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The Scientific Representation of the Living World: A Dual Concept Between Nature's and Humans' Shares

> "Like the other natural sciences, biology has now become quite disillusioned. It no longer searches for truth. It builds its own truth"[1] [JAC 09, p. 25].

The scientific representation of the living world refers to the way in which scientists figure out life. In a way, it is the duplicate of the real object, which is constructed; it is not reality, but it makes sense of this reality. We often speak more specifically of scientific representation to include the concepts, laws and theories that make it possible to understand any area of knowledge. The following discussion will concern the scientific representations of the living world through the history of sciences based on the marine example. Natural sciences are logo-theoretical; namely, they are the result of an abstract rhetoric based on notions, ideas and concepts. "According to them, human endeavors of knowing [should] not produce anything, but only reflect (the ideal of the contemplation of essences) and represent (the ideal of the rhetoric and the book)"[2] [HOT 97, p. 160]. Nature is what it shows [HAD 04], which helps us to explain the assimilation of nature to the sphere of what exists, and what is given (see section 1.1).

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[1] Translation of a French quote.

[2] Translation of a French quote.

Besides the “natural result of life which goes its own way and only recognizes its own law”[3] [MIC 97, p. 142], a modified, handled, transformed and constructed living world that is represented by the life sciences has emerged through human action over the centuries (see section 1.2). This introductory study will question the definition and position that science grants to the living world, without forgetting that they are the result of a history and a specific spatio-temporal context. This reflection will allow us to lay the conceptual and epistemological foundations that are essential for the study of the legal condition of the living world via the case of marine genetic resources.

1.1. Natural sciences: the given living world

Even if we find some kind of continuous representation in the ordering of living beings through the history of the sciences, we should not be deceived. “Scholars” modified classifications according to scientific and technical progress, as they gradually broke free from philosophical and religious dogmas. The 18th Century was a turning point characterized by the drive to know things in an encyclopedic manner. At this time, natural classification became a true scientific endeavor to decipher the characteristics of nature based on observation. “Taxonomy, the science of natural classification, associates a specific language with the aim of fitting the whole of nature into the classificatory space of a table”[4] [SAM 05, p. 24] (see section 1.1.1). At the turn of the 19th and 20th Centuries, a new model of knowledge, based on experiment, was implemented because of the appearance of life sciences. This involved the observation of what was invisible, which had hitherto been impossible. In the 20th Century, the field of the infinitely small opened. Molecular biology, genetics and biochemistry all expanded rapidly. Scientists discovered new methods and techniques to identify species. Systematics became a tool of biodiversity identification (see section 1.1.2).

1.1.1. *Taxonomy: the observation of the living world*

The purpose of taxonomy is to describe and identify living organisms[5]. It implies “some continuum of things (a non-discontinuity, a fullness of

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[3] Translation of a French quote.

[4] Translation of a French quote.

[5] From the Greek *taxis* (placement, ordering) and *nomos* (law). This term was used for the first time in the scientific field in 1813 by the Swiss botanist Augustin Pyramus de Candolle

beings) and some power of imagination, which reveals what is not, and makes it possible thereby to reveal what is continuous"[6]. As "the science of classification; laws and principles covering the classifying of objects" (Collins), it is greatly dependent on the results of the empirical observation of living beings in their environment. This approach consists of unveiling living beings, first to know them better (see section 1.1.1.1), and second, to define, classify and name them, using a postulate and specific method, in order to place them in the living world (see section 1.1.1.2).

