Becoming-Phototroph

Ewen Chardronnet, Aliens in Green

In a recent short story by science fiction author Kim Stanley Robinson,[1] a glimpse of a very green future is offered: in a near future where the iGEM[2] Registry of Standard Biological Parts has significantly grown, synthetic biologists discover bio-bricks in the catalogue that may be combined to make synthetic chloroplast and thus create photosynthesizing human cells. Tattoo needles are modified in order to inject chloroplast-fibroblasts into human skin, in the manner of an ordinary tattoo. The biologists form a limited liability corporation called SunSkin, but soon they decide to become open source, as photosynthesis is, after all, a natural process.

"Once they published the recipe, and the knowledge spread that human photosynthesis worked, the injection method as such became what you might call generic. (…) when you photosynthesize sunlight you will be less hungry. You might also spend more of your day outdoors in the sun, that's right, and subsequently decide that you didn't need quite as much food or heating as before. Or clothing. Or housing, that's right. I don't see all these green naked people wandering around sleeping under tarps in the park like you seem to, but granted, there have been some changes in consumption. Did changes in consumption cause the Great Crash? No one can say. (…) What you call the Great Crash others call the Jubilee. It's been widely celebrated as such."

What could this Great Crash or Jubilee be? A crash of food production and consumption? Over-exploited agricultural lands reverting to natural ecosystems? Rates of starvation, malnutrition, and foodborne illness all of a sudden plummeting? Indeed, a global geological shift.

In 1925, geochemist Vladimir Vernadsky, the inventor of concepts such as the "biosphere" and "noosphere," was already speculating on what he would call "human autotrophy"—a "becoming-plant" of humankind—and its geological consequences:

"What would be the significance of the synthetic production of nutriments to human life and to the life of the biosphere?

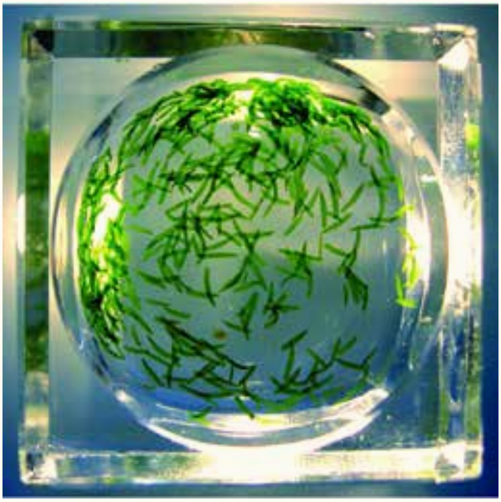
By its accomplishment man would free himself from living matter. From a social heterotrophic being, he would become an autotroph.

The repercussion of this phenomenon within the biosphere would be immense. It would signify the schism of the block of life, the creation of a third branch independent of living matter. By this feat there would appear on the terrestrial surface, and for the first time in the geological history of the globe, an autotrophic animal.

Today, it is difficult, perhaps impossible, for us to grasp the geological consequences of this event—but it is clear that it would be the culmination of a long paleontological evolution, which would represent, not an action of the free will of humanity, but the manifestation of a natural process.

By this achievement, human understanding would produce not only a great social effect, but a great geological phenomenon".

— Vladimir Vernadsky, *Human Autotrophy*, 1925



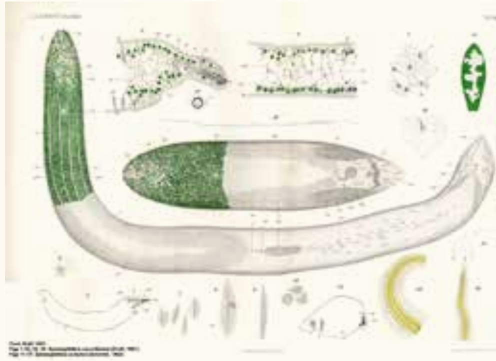
A colony of symbiotic worms Symsagittifera roscoffensis (Courtesy Station Biologique de Roscoff – CNRS-UPMC)

1 Kim Stanley Robinson, *Oral Argument*, retrieved Jan, 21, 2016 from http://www.tor.com/2015/12/07/oral-argument-kim-stanley-robinson/

2 The International Genetically Engineered Machine (iGEM) Competition Foundation organizes an annual student competition in Synthetic Biology.

