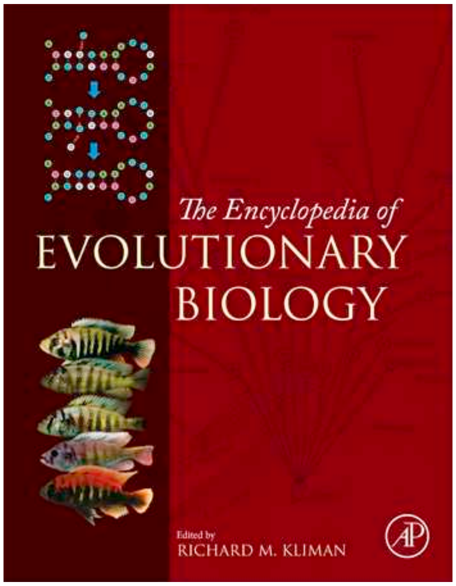

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Symbiogenesis, History of

N Gontier, University of Lisbon, Lisbon, Portugal

Glossary

Archaea Oldest Domain of Life, previously designated as Archaebacteria.

Bacteria Second Domain of Life, previously designated as Eubacteria.

Domains of life/ three-domain classification Based upon results obtained from comparative molecular phylogenetics, Woese *et al.* (1990) undid the prokaryote/eukaryote and five-kingdom classification and instead distinguished three major domains of life: Archaea, Bacteria, and Eukaryota.

Eukaryota/Eukaryotes Third domain of life, containing the Protist, Fungi, Plant and Animal Kingdoms. Eukaryotic cells have a membrane-bounded nucleus that contains the genome, and the cytoplasm often contains various cellular bodies called organelles.

Flagellum/Flagella Whip-like extensions of prokaryotic cells that enable motility. Contrary to eukaryotic undulipodia, flagella are made up of flagelin proteins.

Hereditary symbiosis Symbiotic association that becomes permanent and irreversible, foundational for symbiogenesis.

Horizontal transmission Any type of exchange between distinct individuals that happens during their lifetime and outside of the germ line.

Kingdoms of Life/ five-kingdom classification According to Whittaker and Margulis (1978), life can be classified into five kingdoms: Prokaryotic Monera (containing the Archaebacteria and Eubacteria), Eukaryotic Protoctista (Protists), Fungi, Plants, and Animals.

Lateral gene transfer Horizontal gene exchange between distinct organisms or distinct genomes within the same organism.

Metamorphosis Pre-evolutionary idea that living organisms can transform, or change in form. Transformation and metamorphosis are precursors to transmutation and evolutionary theory.

Microbiome The complete community of microorganisms that inhabit or live on the surface of an organism. The term is sometimes used to specifically refer to the genomes of the microbiota.

Microtubules Tubulin protein structures.

Prokaryotes All Archaea and Bacteria, typified by a free-floating instead of nucleated genome.

Defining Symbiogenesis

Symbiosis occurs when distinct organisms live in close association with one another, while symbiogenesis is both a phenomenon and an evolutionary mechanism (Merezhkowsky, 1905, 1910; Famintsyn, 1907; Kozo-Polyansky, 1924/2010) that results from permanent and hereditary symbiosis (von Faber, 1912; Buchner, 1921, 1939; Wallin, 1927; Lederberg, 1952; Sagan, 1967). Margulis and Dolan (2000, p. 157) define symbiogenesis as the "origin of a new organ, metabolic pathway, behavior, tissue, or other feature as a result of long-term hereditary symbiosis and includes the process by which organelles of the eukaryotic cell evolved from ancient bacterial symbionts."

Symbiogenesis today is well recognized to underlie the origin of mitochondria and chloroplasts. Both are cellular organelles (organ-like bodies), found exclusively in eukaryotic life forms (prokaryotes lack them, **Figure 1**), where they reside inside the cytoplasm of the cell (**Figure 2**). Mitochondria are present in aerobe protist, plant, and animal cells, while algal and plant cells also contain chloroplasts. These organelles once used to be free-living bacteria that, around 2 billion years ago, entered some of the first eukaryotic life forms through phagocytosis (eating or engulfment). The organisms engaged in symbiosis, this became permanent and hereditary, and the once free-living organisms evolved into the organelles (**Figure 3**). The bacterial lineages wherefrom mitochondria and chloroplasts evolved still exist as free-living bacteria today.

That mitochondria and chloroplasts evolved by symbiogenesis has for the most part of history been suggested based upon morphological comparisons between the organelles and bacteria, as well as the fact that these organelles contain their own DNA and have a double membrane, suggestive of bacterial engulfment (Ris and Plaut, 1962; Nass and Nass, 1963). Genetic comparisons between the organellar DNA and the DNA of bacterial lineages has now confirmed their bacterial origin. Chloroplasts evolved from cyanobacteria, and mitochondria evolved from proteobacteria (Bonen and Doolittle, 1975; Bonen and Doolittle, 1976; Bonen *et al.*, 1977; Gray and Doolittle, 1982). Molecular gene-sequencing techniques have furthermore shown instances of lateral gene transfer between the organelles and the nucleus, in both directions. After symbiogenetic acquisition, mitochondrial and chloroplast DNA underwent considerable gene loss (Archibald, 2014; Martin and Herrmann, 1998).

Eukaryotic cells often have many more organelles, and their evolutionary origin remains uncertain. A bacterial and symbiogenetic origin for the lysosomes has been suggested by its discoverer, the Belgian cytologist De Duve *et al.* (1974).

According to Margulis, the nucleated cell also evolved by means of symbiogenesis. As such, it was symbiogenesis that enabled both the evolutionary transition from prokaryotes to eukaryotes, and the subsequent evolution of the four eukaryotic kingdoms.