1.1.1.1. *Revealing the living world: a change in the scale of perception*

According to the French philosopher Pierre Hadot [HAD 04], the idea of nature is linked to the human fantasy of revealing its secrets. The rise of science and the improvement of scientific instruments since the 17th Century have made this achievement possible. During the Age of Enlightenment, the process of revealing nature changed in both the theoretical and practical dimension. It was no longer the work of a few curious amateurs or seafarers, but that of naturalist scholars who established new scientific disciplines such as zoology, entomology, paleontology and so on, and later, in the 21st Century, marine biology. This change in dimension was accompanied by a will to discover and conquer the unknown. "The continuous increase in the number of species known by European scholars went hand in hand with colonial expansion, the great travelers, trade and travel development"[7] [DRO 93, p. 52]. The size scale of the world, in particular the living world, was gradually modified. Field expeditions started to emerge, but remained mainly confined to the terrestrial environment[8]. "Up until the 18th Century, naturalists only had the opportunity to observe marine animals on the return of fishermen or when they were beached on the coast, when their corpses

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(1778–1841), in his *Théorie élémentaire de la botanique ou exposition des principes de classification naturelle et de l'art de décrire et étudier les végétaux* (Elementary Theory of Botany) [PYR 03].

[6] According to the French philosopher Michel Foucault (1926–1984), the signs that cross the entire field of empirical representation "facilitate [...] the development of a simultaneous system according to which representations outline their proximity and their remoteness, their vicinity and their differences – therefore the network which, outside of time, shows their kinship and reproduces in a permanent space their order relationship" [FOU 66, pp. 87–88].

[7] Translation of a French quote.

[8] Botany is a key concern, because animals directly interacting with human beings (farming, pets, hunting, fishing) are very few and easily remembered [LEG 03, p. 7 and following]. Translation of a French quote.

were dried-up and deformed, which distorts their description”[9] [IFR 08, 14]. The collection and study of marine organisms were then barely starting.

Between the 15th and 19th Centuries, marine scientific knowledge was more linked to the progress of navigation, the opening of new sea routes, colonization, trade development, and the joint and systematic collection of information than the study of the marine environment itself. In the 16th and 17th Centuries, science was an extension of geographical exploration, which assessed natural resources. The scientific knowledge of seas was an important element helping the expansion of colonial nations, and conflicting imperial claims had a significant impact on the development of the Law of the Sea, which was confirmed by the great legal controversies of *mare liberum* and *mare clausum* [MON 03, p. 216 and following].

In the 19th Century, knowledge of the marine living world made a giant leap. The French and English empires sent crews to navigate across the seas and oceans in order to discover *terrae incognitae* and new species. Among them were naturalists, whose collection activity was mainly limited to stop-over periods [GLÉ 07, p. 12]. The French navigator and explorer Louis Antoine de Bougainville (1721–1811), “travelled around the world” from Nantes to the South Pacific (Vanuatu, Samoa, Salomon, etc.), passing through Brazil (the Falklands, Rio de Janeiro), aboard the frigate *Boudeuse*, joined by the cargo ship *Étoile* (1766–1769)[10]. The three expeditions (1764–1769) of Captain James Cook (1728–1779) in the Pacific[11], and the voyage of the HMS *Beagle* (1831–1836), aboard which was Charles Darwin (1809–1882)[12], also helped to make significant progress in terms of knowledge of marine species.

Aboard *le Géographe* and *le Naturaliste*, captained by Nicolas Baudin, the French naturalists François Peron and Charles-Alexandre Lesueur

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[9] Translation of a French quote.

[10] *Voyage autour du monde par la frégate du Roi la Boudeuse et la flûte l'Étoile ; en 1766, 1767, 1768, et 1769* (one volume, 1771 and two volumes, 1772).

[11] More than 1,000 plant species, 500 fish and as many birds were collected in all of the Pacific archipelagos [GLÉ 07, p. 13].

[12] After studying medicine, geology and zoology, he became a priest and then boarded the *Beagle*, aboard which he traveled across the Atlantic and Pacific. He became a member of the Royal Society in 1839. Mainly renowned for his theory of evolution, he built his scientific reputation by means of substantial work on coral formations, as well as on *Cirripedia*, an order of the crustacean class to which barnacles and *Sacculina* belong.

brought back more than one hundred thousand samples from their expedition (1800–1804) in New Holland (Australia), which allowed scholars from that time to identify a significant number of new species. The naturalist Jules Dumont d'Urville (1790–1842) succeeded them in this endeavor of discovery. From 1822 to 1840, the frigate navigated the whole world and explored the South Pacific in particular. In addition to the major discovery of the Antarctic[13], he actively took part in the process of revealing the living world[14]. Onshore, the first professional biologists and a few amateur collectors processed the samples and data collected *in situ*. In France, the *Muséum national d'histoire naturelle* (MNHN)[15] employed the great figures of natural sciences of the 19th Century, including Georges Cuvier (1769–1832) and his student Henri Milne Edwards (1800–1885). Both took part in the description and classification of some marine organisms[16].