Indeed, the capability of some marine animals to take advantage of photosynthesis by hosting symbiotic algae has been known since the late 19th century. This capacity, referred to as photosymbiosis, is based on structural and functional complexities that involve two distantly unrelated organisms "living together" with a mutual influence on one another's life processes. These stable, symbiotic associations between multicellular organisms and photosynthetic single-celled organisms play a fundamental role in marine ecology, as exemplified by reef communities and their vulnerability to global climate change.[3] An association between a host (multi- or uni- cellular) and its algae (referred to as a photosymbiont) exhibits a "domestication" of photosynthesis. This can result in nutritional independence as long as the partners are located in the "sunlight zone," the part of a body of water fully exposed to solar energy.[4]

For example, let us consider the tidal acoel flatworm, *Symsagittifera roscoffensis*, and its green algal photosymbiont, *Tetraselmis convolutae*. Together they form a composite photosymbiotic unit. Studies beginning in the late 19th century at the marine biological station of Roscoff (Brittany, France) by its director Yves Delage centered on the origin and the role of the enigmatic "green cells" inhabiting the body of *S. roscoffensis*. These were first thought to be chloroplasts, cells that conduct photosynthesis (Delage, 1886),[5] but these enigmatic, green, photosynthetic corpuscles (termed "zoochlorellae") were unambiguously ascribed to the algae a few years later, in the detailed studies conducted by Keebles and Gamble in 1905 and 1907.[6] These authors documented their original experiments and observations on the biology, ecology, and behavior of *S. roscoffensis* and the associated symbiosis with algae in a book entitled *Plant Animals, A Study in Symbiosis*, published in 1910.[7]



Anatomical representation of the symbiotic worm Symsagittifera roscoffensis (public domain, Graff, 1891)

From Symbiogenesis to Endosymbiosis

Alongside his directorial role at the marine biological station in Roscoff, Yves Delage was Professor of Zoology, Anatomy, and Comparative Physiology at the Sorbonne. His 1896 book with E. Hérouard, *Traité de Zoologie Concrète: la Cellule et les Protozoaires*[8] was one of the few protozoology texts of its time. Together with the anarchist neo-Lamarckian biologist, Marie Goldsmith, Delage edited the journal *L'Année Biologique*[9] which kept biologists abreast of recent contributions to the field. As one of the early neo-Lamarckians in France, Delage was always on the lookout for alternative theories to Darwin's evolution, maintaining a longstanding interest in symbiotic theories of the cell.

Towards the end of his life, Delage became interested in the work of Russian researchers exploring the symbiotic relationship between fungi and algae in lichens.[10] Biologist and botanist Konstantin Merezhkowsky had been proposing a theory of symbiogenesis – that larger, more complex cells evolved from the symbiotic relationship between less complex

3 Photosymbiosis represents around 50% of marine photosynthesis.

4 "The chimerical and multifaceted marine acoel Symsagittifera roscoffensis: from photosymbiosis to brain regeneration", Xavier Bailly *et al.*, *Frontiers in microbiology*, Volume 5 | Article 498, 2014

5 «Études histologiques sur les planaires rhabdocoeles acoeles». *Arch. Zool. Exp. Gén. II* 4, 109–160.

6 F. Keebles and F .W. Gamble, "On the isolation of the infecting organism ("Zoochlorella") of *Convoluta roscoffensis*". *Proc. R. Soc. Lond. B* 77 (1905) : 66–68. doi: 10.1098/rspb.1905.0059 ; F. Keebles and F .W. Gamble, "The origin and nature of the green cells of *Convoluta roscoffensis*". *Q. J. Microsc. Sci.* 51 (1907): 167–217.

7 F. Keebles, *Plant Animals, A Study in Symbiosis* (Cambridge: University Press, 1910).

8 Yves Delage, Edgard J. E. Hérouard, *Traité de Zoologie Concrète: La Cellule Et Les Protozoaires* (Nabu Press, 2010).

9 http://gallica.bnf.fr/ark:/12148/cb32694956m/date

10 As shown by Heinrich Anton de Bary in *Die Erscheinung der Symbiose* (Strasbourg, 1879)

ones. He presented this theory in 1910[11] where he argued that plants' predecessors co-opted chloroplasts—which were once free-living bacteria—and these, over a long period of time, evolved to become part of the basic cell structure of plants.

After WWI, the Russian botanist Boris Kozo-Polyansky was the first to explain symbiogenesis in terms of Darwinian evolution. In his 1924 book *Symbiogenesis: A New Principle of Evolution*[12] he wrote: "the theory of symbiogenesis is a theory of selection relying on the phenomenon of symbiosis". These theories were first dismissed and long ignored, re-emerging almost a half century later to be popularized in the work of zoologist and geneticist Lynn Margulis—co-author with James Lovelock of the Gaia hypothesis in 1973—and her concept of endosymbiosis, a generalization of symbiogenesis theory to a planetary scale. Though she recognized Darwin's contribution to biology, Margulis strongly argued against neo-Darwinism. She explained that certain interpretations of neo-Darwinism were excessively focused on inter-organismic competition. She opposed competition-oriented views of evolution, stressing the importance of symbiotic or cooperative relationships between species.