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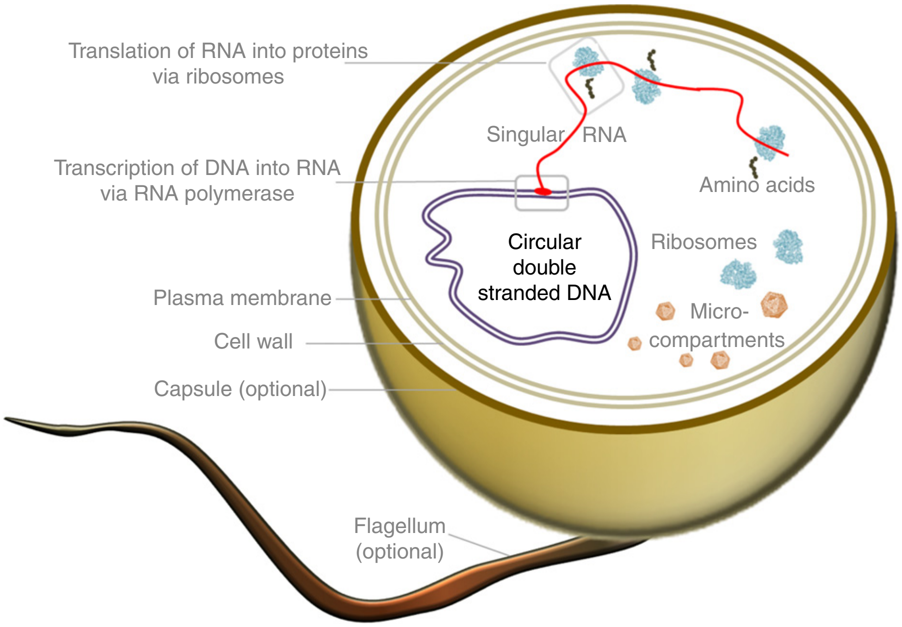

Figure 1 Schematic of a prokaryote. Prokaryotes neither have a membrane-bounded nucleus nor cellular organelles though they often contain micro-compartments that package enzymes and proteins.

From Hereditary Symbiosis to Symbiogenesis: The Origin of Mitochondria and Chloroplasts

Symbiosis research was often conducted in the margins of Darwinian evolutionary biology. Boveri (1904), for example, although a founder of chromosome theory, merely stated that Mendelian factors are transmitted via chromosomes. He also conjectured that the ‘protoplasm’ (cytoplasm) and chromosomes of the cell originated through symbiosis, an idea that was already introduced in 1893 by Shôsaburô Watasé (Sapp, 1994; Carrapiço, 2010, 2015).

Earlier in time, Schimper (1883, p. 112) suggested a single origin for “*Chlorophyllkörner*” (chlorophyll grains) and “*Farbkörper*” (pigment corpuscles) present in the plastids of plant and algal cells (“*plastiden,*” subdivided into colorless “*leukoplastiden,*” green “*chloroplastiden*” and yellow, orange and red “*chromoplastiden*”). He noted that they never arise *de novo* but develop from pre-existing ‘protoplasmic’ structures, and he thought they could divide and ‘metamorphose’ into one another. Because their protein structures (“*Proteïnkrystalle*”) resemble those of ‘living plasma’ (bacteria), Schimper (1885, p. 202) later conjectured that chloroplasts might have resulted from a symbiosis between a colorless and chlorophyll-containing organism.

Merezhkowsky (1905, 1910, 1920a) identified these chlorophyll-containing bacteria as cyanobacteria (“*cyanophyceae*”) and hypothesized that they underlie the evolution of all plant chromatophores (“*chromatophoren,*” pigment-containing cells). Most importantly, Merezhkowsky argued that chloroplasts were different from their bacterial ancestors because they had evolved into new structures by a process he dubbed Symbiogenesis.

For Merezhkowsky (1910, p. 280, my translation), symbiogenesis is an evolutionary mechanism that forms part of a larger theory he introduced on the ‘double’ origin of life:

> All assumed and still assume today, that one plasma underlies all organisms, in other words, that out of non-being, life came forth from one root, from where one tree of organisms developed, first as a common trunk of protists, and then the tree split into two main axes – the plant axis and the animal axis. Until now, there was the general conviction, that the tree of life was a single one. The task set forth in this work, is to demonstrate that there are two trees of life, and that each tree originated on its own and independently from the other one, and this probably happened in different periods of earth’s history. These trees partly developed on their own and independently from one another and partly stringed together and closely grew and developed together. Both trees are responsible for the diversity of organic beings. The idea of a unity of organic nature has to be abandoned in favor of the idea of nature’s duality. (Merezhkowsky, 1910, my translation)

Life evolved from two distinct organismal types, each consisting of different ‘protoplasms’ (“*plasma-arten*”), ″*Mykoplasma*″ (Mycoplasma) and ″*Amöboides Plasma*″ (amoeba-like plasma). Mykoplasma is anaerobe, autotrophic, rich in phosphor and nucleic acid (″*nuclein*″), and experiments demonstrated a heat tolerance of up to 90 °C and a high resistance to poisons. Amöboplasma is aerobe and heterotrophic, low in phosphor and nucleic acids, it can only bear temperatures up until 50 °C, and it is easily poisoned. Based upon these features, Merezhkowsky (1910, p. 281) argued that ″*Mykoplasma*″ originated first because such organisms were better able to survive in the early earth’s atmosphere and environment. Subsequently, and during different periods in time, these distinct life forms merged symbiogenetically. The first merger occurred between primitive bacteria and Monera and gave way to the evolution of amoebas. The second occurred when these amoebas merged with cyanobacteria (**Figure 4**).

