Organellar Evolution

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Eukaryotic organelles supposedly evolved from their bacterial ancestors because of their benefits to host cells. However, organelles are quite often retained, even when the beneficial metabolic pathway is lost, due to something other than the original beneficial function. The organellar function essential for cell survival is, in the end, the result of organellar evolution, particularly losses of redundant metabolic pathways present in both the host and endosymbiont, followed by a gradual distribution of metabolic functions between the organelle and host.

organelle endosymbiosis plastid mitochondrion benefit

1. Introduction

A eukaryotic cell is typical by hosting semiautonomous organelles, such as mitochondria and plastids. These organelles are deeply integrated into the host cell; however, they usually keep some level of independence by encoding a fraction of the organellar proteome and RNAs in their genomes [1][2][3][4], living to some extent like endosymbiotic bacteria [5][6]. Mitochondria and plastids are, with few exceptions, essential for the host cell survival; once the cell has captured an organelle, it can hardly get rid of it [1][2][3][4][6][7]. It is believed that mitochondria and plastids evolved in endosymbiotic events, involving an engulfment or invasion of a free-living organellar ancestor, followed by the endosymbiotic transfer of genes from the captured entity to the nucleus of the host cell, with a consequent import of nuclear-encoded proteins into the organelle [3][8][9]. Symbiosis is an intimate, long-time relationship of two dissimilar organisms living together [10]. Although it is often understood as mutualism, the state beneficial for both partners, symbiosis, in fact, involves a continuum of relationships ranging from mutualism to parasitism [11]. The evolutionary history of plastids by domesticating a cyanobacterium is apparent because they are evolutionarily younger, and a cyanobacterial ancestor was likely acquired by the regular eukaryotic cell capable of phagocytosis [3][8][9].

2. The Plastid Benefit for the Host Is Photosynthesis

When talking about organelles, it is believed that benefits drive symbiotic relationships. However, it can be pretty challenging to trace the original benefit for which the endosymbiont is retained and integrated into the host cell. It is most likely that photosynthesis was the reason for adopting a cyanobacterial symbiont by a heterotrophic eukaryotic host (**Figure 1**) because there is no other way to get photosynthesis into the eukaryotic cell lacking it. Photosynthesis is managed by such complex molecular machinery that convergent evolution of the machinery appears highly improbable [6]. While the lateral gene transfer (LGT) likely stands behind the evolution of photosynthesis in prokaryotes [12][13][14], it played, except the endosymbiotic LGT, no role in the evolution of

photosynthesis in eukaryotes. Instead, the evolutionary history of eukaryotic phototrophs is full of endosymbiotic events involving prokaryotic (at least twice) or eukaryotic phototrophs (many times) as donors of photosynthetic ability. Consequently, compartmentalization always physically separates photosynthesis from the host cell in eukaryotes (**Figure 1**). Photosynthesis has been transmitted throughout the tree of life for the apparent reason of the acquisition of a photoautotrophic lifestyle. Although it was supposed for a long time that plastid endosymbiotic events are rare in evolution [15][16], it recently appeared that at least two and six independent events were likely responsible for the appearance of primary and complex plastids, respectively, not counting complex plastids replacements. In addition to the primary endosymbiotic Archaeplastida, a relatively recent event involving heterotrophic amoebae and a cyanobacterium was proposed for the rhizarian *Paulinella chromatophora*, again with the apparent benefit of photoautotrophy [17][18][19][20][21]. Complex plastids have likely been independently acquired in Euglenophyta, Chorarachniophyta, Alveolata, Stramenopila, Haptophyta, and Cryptophyta [22][23][24][25][26][27][28] (**Table 1**).

Table 1. Selected plastids and their characteristics in various eukaryotes. It demonstrates the reductive evolution of plastids in eukaryotes.