In her research, Lynn Margulis become interested in *S. Roscoffensis* and its symbiotic algae, an example central to her book *Symbiotic Planet: A New Look at Evolution*, published in 1998. Together with her son Dorion Sagan, Margulis wrote the essay "The Transhumans Are Coming,"[13] where *S. Roscoffensis* inspires a speculative "Homo Photosyntheticus" who will conquer the stars, a symbiotic future for mankind ensuring his survival on other planets:

11 Konstantin Mereschkowsky, *"Theorie der zwei Plasmaarten als Grundlage der Symbiogenesis, einer neuen Lehre von der Entstehung der Organismen.", "The Theory of Two Plasms as the Basis of Symbiogenesis: A New Study on the Origins of Organisms"*. Biol Centralbl 30 (1910): 353-367.

12 Boris Mikhaylovich Kozo-Polyansky, ed. Lynn Margulis, *Symbiogenesis, A New Priniciple of Evolution*, (Harvard University Press, 1st edition, 2010)

13 Lynn Margulis, Dorion Sagan, *Dazzle Gradually: Reflections on the Nature of Nature* (Chelsea Green Publishing, reprint edition, 2007), 99.

Culture of micro-algae at Roscoff Marine Station
(Courtesy CRBM - Station Biologique de Roscoff – CNRS-UPMC)

"This could happen to our Homo Photosyntheticus, a sort of ultimate vegetarian who no longer eats but lives on internally produced food from his scalp algae. Our Homo Photosyntheticus descendants might, with time, tend to lose their mouths, becoming translucent, slothish, and sedentary. Symbiotic algae of Homo Photosyntheticus might eventually find their way to the human germ cells. They would first invade testes and from there enter sperm cells as they are made. (This is hardly outrageous: insect bacterial symbionts are known to do exactly this. Some enter sperm, and some are transmitted to the next generation via eggs.) Accompanying the sperm during mating, and maybe even entering women's eggs, the algae—like a benevolent venereal disease—could ensure their survival in the warm, moist tissues of humans.

In the final stage of this eerie scenario, we envision groups of Homo Photosyntheticus lounging in dense masses upon the orbiting beaches of the future, idly fingering green seaweeds and broken mollusk shells."

Animal-plants today

Since then, there have been many studies in marine biology on unique photosymbiotic units. Last year, new aspects of this phenomenon emerged at the Woods Hole Marine Biology Laboratory[14] in Massachusetts while studying the emerald green sea slug *Elysia chlorotica*, a "solar-powered sea slug" that utilizes solar energy via chloroplasts from its

14 JA Schwartz, NE Curtis, and SK Pierce, "Fish labeling reveals a horizontally transferred algal (Vaucheria litorea) nuclear gene on a sea slug (Elysia chlorotica) chromosome". *Biol. Bull.* 227 (2014): 300-312.

algal food. It lives in a sub-cellular endosymbiotic relationship with chloroplasts of the alga *Vaucheria litorea*. The researchers used advanced imaging techniques to confirm that a gene from the alga *Vaucheria litorea* is in the *Elysia chlorotica*'s DNA. This gene makes an enzyme that is critical to the function of the chloroplasts, cell structures typically found only in plants and algae.

It has been known since the 1970s that *Elysia chloritica* "steals" chloroplasts from *Vaucheria litorea*, embedding them into its own digestive cells. This process is referred to as "kleptoplasty." Once inside the slug, the chloroplasts continue to photosynthesize for up to nine months—much longer than they would in the alga. The photosynthesis process produces carbohydrates and lipids, which nourish the slug.

The 'sun-powered' sea slug Elysia chlorotica
(Courtesy National Science Foundation)

How the slug manages to maintain these photosynthesizing organelles for so long has been the topic of intensive study and a good deal of controversy. The Woods Hole scientists confirmed that one of several algal genes needed to repair damage to chloroplasts and keep them functioning is present in the slug's DNA. The gene is incorporated into the slug's genetic information and transmitted to the next generation. Though the slug's descendants must take up new chloroplasts from algae, the genes to maintain the chloroplasts are already present within the slug's genome.

There is no reason why genes from an alga should work inside an animal cell. And yet here they do. They allow the animal to rely on sunshine for its nutrition. So if something happens to their food source, they have a way of not starving to death until they find more algae to eat.