Merezhkowsky thus pioneered in recognizing symbiogenesis’ crucial role in the origin of complex life forms, and his

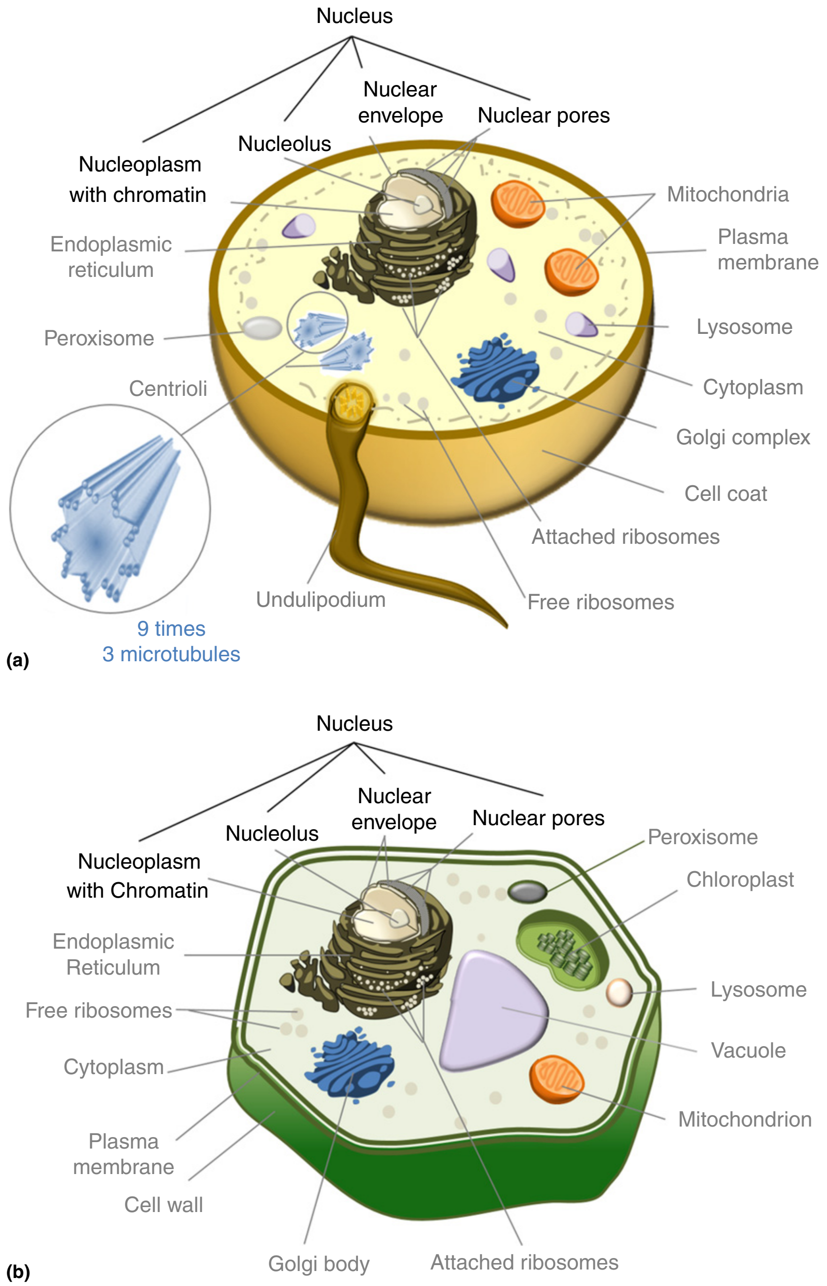

Figure 2 Schematic of an eukaryotic animal and plant cell. All eukaryotic cells have a membrane-bounded nucleus and many also possess numerous organelles.

double origin ideas made him recognize that a 'tree of life' needs to depict these symbiogenetic events.

Also Famintsyn (1907) and Kozo-Polyansky (1924/2010) developed ideas on symbiogenesis. Kozo-Polyansky understood evolution as the outcome of three phenomena: biotic potential or the ability to reproduce, symbiogenesis that generates variation and heritable novelty, and natural selection (Margulis, 1998, p. 1527).

The bacterial and symbiogenetic origin of mitochondria was first put forward by Kozo-Polyansky (1924/2010), Portier (1918) and Wallin (1923). Portier (1918) lived in France and when he suggested a symbiogenetic origin for mitochondria, he battled the successful Pasteur institute where bacteria became associated with disease (Sapp, 1994, 2003). In America, Wallin (1923) proposed that mitochondria evolved from oxygen-respiring bacteria, and he fought a similar battle against understanding bacteria merely as pathogens. For Wallin (1927), bacteria were the "building stones" or "primordial stuff from which all higher organisms have been constructed and modified," through *symbionticism*. Symbionticism is "the fundamental factor in the origin of species" because "microsymbiosis" can lead to new tissues and organs of such significance that they induce speciation.