The second half of the 19th Century was characterized by the rise of biology and marine biology, which was made possible by the influx of new specimens. It was the time of the creation of great collections and a favorable time to wonder about the origin and limits of life[17]. The English biologist Edward Forbes (1815–1854) collected samples in the Aegean Sea at 238 m and concluded that life disappears beyond 500 m, after those of

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[13] He discovered Adélie Land on January 19 1840 during his third expedition with the frigate *Astrolabe* and the gunboat *Zélée*.

[14] During his first scientific expedition on board of *Coquille*, he collected 3,000 plant species (including many algae), 400 of which were new, and 1,200 species of insects, 300 of which were new.

[15] The National Convention Decree of June 10, 1793, an organization regarding the *Jardin national des plantes* and the *Cabinet d'histoire naturelle* under the name of *Muséum d'histoire naturelle*, gave the museum, which was a former royal garden of medicinal plants created in 1635, its own legal existence. Its administration was entrusted to a college of professors and it extended its competence to natural history. See Decree No 2001-916 of October 3, 2001 in the *Muséum d'histoire naturelle*, JORF, No. 233, October 7, 2001, p. 15 803.

[16] From 1826 to 1829, they traveled together along the coasts of the English Channel, from Grandville to Cap Fréhel. The former, besides his work on animal classification, published memoirs for use in the history and anatomy of mollusks in 1817. The latter demonstrated the inaccuracy of Edward Forbes' theory. In 1861, he discovered *Scleractinia* and calcified tube worms on a telegraph cable raised for repair, which was moored between Sardinia and Algeria at a depth of 1,800 m. He also published a Natural History of the Crustaceans in 1834.

[17] In 1859, Charles Darwin presented his theory of evolution for the first time in a scientific and social context favorable to fixism and creationism.

light and photosynthesis[18]. It was not until the discoveries of the French naturalist Henri Milne Edwards and the Norwegian Pastor Michael Sars[19] in the 1860s that it was proven that life did exist in the abysses, although it decreased according to the depth.

In 1872, the gunboat HMS Challenger left the Port of Plymouth for the longest ever circumnavigation[20]. It was the first expedition to be only for oceanographic purposes. All of the scientific disciplines of that time were represented (botany, zoology, etc.) under the authority of the scientific director: the Scottish zoologist Charles Thomson (1830–1882). For the first time, scholars had a laboratory on board. The work performed by the crew to collect and process data was colossal[21]. At the same time in France, stations dedicated to the study of marine biology were created, the first in Concarneau in 1859[22]. The 19th Century ended with large-scale scientific campaigns[23], paving the way for modern oceanography. Even though the marine living world was still mainly unknown, the rapid development of

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[18] This is a simple extrapolation of the results he obtained on site. He referred to the area beyond 500 m as azoic, i.e. lifeless [REY 05, p. 31].

[19] In 1864, the latter collected 92 species of animals, including two living fossils, in a Norwegian fjord, at a depth of 600 m [REY 05, p. 31 and following].

[20] It travelled over 69,000 nautical miles through the Atlantic, Indian, Antarctic and Pacific Oceans.

[21] “Approximately 50 years were necessary for a hundred or so naturalists to go through the massive quantity of collected material, namely 7,000 species, half of which were new to science” [GLÉ 07, pp. 54–55].

[22] Other stations of this type were open in Roscoff (1871), Luc and Wimereux (1874), Banyuls-sur-Mer (1881), Sète (1882), etc. They were equipped with aquariums and pools in order to observe specimens *in vivo* and overcome the difficulties encountered by marine biologists at sea (transport, space, and harvest and conservation of living organisms).