This biological adaptation is also a mechanism of rapid evolution. When a successful transfer of genes between species occurs, evolution can basically happen from one generation to the next, rather than over an evolutionary timescale of thousands of years.

Microbiologists at the Marine Biology Station in Roscoff have also been studying the possible occurrence of lateral gene transfer from the symbiont to the host in the *S. roscoffensis* worm. Although the exchange of genetic material between multi-cellular organisms and symbionts is thought to be very rare, the symbiosis of *S. roscoffensis* might indeed involve such gene transfer.[15]

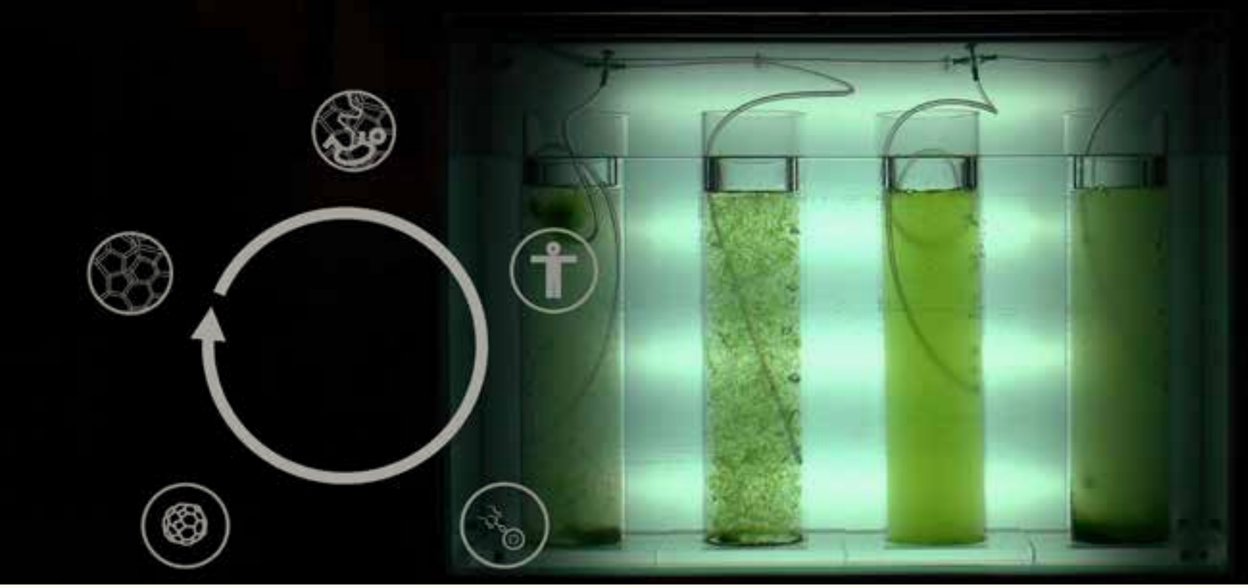
The human-algae

Ocean animals are not the only animals that have stolen secrets from the plant kingdom to tap into solar energy. There's the pea aphid, which charges up a solar-powered backpack using light-harvesting pigments called carotenoids. And the oriental hornet might use a similar trick, utilizing a pigment called xanthopterin to convert light energy to electricity. But neither of these creatures are truly photosynthetic—both lack the critical ability to turn carbon dioxide into sugar.

A single vertebrate, the spotted salamander, has been proven to use algae to solar-power its embryos as they develop inside eggs. Normally, our immune systems would destroy any foreign algae that tried to enter our bodies. The salamander gets away with it for two possible reasons. Firstly, the algae invade before its immune system has fully developed. Secondly, salamanders have strangely inefficient immune systems. This might account for their incredible ability to regenerate lost body parts, but it could also mean that they recognize their own cells in a very different way to other animals. Perhaps this lax self-recognition is what has opened the door for invading algae.[16]

15 Ibid. note 4

16 Ryan Kerney *et al.*, "Intracellular invasion of green algae in a salamander host", *PNAS*, April 2011 vol. 108 no. 16, http://www.pnas.org/content/108/16/6497



HUMALGA by Spela Petric and Robertina Sebjanic

Related to this premise of bio-cultural exchange, new media artists Robertina Šebjani—and Špela Petri—imagine a bio-engineered, post-technological trans-species of humans and algae, the *Humalga*. Their speculative project *Humalga: Towards the Human Spore* (2013) explores a genetic hybrid between a nutritionally self-sufficient organism and an organism that depends on external nutrition, manifested as two distinct bodyforms linked by a complex life cycle.[17] Much like the jellyfish, who lives a part of its life cycle as a free-swimming sexual medusa and part as a sessile, asexual polyp, the Humalga is both human and alga, intermittently alternating generation after generation; two metabolically irreconcilable blueprints connected through a shared code. And because chloroplasts are such a precious evolutionary acquisition, the human stage must hold on to them throughout its life, expressed in skin cells, generating some, but not nearly enough of the necessary energy to feed the incredibly expensive animal.