Organism	Supergroup	Type of the Plastid	Genes (Cds)	Genome	Reference
Arabidopsis thaliana	Archaeplastida	primary	85	circular	[29]
Porphiridium purpureum	Archaeplastida	primary	224	circular	[30]
Helicosporidium sp.	Archaeplastida	primary	26	circular	[31]
Polytomella sp.	Archaeplastida	primary	0	circular	[32]
Paulinella chromatohpora	Cercozoa (SAR)	primary (cyanelle)	867	circular	[33]
Euglena gracilis	Eugenophyta	complex (secondary)	67	circular	[34]
Euglena longa	Eugenophyta	complex (secondary)	46	circular	[35]
Heterocapsa triquetra	Dinophyta (SAR)	complex	14	Circular (minicircles)	[36]
Hematodinium sp.	Dinophyta (SAR)	-	-	-	[37]
Thalassiosira pseudonana	Bacillariophyta (SAR)	complex	141	circular	[38]
Chromera velia	Apicomonada (SAR)	complex	78	linear	[39]

Organism	Supergroup	Type of the Plastid	Genes (Cds)	Genome	Reference
Vitrella brassicaformis	Apicomonada (SAR)	complex	94	circular	[39]
Toxoplasma gondii	Sporozoa (SAR)	complex	29	circular	NCBI
Cryptosoridium muris	Sporozoa (SAR)	-	-	-	[40]

Photosynthesis as a beneficial function is, however, not essential for the host cell's survival. Many photoautotrophic lineages became secondarily heterotrophic (**Figure 1** and **Table 1**). Various eukaryotes have lost photosynthesis, being either forced by the lack of access to light or by chemical (e.g., antibiotic) disruption of the photosynthetic molecular machine [11][28][41][42][43][44][45][46][47]. For example, apicomplexan parasites (*Sporozoa*, *Apicomplexa*) likely became secondarily heterotrophic because of the easy availability of the organic carbon from the host or by the switch of the ancestral photoparasite from translucent to the opaque host [11]. Additionally, we have to consider that photosynthesis is not only beneficial for the primary producer, as it is quite costly and stands behind the outstanding production of reactive oxygen species (ROS), which can heavily damage the cell [42]. Additionally, a strictly phototrophic lifestyle forces the organisms to live in the access to light and thus limits their environmental distribution.

