, and in *Spirals I and III*, we made use of perspective to distort the spiral shape and focus on the most relevant set of branches. In this case, we focus on the plant branches and show key evolutionary milestones such as the appearance of vessels, seeds and flowers. (© Joana Ricou and John Pollock)



up and down as needed to clarify events that happened close in time but in a specific order.

It is also accepted that within and between the bacteria and archaea domains HGT continues to be a ubiquitous evolutionary process [28,29], which is likely common across most unicellular life. Adding an artistic interpretation of HGT to the unicellular branches of the spiral created solid concentric lines interspersed across half the spiral, suggesting that the pattern of evolution is a combination of vertical and horizontal processes (Fig. 5). With this addition, the *Spiral* becomes a "partial web" that includes vertical and horizontal processes, as the horizontal processes are only in the unicellular branches.

Diversity

As Lynn Margulis put it, "[for] most people today, life is readily divided into three categories: plants . . . animals . . . and germs (to be vanquished)" [30]. We wanted the *Spiral* to give a broader view of the variety of organisms on our planet, in particular to address the microscopic majority of the biosphere. The *Spiral* shows the top-level organization of life as the three domains Archaea, Bacteria and Eukarya. However, to depict intra-domain diversity accurately, the *Spiral* should have many more branches for Bacteria than the other two domains combined. Since Eukarya includes animals, plants and fungi, which are organisms our audience would more easily recognize, we chose to show each domain at different levels of detail. Bacteria is represented with a subselection of its kingdoms, while Eukarya is represented down to the deeper level of phylum. Thus, multicellular life is represented at a higher level of detail (and appears to have relatively more branches) than unicellular life. Working with the visual and semantic contents of the branches highlighted for us the utility but also the limitations of the taxa. Taxonomy is a classification system based on evolutionary relationships and, as such, is equally in flux. So, in the *Spiral* series, we decided to obfuscate lower taxa distinctions in order to clearly identify meaningful groups.

Returning to the web visualization, we noted that horizontal transmission of genetic material in multicellular life is considered the exception, as opposed to its prevalence in unicellular life. Multicellular life is part of Eukarya and so should appear to constitute close to 10% of the biosphere and not the apparent 50% that we depict. In this way we realize that a net-like pattern is the rule, not the exception. Emerging research in hybridization [31], the role of viruses [32] and transposons [33,34], or the particular case of documented HGT between bacteria and fungi [35], or hybridization in human evolution [36] supports this line of investigation, suggesting that the spiral (or radial) shape is likely a first step towards the understanding of the evolution of life as a web (Fig. 5). With this addition, we postulate that, in the future, evolution will be modeled as a web (not a partial web).

Common Root and Branches

The existence of a Last Universal Common Ancestor was predicted by Darwin

Fig. 8. *Spiral of Life III*, detail. Evolutionary milestones in the evolution of animals were explicitly labeled and illustrated. (© Joana Ricou and John Pollock)

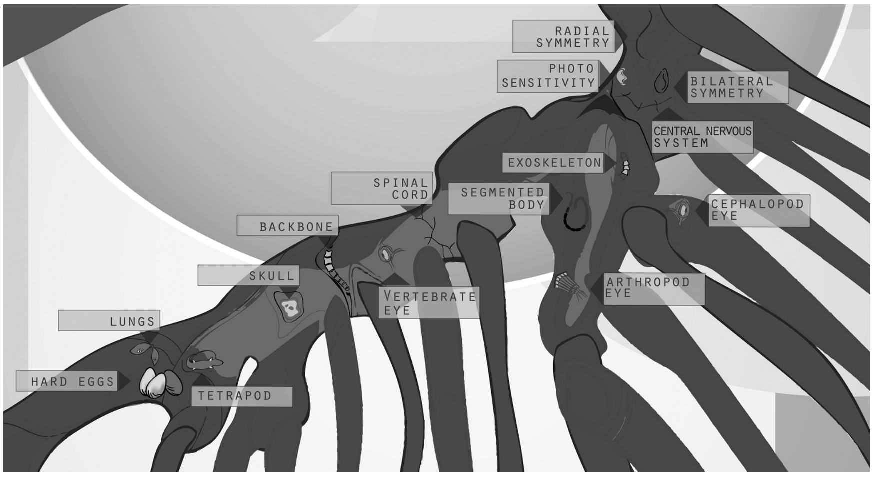


Fig. 9. *Spiral of Life V: Bird Evolution*, digital art on cintra, 6 × 5 ft, 2009, National Aviary, Pittsburgh PA. This piece contextualizes the evolution of modern birds. The main spiral is depicted in the lower center and the "dinosaur" branch is exploded to show the demise of the dinosaurs and the relatively recent evolution of birds and their diversification. (© Joana Ricou and John Pollock)