Genetically modified green men/women?

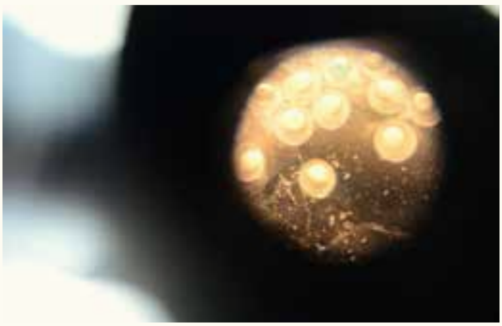
Synthetic biologist designers have spent a lot of time reflecting on how to engineer new symbioses, including animal cells that are able to photosynthesize. In a recent popular experiment, artist and synthetic biologist Christina Agapakis explored the potentialities on a shorter timescale following the injection of photosynthetic bacteria in zebrafish embryos. The fish do not die, and neither do the bacteria. If E. coli—even dead ones—were injected, the embryos would die within an hour. But when injecting photosynthetic bacteria, the fish would still grow.[18] It is a fascinating demonstration of biological versatility, but a far cry from creating, *de novo*, an organism that lives off the sun. The difficulty stems from the fact that a large surface area is needed to capture enough sunlight to make a meal. With leaves, plants are able to harness an enormous amount of solar energy relative to their size. Thick, fleshy humans, with our low surface-area-to-volume ratios, do not possess the necessary bandwidth.

If we humans wanted chloroplasts for ourselves, or our livestock or pets, we would need to genetically modify the host animal to express proteins required for chloroplast function. It has been estimated that about 70-90% of the genes required for chloroplast

17 To learn more about the xenogenesis scenario, consult the artists' websites: http://robertina.net/humalga/ and http://www.spelapetric.org/portfolio/humalga/

18 Agapakis et al, "Towards a Synthetic Chloroplast", 2011, retrieved from *DOI*: 10.1371/journal.pone.0018877

function are provided by the plant's genome[19]. It would probably be entirely feasible for chloroplasts, along with the required genes, to be added to skin stem cells and applied as a skin graft, as there is already significant existing research in this area for burns victims. This approach has been used to produce proteins in mice,[20] and so should be feasible for producing sugar by photosynthesis in humans. At first this graft may require regular replacement, but eventually the chloroplasts will be sustainable within the skin. As in S.K. Robinson's sci-fi short story, the photosynthesizing skin would necessarily be green, and us, little green men/women. Eventually other pigments could be engineered. The plant-person would also need much more water than an average human.



HUMALGA by Spela Petric and Robertina Sebjanic photo by Julian Abram-Togar

Although photosynthetic humans would need less food, it wouldn't be substantially less. Still, researchers argue that over a large population, it could slightly reduce the need for farmland, and that this process could be applied to livestock too. With a large number of livestock, it could noticeably reduce the area of land required to feed cattle or horses. It makes one smile to think of some sort of "green sacred cows" and of what would happen to hairy animals like sheep, given that their coats would reduce the light available for photosynthesis. But there we are, drifting again into sci-fi fantasy land. ■

19 William Martin and Reinhold G. Herrmann, "Gene Transfer from Organelles to the Nucleus: How Much, What Happens, and Why?" *Plant Physiol.* 118 (1998): 9–17.

20 Fernando Larcher *et al*, "A cutaneous gene therapy approach to human leptin deficiencies: correction of the murine ob/ob phenotype using leptin-targeted keratinocyte grafts," *The FASEB Journal* vol. 15 no. 9 1529-1538

Ewen Chardronnet (France) is an author, journalist, curator and investigative artist. Currently acting as curator of the artists-in-residency program at the Roscoff Marine Station (Brittany, France), he has since the early 90s participated in many artistic endeavors and published as an essayist in numerous publications. He has lectured extensively and has served on various boards and committees in the field of art and technology. He is co-founder with the artist group Bureau d'études artist group of The Laboratory Planet journal and the recent Aliens in Green project. Ewen is active in the field of space culture for twenty years and just released a non-fiction narrative book on the secret history of the American space program (*Mojave Epiphanie*, Inculte, March 2016).