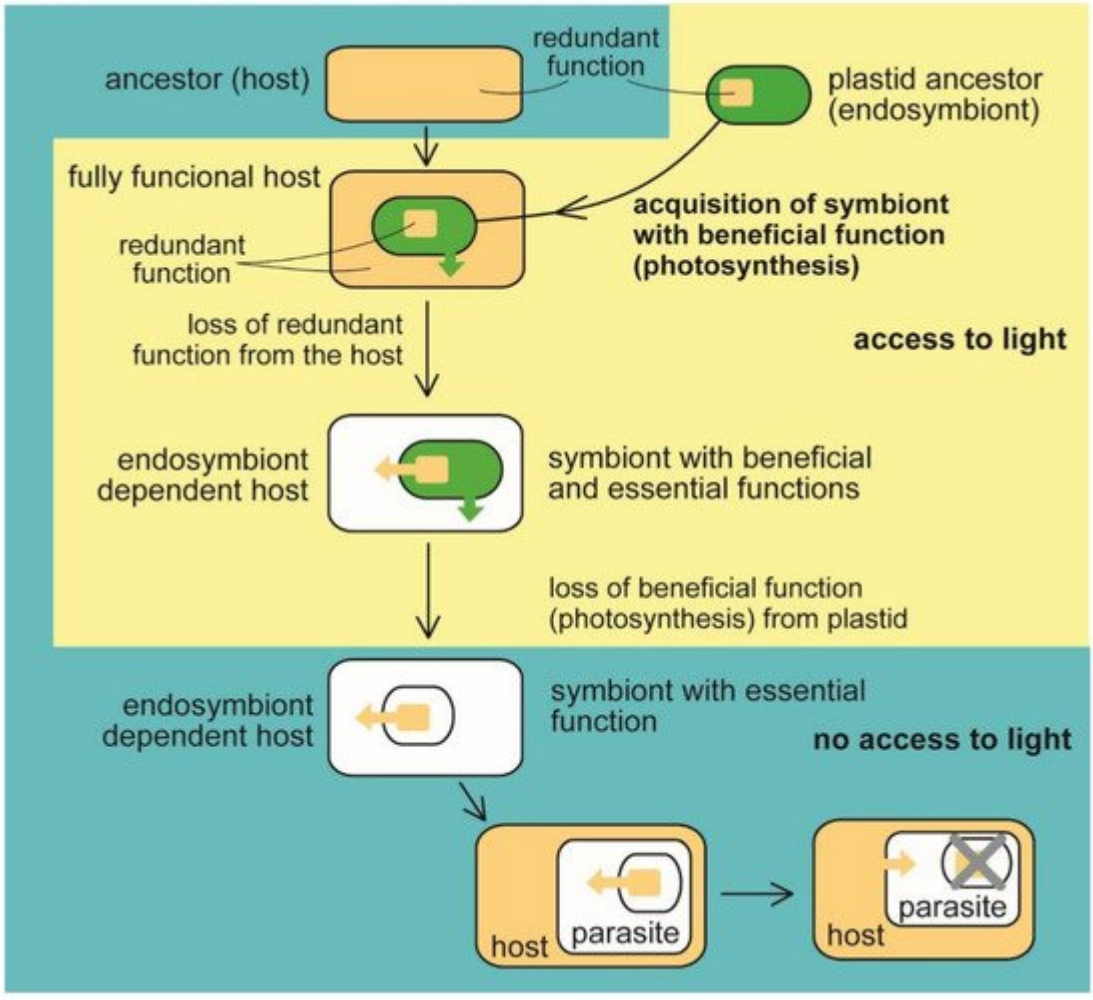

Figure 1. Evolution of benefit and essential function in the plastid. The heterotrophic host acquired a photosynthetic endosymbiotic bacterium with the function (photosynthesis) beneficial for the host. The host cell lost the redundant function (e.g., synthesis of heme, fatty acids, and isoprenoids). At the same time, the delegation of the syntheses to the endosymbiont makes it essential for host survival (eukaryotic phototrophs, e.g., Archaeplastida and *Paulinella* sp., and algae with complex plastids such as Ochrophyta, Cryptophyta, Haptophyta, Dinophyta, Apicomplexa, Euglenopyhta, Chlorarachniophyta [1][2][3][11]). The endosymbiont retained its indispensability for the host even when it had lost photosynthesis, the original beneficial function (in nonphotosynthetic algae, e.g., *Helicosporidium* sp., *Polytomella* sp., *Euglena longa*, apicomplexan parasites, for example, *Plasmodium falciparum*, *Toxoplasma gondii* [1][2][3][7][11] **Table 1**). Switching to parasitism and scavenging the essential compounds from the host allows the complete loss of the plastid (apicomplexan parasite *Cryptosporidium* [39], parasitic dinoflagellate *Hematodinium* [37]).

Therefore, many phototrophs are, in fact, mixotrophs, which can still live heterotrophically. Such organisms may be prone to losing photosynthesis when getting to the nutrient-rich environment or finding a successful heterotrophic strategy, such as predation or parasitism. Moreover, many protists combine the phototrophic and heterotrophic lives to overcome a reduced availability of various compounds present in host or prey but rare in their environment, such as, for example, nitrogen, phosphorus, iron, and sulfur [11]. Therefore, photosynthesis was frequently lost from green parasitic algae [28][41], euglenophytes [43], apicomplexan parasites [11][28][44][45][46][47], and dinoflagellates [45]. Various secondarily heterotrophic strategies, including parasitism, have evolved repeatedly during the evolution of life among former phototrophs [11][35][36]. It is worth noting that such trophic switches are often found in the same taxonomic groups, such as, for example, in myozozans, group of alveolate protists, consisting of dinoflagellates, apicomplexan parasites, and apicomonads (chromerids and colpodellids). Apicomplexans and dinoflagellates are also the only known algae shown to lose their plastids completely. The plastid is absent from the apicomplexan parasitic genus *Cryptosporidium* [39] and gregarines [48], and the parasitic dinoflagellates of the genus *Hematodinium* [37]. The plastid losses have happened exclusively in parasites thanks to their ability to scavenge the essential compounds originally produced by plastids from the host (**Table 2**).