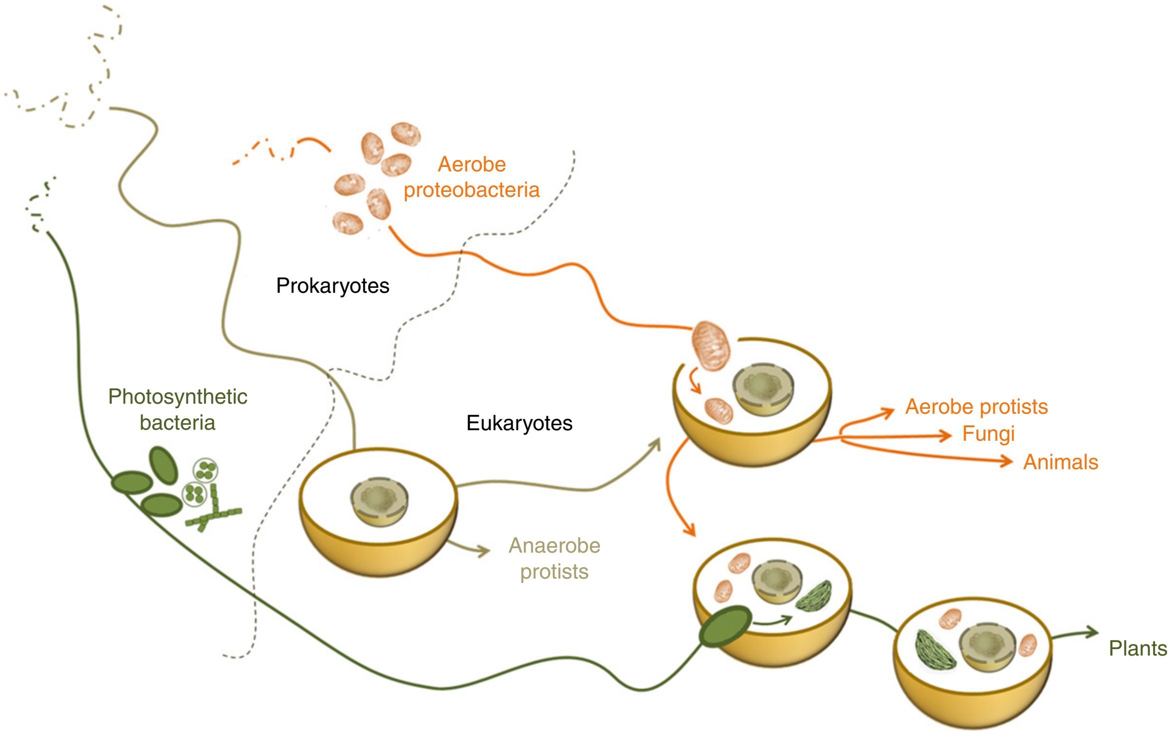

Figure 3 The origin of mitochondria and chloroplasts by symbiogenesis. Mitochondria evolved from aerobe proteobacteria, and chloroplasts from photosynthesizing cyanobacteria.

Earlier, von Faber (1912) had introduced the notion of "*erbliches Zusammenleben*," a concept Cowles (1915) translated as 'hereditary' and adopted by Buchner (1965). Also Wallin (1927) understood symbionticism as a 'hereditary mechanism.' Natural selection explained how species differentiate and evolve, but Darwin lacked clear theories on heredity and the origin of novel variation. For Wallin (1927, p. 121), symbionticism could complement Mendelian hereditary laws and theoretical genetics, because it introduces new genes and thus new hereditary variation: "on the basis of the new point of view that is associated with Symbionticism, we are forced to the conclusion that new genes must be acquired in organic evolution."

When Wallin suggested that mitochondria carry 'hereditary material' that can become part of the 'germ line,' 'genes' were still theoretical concepts presumably located on 'chromosomes.' Scholars that we now call adherents of 'cytoplasmic heredity' suggested that also the cytoplasm and the various organelles that house inside eukaryotic cells carry hereditary information.

One of them was Lederberg (1952), who in the 1940s reported on bacterial conjugation and transduction (**Figure 5**), two processes now characterized as mechanisms of horizontal gene transfer. For Lederberg (1952), however, both were instances of 'hereditary symbiosis' and 'infective heredity.'

Wallin and Lederberg's ideas that extrachromosomal, cytoplasmic structures such as plasmids or mitochondria carry hereditary material, and that these genes can become transferred to the nucleus were proven correct. Working at the Rockefeller Institute of Medical Sciences in New York, the Belgian cytoplasmic cell biologist Albert Claude, made the first electron-microscopy images of eukaryotic cells in 1945 (Palade, 1971). These enabled better visualizations of the cellular organelles and later, Ris and Plaut (1962) and Margrit and Silvan Nass (1963) respectively found DNA in chloroplasts and mitochondria, and linked it to symbiogenetic theories. Nonetheless, these ideas were overshadowed by the Modern Synthesis that advanced selectionist views of evolution. It was only through Margulis' work (Sagan, 1967) that data on symbiogenesis became widely recognized.

Lynn Margulis' Serial Endosymbiotic Theory

Our modern notions of symbiogenesis come from Lynn Margulis (Sagan, 1967), who from the 1960s onward, has introduced the Serial Endosymbiotic Theory (SET) (Sagan, 1967; Margulis, 1970, 1991, 1998; Margulis and Fester, 1991; Margulis and Dolan, 2001; Margulis and Sagan, 2002). Besides advancing a symbiogenetic origin for mitochondria and chloroplasts, according to SET also the eukaryotic nucleus evolved by symbiogenesis. In fact, according to Margulis, who endorsed a five-kingdom classification of life (Whittaker and Margulis, 1978; Margulis and Schwartz, 1997), all four eukaryotic kingdoms evolved as a result of three distinct symbiogenetic events (**Figure 6**).

SET gives the following chronological sequence of events (Margulis *et al.*, 2000; Margulis, 2010). In a first merger, fermenting thermoplasma-like archaebacteria (*Thermoplasma acidophilum)* merged with motile spirochete-like eubacteria, and evolved into the first anaerobe proto-eukaryotic cells (cells with a beginning nucleus). This first symbiosis is called motility symbiosis (**Figure 7**), because it presumably led to the