[23] The American Alexander Agassiz (1835–1910) traveled across the Atlantic with the *Blake* from 1877 to 1880 and the *Albatros* in 1891. The French scholars Léopold de Folin (1817–1896) and Alphonse Milne Edwards (1835–1900) explored the Bay of Biscay, the Azores, the Canaries and the Sargasso Sea on board of *Travailleur* and *Talisman* between 1880 and 1883. The collections of harvested animals are exhibited in the *Muséum d’histoire naturelle* in Paris. The navigator and scholar Prince Albert I of Monaco (1848–1922) traveled, from 1885 to 1915, across the North-East Atlantic, from Spitzberg to Cap-Vert and the Azores, successively on board of *Hirondelle*, *Princesse Alice I*, *Princesse Alice II* and finally *Hirondelle II*. Off the coast of Cap-Vert, he discovered a fish at a depth of 6,035 m. Beside his great scientific discoveries, he created the Oceanographic Institute of Monaco in 1889, where there is a large collection of abyssal species brought back from his expeditions, as well as an aquarium containing the fauna and flora of the Mediterranean seabed.

techniques and knowledge facilitated a paradigm shift in the observation scale of the living world in general.

The 18th and 19th Centuries, the age of the exploration of seas and oceans, highlighted the triumph of the freedom principle under the pressure of the learned societies of Europe over their governments to promote science. To guarantee the fundamental principle of the freedom of discovery, exploration and scientific research in the high seas, which had to adapt to the recurring maritime disputes of the time, governments gave vessels on scientific missions safe conducts to protect them in the high seas, in coastal areas and foreign ports [MON 03, p. 221].

1.1.1.2. *Classifying the living world: discovering order in nature*

Discovering the order of things or putting them in order? Out of these two tendencies of natural sciences, taxonomists give priority to the former, because the obvious risk of the latter is to run classificatory criteria by the subjectivity of the classifier. The history of natural sciences selected numerous classification systems, the first ancient ones being utilitarian[24]. It was only in the 18th Century that the first true scientific classifications emerged. The latter represented the living world in the form of a single and stable set based on a very specific organizational plan.

The Swedish botanist Carl von Linné (1707–1778), in his famous book *Systema Naturae* [VON 00], offered an attempt at systematic classification of the living world into three kingdoms: the animal kingdom, the plant kingdom and the mineral kingdom. This classification is called fixist, because it implies the immutability of the species created by God according to an organizational plan. The living world is ordered in a hierarchical manner: species that share the greatest number of common traits (criteria of morphological similarities and assumed affinities) are grouped into genera, genera into families, families into orders, orders into classes and classes into branches. This method of organization is worthy of criticism, since it is

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[24] Aristote de Stagire (384–322 BC) was the first "classifying scholar" to try to group together the few four hundred animal species he knew, by dividing them according to morphological criteria: the *enaima*, with red blood, and the *anaima*, without. He was also interested in marine organisms, which he observed and dissected during a 3-year stay in Lesbos in the Aegean Sea [HUG 04, p. 176].

based on a system of axiological values and not on scientific truth[25]. Furthermore, Carl von Linné established the first "binomial" zoological nomenclature (*genus, species*), a description which still today allows scientists all over the world to unequivocally name species[26].

At the beginning of the 19th Century, French botanist and zoologist Jean-Baptiste Monet, Chevalier de Lamarck (1744–1829), developed the first theory disproving fixism. According to him, "the dogmatic tradition of a creator god is no longer required; species transform and give birth to new species under the influence of environmental factors to which they adapt"[27] [quoted by GLÉ 07, p. 10]. He is the father of transformism, a theory according to which species derive from each other through successive transformations [LAM 94]. The theory of evolution succeeded it, the initial foundations of which were laid by the English naturalist Charles Darwin (1809–1882), in his 1859 book entitled "On the Origin of Species" [DAR 17]. He claimed that species have a common ancestor and are derived from one another. Natural selection is the driving principle of evolution. The resulting classification is purely genealogic, as species are ordered according to their degree of evolutionary kinship. This theory flew in the face of the religious and anthropocentric theories of the time.