Table 2. Examples of mitochondria and MROs and their characteristics in various eukaryotes. It demonstrates the reductive evolution of mitochondria, from mitochondrial organelles with large genomes to hydrogenosomes and mitosomes lacking genome and eukaryotic cells without mitochondrion.

Species	Taxonomy	Type of Mitochondrion	Genes (Cds)	Genome	Reference
Andalucia godoyi	Jakobida	Aerobic/OXPHOS	67	circular	[49]
Reclinomonas americana	Jakobida	Aerobic/OXPHOS	66	circular	[50]
Homo sapiens	Metazoa (Obazoa)	Aerobic/OXPHOS	13	circular	[51]
Nymphaea colorata	Archaeplastida	Aerobic/OXPHOS	42	circular	[52]

Species	Taxonomy	Type of Mitochondrion	Genes (Cds)	Genome	Reference
Nyctotherus ovalis	Ciliophora (SAR)	Anaerobic/H-producing	16	linear	[53]
Plasmodium falciparum	Sporozoa (SAR)	Aerobic/OXPHOS	3	linear	[54]
Chromera velia	Apicomonada (SAR)	Aerobic/OXPHOS	2	linear	[55]
Amebophrya ceratii	Dinophyta (SAR)	Aerobic/OXPHOS	0	-	[56]
Neocallimastix sp.	Chytridiomycota (Obazoa)	Hydrogenosome	-	-	[57]
Giardia intestinalis	Metamonada	Mitosome (Fe-S clusters)	-	-	[57]
Monocercomonoides sp.	Oxymonadida	-	-	-	[58]

3. A Beneficial Function of the Mitochondrion

In contrast with plastids, the hypothetical benefit responsible for acquiring mitochondria is the subject of speculation. Frankly speaking, it is not even clear if the mitochondrion was indispensable for forming an early eukaryotic cell [59] or when it was acquired in the course of evolution (early versus late acquisition). The discovery of the eukaryote lacking a mitochondrion proved that the organelle is not essential for the eukaryotic cell as it exists now when the organism is a secondary anaerobic (**Figure 2**) [58]. Generally, mitochondria are great examples of reductive evolution. The diversity of this organelle involves mitochondria with large circular genomes (e.g., in jakobids [49][50][60]), mitochondria with highly reduced genomes (e.g., those in apicomplexans; [61]), mitochondria-related organelles (MRO), e.g., mitosomes and hydrogenosomes without genomes [57], and, in the end, completely lost mitochondrion (in oxymonads; **Table 2** [58]). Consequently, various such organelles possess diverse molecular machinery: the complete respiratory chain of aerobic mitochondria or variously reduced respiratory chains lacking particular complexes: complex I (myzozans, e.g., apicomplexan parasites, and some fungi), complexes III and IV, while complexes I, II, and V retained [62], complexes I and III in chromerids [55][61] and the dinoflagellates of the genus *Amoebophrya* [56]), or complexes III, IV, and ATP synthase in (some) hydrogenosomes [57]. The missing complexes are substituted by alternative sources of electrons (e.g., alternative NADH dehydrogenases, L- and D-lactate cytochrome *c* oxidoreductases), or the electron transport chain was even completely lost (MRO).