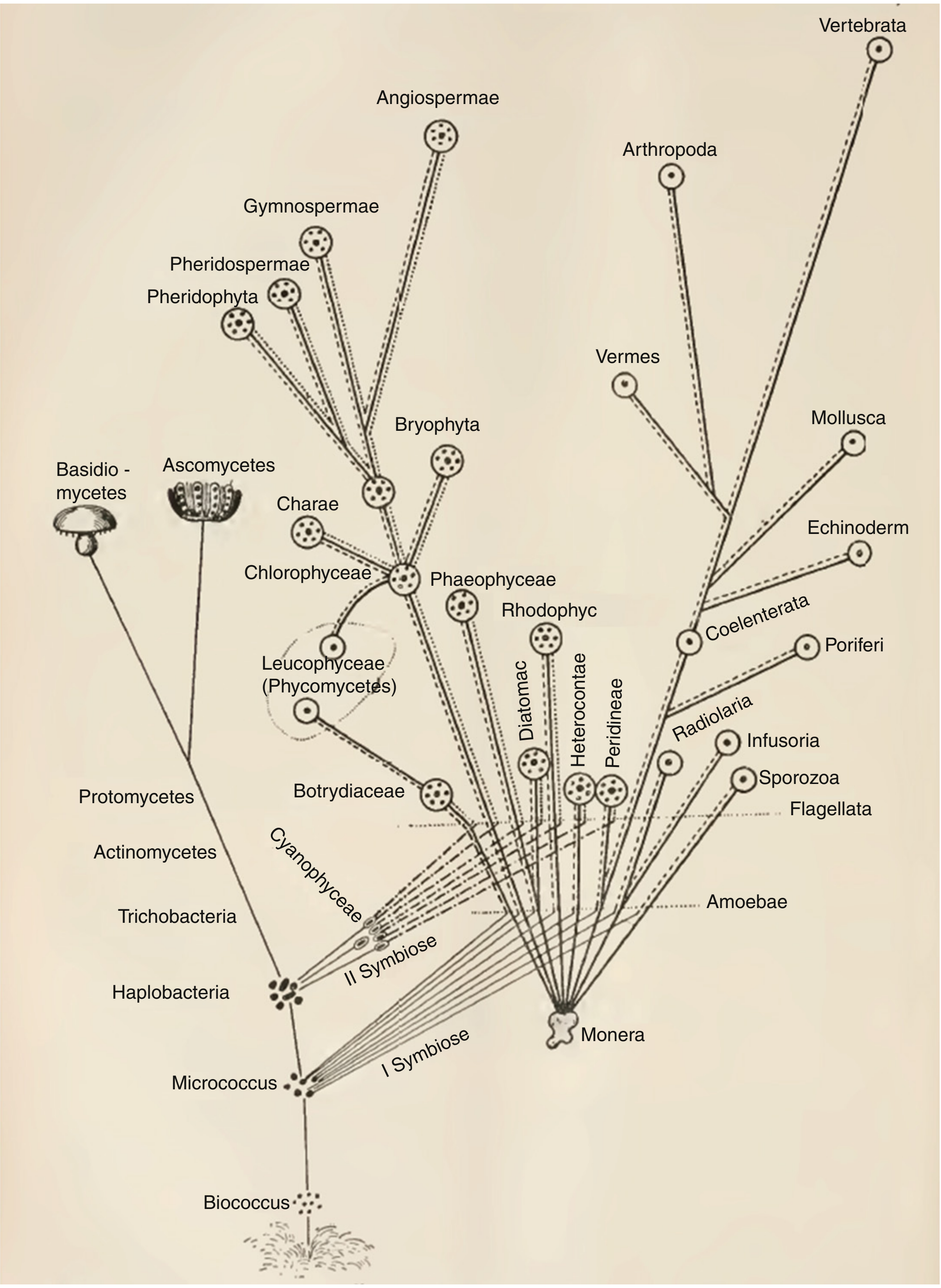

Figure 4 Merezhkowsky's polyphyletic tree of life (Merezhkowsky, 1910, p. 356). "*Mykoplasma*" is depicted by thin lines, "*Amöboplasma*" by thick lines, and the Cyanobacteria by interrupted lines. Mykoplasma evolved out of spontaneously generated biococci ("*Urbakterien*" or primitive bacteria), and this lineage evolved bacteria and fungi. Amöboplasma evolved out of spontaneously generated Monera. In a first symbiosis, Micrococcus on the Mykoplasma line merged with Monera resulting in the first Amoebae. A second symbiosis occurred between amoebae and Cyanobacteria (from the Mykoplasma line) resulting in flagellates. Consequently, he separated between three kingdoms: the kingdom of Mykoiden that never engaged in symbiosis (the thin line on the left); the animal kingdom resulting from a single symbiosis (the thick and interrupted lines); and the plant kingdom resulting from a second symbiosis event (thick, interrupted, and dotted lines). Leucophyceae were considered a side branch of plants.

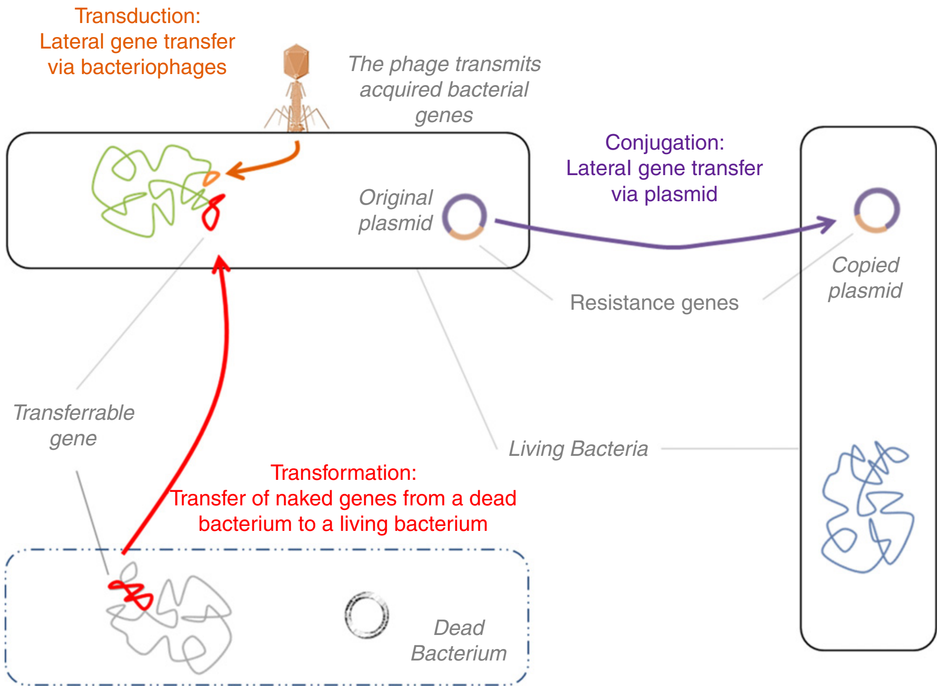

Figure 5 The three basic modes of lateral gene transfer amongst prokaryotes. In transduction, bacteriophages serve as vectors for the horizontal transmission of bacterial genes. In transformation, naked genes are picked up from their surroundings; and during bacterial conjugation, a single strand of a double-stranded plasmid (extrachromosomal DNA) is horizontally transferred from a donor to a recipient.

evolution of undulipodia and cilia (eukaryotic motility organelles that resemble tails and hairs) as well as centrioli (that form the centrosome which is the microtubule-organizing center that enables mitosis).

Evidence for motility symbiosis is found in the structure of undulipodia and centrioli. In cross section, centrioli are made up of microtubules organized according to a [9(3) + 0] pattern (Figure 2(a)). The same pattern is found in the cross section of the basal bodies (kinetosomes) of undulipodia and cilia (Figure 8). In their shaft (the axoneme), undulipodia and cilia have a [9(2) + 2] microtubular pattern. The structure of eukaryotic undulipodia is universal, and its morphological resemblance to the microtubular organization of centrioli makes Margulis assume that they share an evolutionary homologous origin, which she attributes to come from spirochete-like bacterial ancestors (Margulis *et al.*, 2000, 2006).