Fig. 10. ***Spiral of Life VI*****, approximately 8 ft diameter, soft sculpture, 2010, Children's Museum of Pittsburgh. Joana Ricou performs the *Story of Evolution*, reading the sculpture like a book with children, exploring the vertical and horizontal processes as physical structures. The soft sculpture doubled as a storytelling stage and a tactile playground. (© Joana Ricou and John Pollock. Photo © Josh Gates.)**

and supported by several investigations, including a recent 2010 *Nature* study [37]. Thus, the origin of life is represented as a single point or single line in many diagrams. In the *Spiral*, however, we chose to represent the origin as a large and knotted root (Fig. 4) to suggest the origin of life to be a tumultuous jumble of building blocks and not a single entity (as the term Last Universal Common Ancestor would imply)—arriving at an image similar to Fig. 3. This depiction implies the possibility that the origin of the three domains may be more primitive or more varied than previously thought [38], reinforcing the possible role of other genetic elements such as plasmids and viruses [39,40], and the likelihood that horizontal processes may have been the primary mechanism for evolution at this early stage [41].

The branches of a traditional diagram are also simple lines, but in the *Spiral* the branches were drawn as organic shapes to suggest that within a population each lineage waxes and wanes, and evolution does not imply increasing numbers or complexity (Color Plate A).

Collapsing Time

The distribution of taxa represented in the *Spiral* is biased toward multicellular organisms, as mentioned above. Multicellular life emerged around 1 billion years ago (bya), which is significantly later than unicellular life (see Fig. 6). To allow the image to show more detail in the evolution of multicellular life, we collapsed the timeline with a combination of both non-linear and linear representations along the radius. A logarithmic scale is used between 4 billion and 900 million years ago, and a linear scale is used between 900 million years ago to today. The multiplicity of installations of the *Spiral* series at different venues allowed us to counterbalance these compromises by making different decisions at each host institution.

The Series

We created a series of six pieces based on the *Spiral* symbol, each to inhabit a different cultural institution in Pittsburgh (Article Frontispiece and Figs 7–10) [42]. We wanted the *Spiral* to become a recurrent theme that capitalized on the strengths of distinct cultural institutions. The identity, mission and audience of each host influenced the individual pieces. Thus each gained a unique style and story. By complementing the content of each collection and the educational and experiential goals of each museum, we created a significant point of access and communication between the science of evolution and the public perception. Patrons who visit more than one cultural institution begin to recognize the common elements of the *Spiral of Life* and therefore build a stronger understanding and acceptance of the science that is revealed with these images.

This objective of creating a core symbol that is explored by a series of interpretative pieces led us to create an image that is significantly richer in information than any of its instances yet is flexible enough for visitors to see it from different points of view and at different levels of detail. This process also kept the work scientifically honest, a particular concern in creating work that intends to teach and that we hope may contribute not just to the appreciation of art but also to the understanding of science. These are goals that we feel resonate with the challenges articulated by C.P. Snow over 50 years ago.

The development of the *Spiral* allowed us to reveal evolution as a pattern of vertical and horizontal processes, but much room remains for continued exploration in the re-conceptualization of the 21st-century understanding of evolution. Future work will include the rhythms of evolution: punctuated equilibrium, the role of viruses, the redefinition of sexual reproduction in evolution and much more.

Acknowledgments

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Glossary

cladogram—a diagram used to show ancestral relations between organisms.

evolution—the principle that organisms change over time due to natural selection.

horizontal processes, horizontal gene transfer—processes where different species of the same generation pass genetic information to one another. Horizontal gene transfer (HGT) refers specifically to transfers of genetic material. Bacterial conjugation is a horizontal process, where a bacterium can pass a copy of an extra-chromosomal plasmid to another bacterium. Endosymbiosis is the process where two organisms fuse and give rise to a new kind of organism.

vertical processes—mechanisms that allow an individual organism or population to pass on genetic information to the next generation. Reproduction is a vertical process.

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Joana Ricou is an artist who explores contentious and/or complex biological concepts in a variety of 2D media, from oil painting to animation, videogames and the Web <www.joanaricou.com>. Ricou is Art Director for the Partnership in Education. Ricou has a Bachelor's in Science and Arts from Carnegie Mellon University and a Master's in Multimedia Arts from Duquesne University.

John Pollock, Ph.D. (biophysics), is an Associate Professor of Biological Sciences at Duquesne University with primary research in the molecular biology of the developing nervous system <www.duq.edu/science/faculty/pollock.cfm>. He is also the Director of Partnership in Education, which uses art and multimedia to reveal fundamental principals of science <www.sepa.duq.edu>. Principal support comes from a Science Education Partnership Award and a Darwin Evolution/Revolution Award, both from the National Center for Research Resources (NIH).