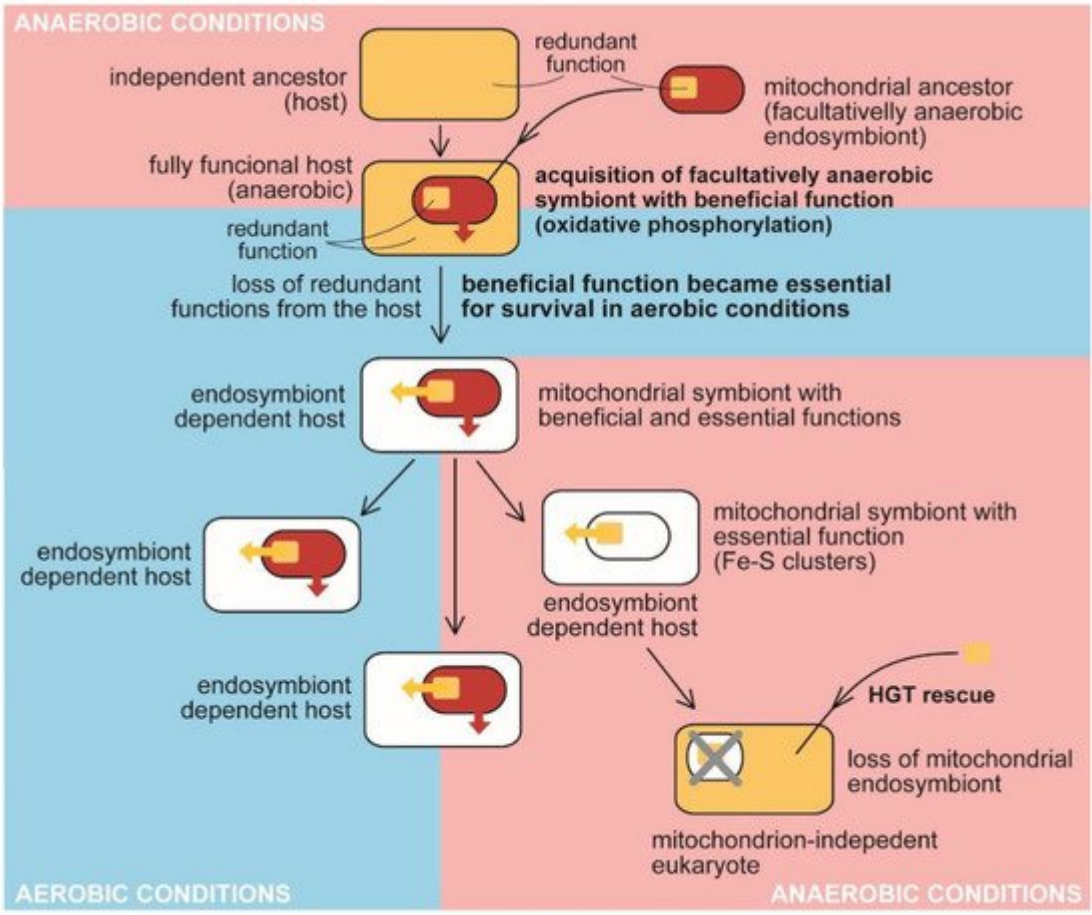

Figure 2. The traditional view on the evolution of benefit and essential function in the mitochondrion. Anaerobic host acquired a facultatively anaerobic endosymbiotic bacterium with the function beneficial for the host, presumably detoxifying oxygen. It became essential for the host in aerobic conditions. The redundant function was lost from the host (e.g., synthesis and assembly of Fe-S clusters). At the same time, the delegation of the synthesis to the endosymbiont makes it essential for host survival. The endosymbiont retained its indispensability for the host even when it had lost the original beneficial function by adaptating to anaerobic conditions. The acquisition of bacterial Fe-S clusters synthesis and assembly in the cytosol of oxymonads through HGT allowed the loss of the mitochondrion (MRO) [58].

Mitochondria host a wide range of metabolic functions, with oxidative phosphorylation being the most prominent (**Figure 2**), although it is found only in classical mitochondrial organelles, and lost from highly reduced MROs. In addition to that, mitochondria can be responsible for the metabolism of amino acids and nucleotides, steroid biosynthesis, heme synthesis, fatty acid catabolism, iron-cluster biogenesis, and many others [57][63][64][65][66]. Such metabolic complexity makes the search for the original beneficial function of the mitochondrion difficult. Various hypotheses have been formulated to explain the primary reason for acquiring a mitochondrion. It is further complicated by extensive genetic rearrangements of the organelle during organellogenesis because a substantial part of the mitochondrial proteome does not originate from the supposed mitochondrial ancestor [57].