In a *second* merger, oxygen-respiring proteobacteria entered the cell's cytoplasm and engaged in permanent and hereditary symbiosis. The endosymbiotic bacteria evolved into mitochondria. Aerobic protoctists evolved, that, amongst others, includes amoebozoa and tailed (mastigote) cells, and from here all fungi and animals evolved.

In a *third* merger, early aerobic protoctists additionally engulfed photosynthesizing cyanobacteria that evolved into chloroplasts and gave way to the plant kingdom.

Wider Applications and Implementations of Symbiogenesis

Today, evidence is accumulating that endosymbiotic mergings occurred repeatedly. Sometimes the original merging bacteria as well as the organelles they evolved into were lost, and eukaryotes engulfed eukaryotes that already possessed organelles of bacterial origin. In this regard, scholars distinguish between primary, secondary, and tertiary endosymbiosis (Archibald, 2014; Raven, 1970; Stanier, 1974; Zook, 2015). In primary endosymbiosis, a prokaryote is engulfed by an eukaryote (a cyanobacterium enters a protist, leading to a photosynthetic eukaryote: a green algae). In secondary endosymbiosis, the product of primary endosymbiosis (the algae) is engulfed into another eukaryote where it wholly functions as an organelle (the transition from green to red algae); and in tertiary endosymbiosis, a eukaryote engulfs the product of secondary endosymbiosis (what happened when dinoflagellates evolved).

Nonetheless, an endosymbiotic origin for the eukaryotic nucleus remains debated. Some scholars assume that the outer membrane of prokaryotes merely folded inward thereby forming the membrane-bounded nucleus as well as the endoplasmic reticulum (Archibald, 2014). But these theories leave aside speculations on the origin of pro- and eukaryotic transcription and translation machineries that enable information to flow from DNA to RNA to proteins (Figure 1), as well as the origin of the eukaryotic chromosomes and mitosis.

Other scholars suggest that the eukaryotic nucleus evolved from viral symbiosis. For Livingstone Bell (2001), eukaryogenesis resulted from a symbiosis between a double-stranded DNA virus and a methanogenic Archaea. Villareal and Defilipps (2000) suggest that eukaryotic replication evolved from symbiogenetically acquired DNA viruses. The genes of these viruses and their host underwent hypercyclic organization and DNA compartmentalization into the complex eukaryotic chromosomes. Besides including virolution into the

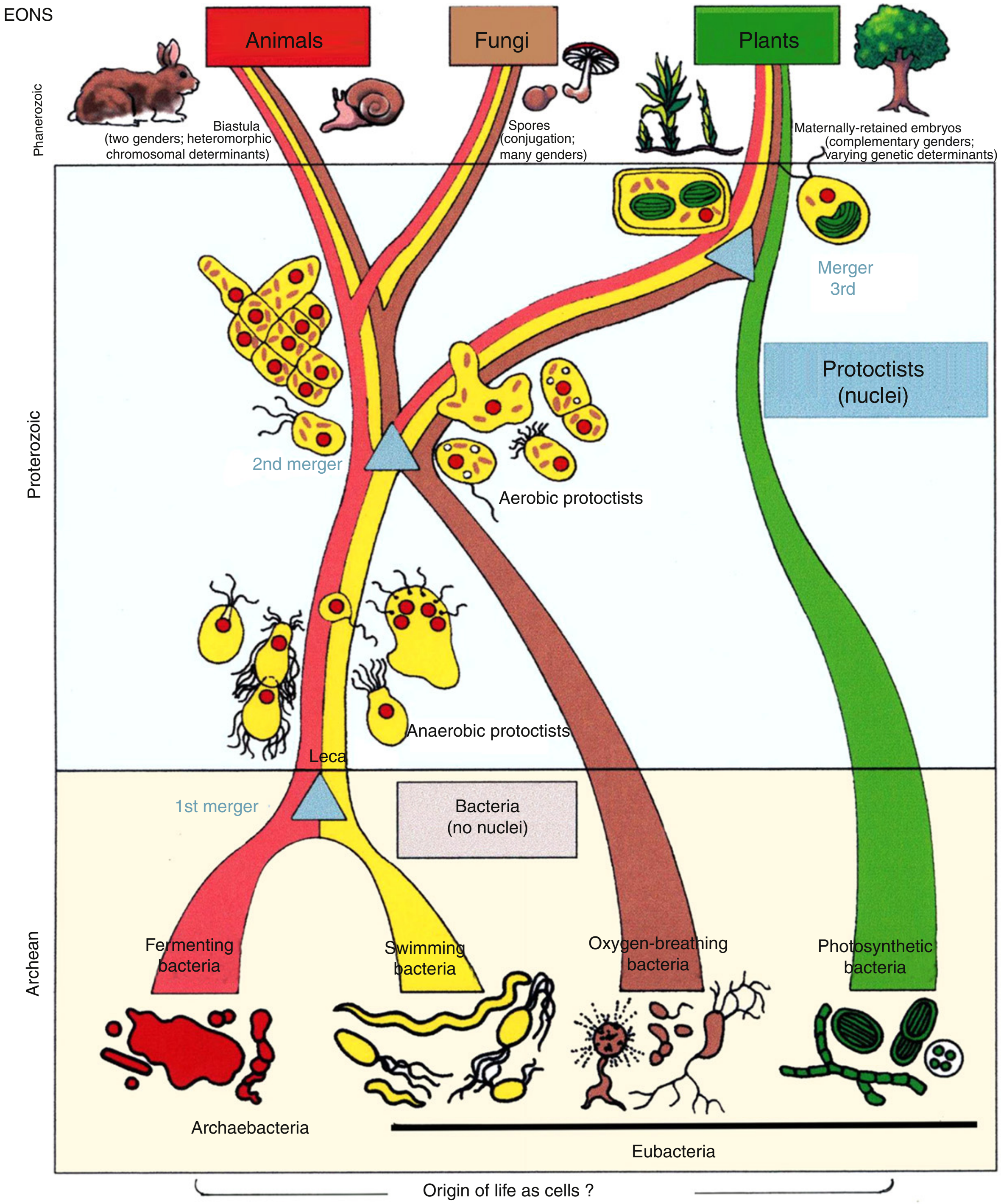

Figure 6 The origin of the four eukaryotic kingdoms according the Lynn Margulis' Serial Endosymbiogenetic Theory. The evolutionary transition from prokaryotes to eukaryotes happened because of symbiogenesis. Reprinted with permission and the courtesy of Ricardo Guerrero.

symbiogenetic framework, this research combines Eigen's (1996) theories on the origin of the genetic code with symbiogenesis theory, an idea already put forward in the 1980s by Dyson (1985).