From Charles Darwin's work, natural classifications ceased to be purely descriptive. They became phylogenetic, i.e. they highlighted the proximity between living beings[28]. Scientists gradually discovered the living world

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[25] Fixism and the similar theory of creationism have greatly influenced the scientific representation of nature and still have supporters within the scientific community, mainly in the United States and Germany (intelligence design). Anthropocentrism and ethnocentrism have similarly pervaded scientific rhetoric. Living organisms are still sometimes presented through a degree of apparent complexity (size, importance), from humankind to bacteria. This disturbingly reminds us the great chain of beings (or *Scala Naturae*) of Charles Bonnet (1720– 1793), which was an archaic classification representing living or non-living natural entities in the form of a scale with increasing complexity within which humankind is the most elaborated of all.

[26] The name of a species is the combination of two Latin words (up to three in some disciplines, for a species, variety or form), generally written in italics, corresponding to the name of the genus in capitals followed by one or two adjectives characterizing the species.

[27] Translation of a French quote.

[28] Mutability is an integral part of this form of classification, as living beings are classified according to evolutionary attributes and not immutable traits.

order. Thus, its organization went from three kingdoms in 1866[29], to four in 1956[30] and then five kingdoms in 1969[31]. During the second half of the 20th Century, cladistics[32], introduced by German zoologist and entomologist Willi Henning (1913–1976), contributed to the rapid development of phylogenetic systematics[33]. The relationship of descent between living beings highlighted by Charles Darwin was replaced by the matter of ancestry. Only monophyletic taxa, namely species with a common ancestor, were then taken into consideration [FOR 06, p. 356]. Some traditional groups, such as fish and algae were excluded, because they were polyphyletic: they could not be defined according to a derived trait common to all the organisms of this group[34]. Thanks to the progress made in the field of biochemistry and molecular biology, the American microbiologist Carl Richard Woese (1928–) offered, in 1977, a phylogenetic taxonomy dividing the living world into three main domains: eukaryotes, eubacteria and archeobacteria. It disrupted the traditional classification by kingdom of the living world[35].

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[29] The German zoologist Ernst Haeckel (1834–1919) was the first to offer a phylogenetic tree composed of three kingdoms (1866): the animal kingdom, the plant kingdom and the Protista kingdom, within which he classified unicellular organisms that were in the process of being described at the time [LEG 03, p. 31].

[30] In his 1956 book "The Classification of Lower Organisms", the American biologist Herbert Faulkner Copeland (1902–1968) advocated a division of classification into four kingdoms: *mychota* (blue-green algae and bacteria), protoctists (eukaryotes algae, mushrooms, molds and protozoa), plants (embyophytes and green algae) and animals (sponges included).

[31] In 1969, the American biologist Robert Harding Wittaker (1920–1980) enriched the nomenclature of the living world based on an organization into five kingdoms: Monera (prokaryotes), Protista (unicellular eukaryotes), plants (photosynthetic multicellular eukaryotes), fungus (non-photosynthetic multicellular eukaryotes: mushrooms) and animals (heterotrophic multicellular eukaryotes).

[32] Cladistics, or cladism, is the "classification of living beings based on their degree of phylogenetic kinship without considering their morphological similarities" [FOR 06, p. 141].

[33] Willi Henning suggested that biological classifications should be strictly hierarchical, reflecting the kinship between taxa.

[34] For a long time, the fish group was considered as a sole group composed of invertebrates that did not exit water and did not have exclusive attributes. We now know that the trout is genetically closer to humans than sharks. Similarly, marine algae are not a unique evolutionary group regarding systematics.

[35] In traditional taxonomies, the kingdom (*regnum* in Latin) is the highest level of classification of the living world. In the new classification of three domains, the kingdom becomes the second level, above branch, class, order, family, genus and, finally, species.