The hydrogen hypothesis [67] proposed that the primary benefit of pre-mitochondrial symbiont was hydrogen production for the host, methanogenic Archaea. Some eukaryotes, such as *Acanthamoeba castellanii*

(*Amoebozoa*), *Brevimastigomonas motovehiculus* (Rhizaria), *Blastocystis* spp. (*Stramenopila*), *Nyctotherus ovalis* (*Alveolata*) still contain hydrogen-producing mitochondria with complete (*Acanthamoeba*) or reduced respiratory chains [57][62][68]. Others host hydrogenosomes, organelles believed to represent modified hydrogen-producing mitochondria [69][57], which have lost the ATP generating part of the respiratory chain and retain just complex I (NADH hydrogenase), or complex II (succinate dehydrogenase) or both [53]. Martin et al. [69] also claim that the mitochondrial ancestor was a facultatively anaerobic bacterium.

Another possible beneficial function of a pre-mitochondrion was proposed by Thomas Cavalier-Smith [70], who speculated that the ancestor of mitochondrion was a photosynthetic purple bacterium, and the primary benefit was photoautotrophy, similar to plastids. This hypothesis assumes that both symbiont and host were facultative aerobes and that the host already has oxidative phosphorylation. A phototrophic symbiont would have an immediate intracellular synergy between a photosynthetic symbiont fixing CO_2 and respiring and a phagotrophic host using oxygen and excreting CO_2 [70].

Other hypotheses suppose that the primary benefit of the mitochondrion is related to dealing with free oxygen in the environment, preferring aerobic heterotrophic respiring bacterium as a mitochondrial ancestor [57]. Oxygen appeared in higher levels during the Great Oxidation Event between 2.4 and 2.1 Bya (billion years ago) [71]. If we take into account the possibility of early acquisition of mitochondrion, the oldest estimates of its appearance touch 2.1 Bya (1655–2094 Mya), while the youngest move around 1 Bya (943–1102 Mya) [72]. One of the earliest views on mitochondrial evolution supposes that the mitochondrion-free anaerobic eukaryotic ancestor acquired aerobic mitochondrion to detoxify oxygen accumulated in the environment after the Great Oxidation Event [73][74]. This scenario would even fit the timing of appearance of eukaryotes between 1 and 2 Bya. However, geochemical data indicate relatively low oxygen levels during the diversification of eukaryotes [71][75]. Moreover, Zimorski et al. [75] argued that those are metabolic processes in the mitochondrion, particularly electron transport chain generating reactive oxygen species, which may harm the cell and must be detoxicated. Therefore, oxidative phosphorylation can hardly be the primary benefit, at least in light of the oxygen detoxification hypothesis. However, we cannot ignore the fact that there is no eukaryote without classical mitochondrion with oxidative phosphorylation known that can permanently live in the presence of oxygen. The use of enzymes that can react with free oxygen does not allow obligate anaerobes to inhabit an oxygen environment. When looking at strictly anaerobic bacteria, they rely on low-potential flavoproteins used for anaerobic respiration. Exposure to oxygen likely causes superoxide and hydrogen peroxide production. They inactivate enzymes with these functional groups through the oxidation of dehydratase iron-sulfur clusters and sulphydryls. However, anaerobes utilize several classes of dioxygen-sensitive enzymes absent from aerobes, which maintain the redox balance during anaerobic fermentation. Their reaction mechanisms require exposure of the solvent of radicals or low-potential metal clusters to the oxygen that can react with it. Additionally, hydroxyl radicals damaging DNA and other biomolecules are generated because hydrogen peroxide oxidizes free iron [76]. Analogously, we can expect that oxygen could not be tolerated by anaerobes involved as the host cell in the early eukaryotic endosymbiotic events. A mitochondrial ancestor could eventually invade the host cell as an energy parasite. The proposed intracellularly parasitic ancestor of the mitochondrion was predicted to bear the ATP/ADP translocase importing ATP from the host. In such a case, there was no beneficial

function behind a selection of an endosymbiont (parasite) in the event because the benefit was provided by the host cell [77].

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