Beyond eukaryogenesis, it is a fact that all eukaryotic life forms are prone to "viral colonization" (Villareal, 2000; Villarreal and Witzany, 2010, p. 699). Current microbiome and viriome projects are making scholars debunk the idea that viruses or microbial agents are mere pathogens or parasites. Rather, as mutual and commensal symbionts, these agents can introduce new genetic material that can become heredity and thus lead to symbiogenesis.

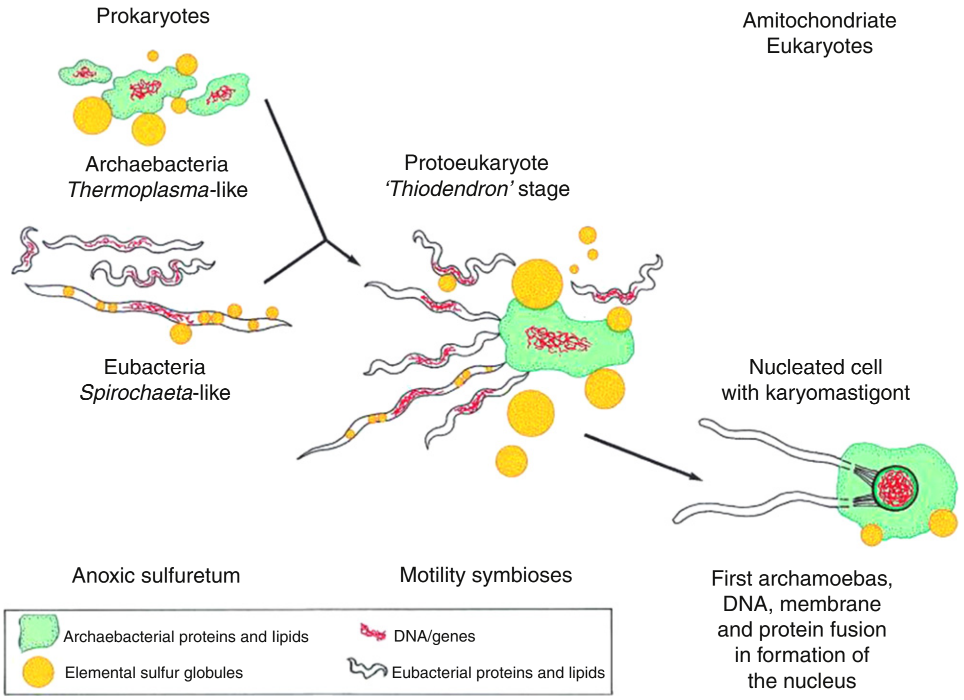

Figure 7 Schematic of motility symbiosis. The first symbiotic merger between spirochete and thermoplasma-like organisms enabled proto-eukaryotic cells to acquire intra- and extracellular motility. Intracellular motility is necessary for the compartmentalization of genes into protein-rich chromosomes as well as for mitosis, the process whereby these chromosomes are doubled and pulled apart during division. Reprinted from Margulis, L., Dolan, M.F., Guerrero, R., 2000. The chimeric eukaryote: Origin of the nucleus from the karyomastigont in amitochondriate protists. PNAS 97 (13), 6954–6959, with permission and courtesy of Ricardo Guerrero.

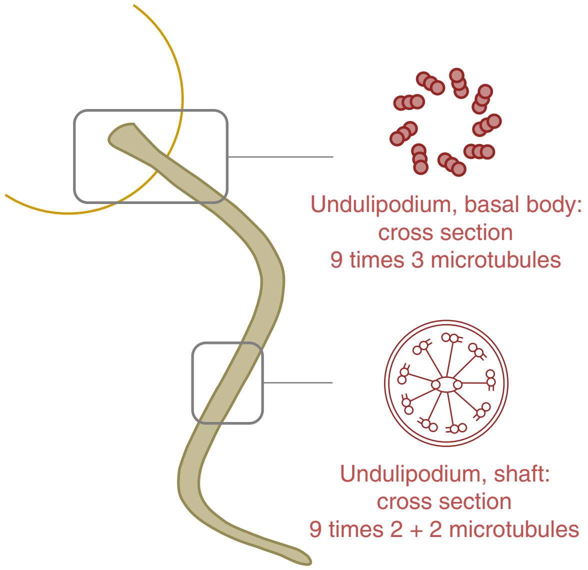

Figure 8 Cross section of a eukaryotic undulipodium. Its shaft has a 9 times 2 + 2 microtubular pattern while its basal body has a 9 times 3 microtubular pattern. The latter is identical to the icrotubular organization of centrioli, organelles that enable mitotic spindle formation (compare **Figure 2**).

Viruses mostly affect an organism's somatic cells during ontogeny. Upon infection, they either integrate into the host's DNA, or they use the host's metabolic apparatus to form new viruses, thereby destroying the cell upon release (Gontier, 2015a,b). Endogenous retroviruses (ERVs), however, are able to integrate into the germ line where they can influence phylogeny. Especially vertebrate genomes contain many remnants of ERVs, and ERVs in turn resemble mobile genetic elements (retrotransposons) that can become transferred laterally. This implies that ERVs "… have invaded the germ cell lines of every species of vertebrate. Here they replicate in Mendelian Fashion, as an integrated part of the sexual reproduction of the host, to inhabit the genome of all future generations" (Ryan, 2004, p. 560). Ryan (2002, 2004, 2009) considers such "… viral infection of host germ cells as a widespread but little-explored source of endosymbyotic creativity" (Ryan, 2006, p. 657), because the new symbiotic union can introduce new hereditary features.