Unlike traditional descriptive classifications, new phylogenetic classifications are based on a tree model (spherical bush), at odds with transcendence and anthropocentrism. The place of the different living organisms in the tree becomes a question of method, which indicates an objectifying will[36]. Nevertheless, modern classifications only provide a partial description of reality. They change as scientific knowledge becomes clearer, but also according to disciplines and schools[37]. According to the current most common scientific classification, the living world is divided into five kingdoms, which are all present in the marine environment. These are prokaryotes/monomers (bacteria and archaebacteria), mushrooms (multicellular eukaryotes), protists (unicellular eukaryotes), plants (multicellular eukaryotes) and, finally, animals (multicellular eukaryotes).

1.1.2. *Systematics: the identification of the living world*

Systematics refers to both the method used, for example phylogenetic systematics, and the result obtained, for example sponge systematics[38]. It is a passive process of identification that helps us to make sense of the living world. This process generally starts with the collection of specimens and ends with the publication of the name and description of the newly described species[39]. It is composed of four main actions: recognizing, defining,

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[36] Traditional classifications classified species according to the presence or absence of numerous characteristics (biological, phenotypic, anatomical, physiological, ethological, food behavior, etc.). Phylogenetic classification, for its part, is based on what living beings have in common (at both the morphological and molecular levels), and not on what they do not have in common (for example, the “invertebrate” categories are removed), or on what they do (the terms “viviparous”, “burrowing”, etc. will then be avoided). It is a negative classification, which is neither ecological nor anthropocentric.

[37] Scientific publications refer to various classifications, from the slightly revised traditional classification to strictly phylogenetic classifications, through different combinations, for instance classifications maintaining preexisting categories while adapting to recent discoveries in terms of phylogeny. For example, phenetic methods, in contrast with cladistics, attempt to qualify the general similarity between organisms by calculating a global similarity index between two taxa, namely a distance for each couple of taxa [LEC 06, p. 31].

[38] According to the French systematists Guillaume Lecointre and Hervé Le Guyader, this is the science of combining concepts, objects and names. It is inseparable from taxonomy and merges with it, because they are both simultaneously practiced by the same people [LEC 06, p. 31].

[39] The publication of a new species name can take years. In fact, systematists sometimes must carry out comparative studies to know whether the species has already been named and

classifying and naming[40]. For the last 15 years, systematics has undergone profound changes[41]: because of molecular phylogeny and the computerized search for the most parsimonious classifications, systematics is no longer considered as an "art", but as a real science characterized by its objectivity and the transparency of its procedures [LEC 04, p. 41]. In the current unprecedented context of exploration and identification of the marine living world, it is like a "timely advanced mega-scientific endeavor" [KAI 11, p. 33] concerning the inventory of the living world (see section 1.1.2.1), the study of its diversity and the understanding of the mechanisms influencing its evolution (see section 1.1.2.2).

1.1.2.1. *The living world inventoried*

Our knowledge of biodiversity, which is far from homogenous and complete, has never stopped evolving, and the unknown areas have never stopped growing[42]. Nowadays, the estimate of the number of species described so far is approximately 1.5, and the estimate of the number of species yet to be discovered is between 2 million and 6 billion but most project around 11 million species or fewer [BRE 17]. These are only estimates. The number and ratio of species by taxon are uncertain and

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described. These studies can require the dissection of specimens, or even the molecular analysis of their DNA. It is increasingly frequent that the publication is in electronic form.

[40] Systematics aims to describe organisms by means of interspecific relationship and their degree of proximity. In addition to its purpose, it groups together disciplines of taxonomy, nomenclature and pure classification. Taxonomy prioritizes the groupings made. The nomenclature is used by taxonomy to name hierarchies. On the other hand, classification deals with inserting a group into the system thus prioritized. The ICZN (International Code of Zoological Nomenclature) presents, manages, publishes and updates all of the rules of the nomenclature *in extenso*. Systematics is divided into several schools: phenetics, phylogenetics and evolutionary systematics.

[41] The actual role of this discipline has greatly increased. It is now integrated into numerous R&D projects on marine biodiversity. It is an essential step for the study and identification of an organism. It helps us to prepare subsequent scientific studies. It is useful for identifying species; conducting fundamental research in biology and ecology; making lists of protected, threatened, exotic or invasive species; managing and sustainably using biological resources; and, finally, establishing collections.

[42] According to Carl von Linné in the 18th Century, the world had approximately 67,000 species, including 9,000 described in his book *Systema Naturae*. Until the 1950s, the estimated number of species on Earth was between 1.4 and 6 million. In the 1980s, scientists believed that the 1.6 million inventoried species represented approximately 50% of animal and plant species.

changing because of the growth of collections, the improvement of identification technical tools and natural causes, such as evolution and extinction. The lack of systematic knowledge is more significant among some taxa, such as marine taxa. The identification of microorganisms and sponges is only just beginning [GUE 05 b, p. 50], but an acceleration is under way thanks to the recent progress of molecular biology and metagenomics (linked to high-throughput sequencing), whereas the identification of animals and plants is more advanced, or even nearly complete. The best inventoried marine groups are invertebrates, corals and mollusks, which are recognized indicators of marine biodiversity, as well as algae. The classification of eukaryotes is only at the deciphering stage and few species have been genetically described. Species of the Western temperate terrestrial areas are the most studied and, therefore, the best known [SEU 97, p. 25]. Unlike species in terrestrial areas, particularly well-known Western temperate species, only approximately 17% of the species of marine areas, which cover 71% of the planet surface area, are known[43]. In these areas, tropical reefs and polar regions are examples of ecosystems that harbor still largely unknown species[44].

At the end of the 1970s, the discovery of the first hydrothermal vents was the beginning of the systematic exploration of the deep marine environment[45]. “The deep hydrothermal ecosystem is a very productive biotope based on bacterial production and populated by an original fauna, habitat, able to exploit a discontinuous, unstable and toxic habitat”[46], which foreshadows an extraordinary diversity. From the 1980s, specific geological environments have been the subject of further exploration and research: aforementioned hydrothermal vents, oceanic ridges, cold seeps located along continental margins, sedimentary environments, canyons, deep-sea trenches, etc. Although biomass is far less dense on the seabed, diversity is higher. All

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[43] 242,649 species accepted on November 1, 2017: World Register of Marine Species (WORMS), available online at: http://www.marinespecies.org/.

[44] See the reports of the United Nations Secretary-General on the Oceans and the Law of the Sea, A/60/63/Add.1, July 15, 2005, section 55; doc. A 62/66, March 12, 2007, section 134.

[45] The first active hydrothermal vents were discovered in 1977 by a team of geochemists and geologists from the University of Oregon, during the dive of the American submarine *Alvin* on the oceanic ridge of the east Pacific, near the Galápagos, at a depth of more than 2,500 m.

[46] Program of the deep environment laboratory of the IFREMER (French Research Institute for Exploitation of the Sea): “*Écosystème hydrothermal profond*” (Deep hydrothermal ecosystem); presentation available online at: www.ifremer.fr/droep/j-prog.html. Translation of a French quote.

of these ecosystems contain organisms equipped with adaptation capacities specific to these extreme environments. These unique characteristics explain their scientific and biotechnological value, as their genetic registry is varied, original and extreme[47].

In the 1990s, scientists, who were worried by the lack of knowledge and its consequences in terms of management and preservation of the environment, became aware of the importance of systematics. Collections were modernized and numerous biodiversity digital inventory projects emerged. The most significant of these was the Census of Marine Life (CoML)[48]. From 2000 to 2010, this international initiative on the diversity, abundance and distribution of marine life, mobilized 2,700 researchers from more than 670 institutes of 80 countries. By relying on extensive work to collect archives and specimens[49], CoML researchers made the first global inventory of marine species: 6,000 new potential species were discovered, including 1,200 species that met the description standards of systematic biology. The number of known marine species went from approximately 230,000 to nearly 250,000 [AUS 10, p. 3].