Beyond influencing ontogeny and phylogeny, both symbiosis and symbiogenesis also impact evolution at the grand scale, by altering ecology from the environmental level all the way up to the biosphere. Winogradsky (1890, 1893) first discovered that the roots of legumes and the soil that surrounds these plants contain nitrogen-fixing bacteria. He later discovered the role these bacteria play in the earth's nitrogen-cycle. By launching 'microbial ecology' as a new research area, and by introducing the "*cycle of life*" concept (Ackert, 2007), Winogradsky helped bacterial research to transcend the medical disciplines.

Symbiogenesis also impacts the oxygen cycle. The Great Oxygenation Event marks the transition from an oxygen-low to an oxygen-rich atmosphere, estimated at 2.3 billion years ago. The transition was induced by photosynthesizing cyanobacteria that originated 200 million years earlier. The new oxygen-rich atmosphere severely threatened the older obligate anaerobe Archaea and Bacteria. Oxygenation in turn caused methane to decrease which initiated the Huronian glaciation (Margulis and Fester, 1991). This environmental crisis triggered the first major extinction event (the oxygen catastrophe) as well as the evolution of aerobe bacteria. It also underlies the rise of symbiogenesis as an adaptive environmental response because some of the newly evolved aerobe bacteria became integrated as endosymbionts to subsequently evolve into cellular organelles.

As early as the twentieth century, such ecological and systems theoretical approaches led Reinheimer (1913) to provide a "*bio-economic*" view of life, wherein he introduced the concept of a "*web of life*" (Carrapiço, 2015). And many symbiologists today continue to link their theories to the idea that earth or 'Gaia' is a living superorganism (Lovelock, 1972; Lovelock and Margulis, 1974; Volk, 1998).

Reception of Symbiosis and Symbiogenesis in the Modern and Extended Synthesis

Ideas on symbiology first associated with sociopolitical ideologies and pre-evolutionary thought. After the introduction of natural selection theory, symbiology associated with vitalism, ecology, systems and hierarchy theory, cytoplasmic inheritance research, the biomedical sciences, and insight into the mechanisms of lateral gene transfer (understood as a form of hereditary symbiosis). These fields formed part of the 'eclipse of Darwinism' and developed in the margins of the Modern Synthesis that focused on selectionist, vertical-descent theories. From the onset, symbiologists have

Figure 9 Pioneers in symbiogenesis research. From left to right and top to bottom: Andrey Sergeevich Famintsyn (1835–1918), Constantin Sergeevich Merezhkowsky (1855–1921), Andreas Franz Wilhelm Schimper (1856–1901), Paul Portier (1866–1962), Ivan Emmanuel Wallin (1883–1969), Paul Buchner (1886–1978), Boris Kozo-Polyansky (1890–1957), Joshua Lederberg (1925–2008), and Lynn Margulis (1938–2011).

in addition adhered to holistic, inter- and transdisciplinary stances, that counter the mechanical and reductionist approaches that characterized the division of the sciences at the turn of the twentieth century.

Its early associations with Western socialist thought (including Marxism) is not to be underestimated as a 'red flag' for neoliberal sociopolitical and Darwinian thought. In biology, symbiosis and symbiogenesis have often been typified as 'laws' of nature that either complement or contradict the 'laws' or 'mechanisms' of natural selection. Both presumed 'laws of nature' have been interpreted either in terms of struggle and competition, or cooperation and socialism, leading to both laws being understood as mutually exclusive. Nonetheless, by emphasizing cooperation and 'favoring' symbiosis over competition, symbiology too has, like competitive natural selection theory, been used to justify false believes on eugenetics, racism, hegemony, and national-socialism in order to obtain a 'higher good.' Early symbiologists and especially their critics often defined symbiosis in terms of parasitism, or as 'master–slave' relations (Sapp, 1994). Scholars such as Kropotkin, Reinheimer, Merezhkowsky, and Wallin understood symbiosis as a natural law necessary for progress, and especially Reinheimer and Merezhkowsky also saw symbiosis as a means for acquiring a 'higher good,' a 'better' and 'more cooperative' society that could be obtained by eugenetics. Merezhkowsky (1920b), for example, saw in symbiogenesis a justification for ethnic cleansing in order to develop a 'higher' society where mutualism would only arise amongst a select and chosen group (Sapp *et al.*, 2002).

Though both natural selection theory as well as theories on symbiosis and symbiogenesis find their historical roots in secular, Western sociocultural ideologies, both theories today are decoupled from such sociopolitical references. Nonetheless, the Serial Endosymbiogenetic Theory only became recognized post-synthetically, when molecular (phylo)genetics evidenced its basic morphologically obtained tenets.

Research on both symbiosis and symbiogenesis furthermore introduces new units and levels of evolution, including the *superorganism* (Spencer, 1876; Wheeler, 1928; Carrapiço, 2015), the *holobiont* (Margulis and Fester, 1991; Guerrero *et al.*, 2013), *symbiome* (Sapp, 2003), *symbiont* (Gontier, 2007), and *hologenome* (Rosenberg et al., 2007), as well as new means to draw evolutionary phylogenies (Brucker and Bordenstein, 2012), which today designates the rising field of *symbiomics* (after Sapp, 2003).

Currently, scholars associated with these disciplines are either pleading for an extension of the Modern Synthesis that incorporates the findings of symbiology with those of the Neo-Darwinian paradigm, while others are arguing for, or, a rupture with the latter in favor of a new evolutionary biology. The debates remain unsettled, but it is certain that increased genetic evidence for the symbiogenetic origin of life is causing for symbiosis and symbiogenesis to have finally received the scientific attention they deserve (Figure 9).

Acknowledgments

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See also: Complexity, the Role of Oxygen in Evolution of. Endogenous Retroviruses and Coevolution. Endosymbiotic Theory. Microbiome. Origin of Life, RNA World and. Origins of Life, History of. Plasmid Driven Evolution of Bacteria

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