Likewise, the purpose of the expedition Walters Shoal (scientific component of the IUCN FFEM-SWIO project)[50], which took place from April 23 to May 18, 2017, was to acquire scientific data to improve the knowledge and understanding of a group of submerged mountains called Walters Shoals located 700 km away from Madagascar in the high seas. The ambition of the institutional stake holders (IUCN, FFEM, IRD, MNHN, IDDRI) and the scientists on board of *Marion Dufresne* was not only to make a complete inventory of the fauna associated with these deep-sea ecosystems (algae, molluscs, crustaceans, fish, marine birds, etc.), but also to make progress with international negotiations on the conservation and sustainable use of marine biodiversity beyond the limits of national jurisdiction.

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[47] Interview with Mrs. Sophie Arnaud-Haond, research executive in evolutionary biology and ecology, IFREMER, Plouzané, January 19, 2011.

[48] For more information, see www.colm.org, [AUS 99, GRA 99, ODO 03, AUS 08, AUS 10].

[49] More than 540 expeditions were conducted in all types of environments (polar, temperate, tropical) and at all depths.

[50] For more information on the IUCN FFEM-SWIO project: https://www.iucn.org/fr/theme/milieu-marin-et-polaire/projet-ffem-swio and on the Walters Shoal scientific project: https://www.iucn.org/fr/theme/milieu-marin-et-polaire/exp%C3%A9dition-walters-shoal.

Another significant example of marine biodiversity inventory is the 11 expeditions of the schooner *Tara* and especially the expeditions Tara Arctic (2006–2008), Tara Oceans (2009–2013), Tara Mediterranean (2014) and Tara Pacific (2016–2018), the common objective of which was to study and understand the impact of climate change and ecological crises on oceans. Thus, the international, multidisciplinary and hybrid expedition Tara Oceans consisted of a 5-year circumnavigation in the northern and southern hemispheres to study planktonic ecosystems, in particular marine microorganisms, which were unknown despite being important indicators of the state of the oceans and climate, at the core of the food chain and a source of innovation linked to the discovery of genes of interest. In 2016, the schooner started a new 2-year circumnavigation of 100,000 km in the Pacific Ocean. The expedition focused on coral ecosystems in the face of climate change and anthropic pressures. The Tara project involved approximately 100 scientists from numerous countries, including 20 or so scientists who coordinated the sampling and acquisition of data *in situ* and their analysis *ex situ*. The scientific disciplines represented were complementary and ranged from physical and chemical oceanography to plankton biology, as well as genomics, microbiology, modeling, ecology and bioinformatics[51].

In order to describe species and their environment as accurately and as fast as possible, modern systematics relies on bioinformatics[52]. The DNA barcode, for example, helps to identify species by means of a small DNA sequence derived from a single location on the genome[53]. Intangible results of inventories (scientific name, description, location, genetic barcode, etc.)

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[51] For more information on the Tara project, see http://oceans.taraexpeditions.org/.

[52] Bio-informatics is a booming multidisciplinary science that uses advanced technologies in IT, biology, mathematics and physics. It ensures the storage and development of information relevant for biologists [GIB 02].

[53] This technique is used on a large scale within the framework of the Barcode of Life Data System (BOLD). It helps to compensate for the slow pace of morphological identification as well as to access new species with difficult morphology, such as microorganisms and invertebrates. It relies on the development of an automated catalogue. Once the catalogue is established, the method consists of establishing one barcode per new specimen, so that it can then be compared with those of specimens already identified, in order to detect potential unknown, similar or evolutionary species. The DNA barcode has the advantage of being computerized. As for its limits, they mainly concern the difficulty in differentiating between species that are slightly different from the genetic point of view, hybrids or species that have recently diverged. For more information, see www.boldsystems.org.

are compiled in digital databases, which are for the most part accessible on line, freely (open source) or subject to intellectual property rights[54]. However, the improved accessibility of scientific data conceals numerous obstacles with which systematics is confronted. The lack of qualified staff and funding, especially in Southern countries, is recurrent. Systematics finds it hard to maintain its autonomy. It is neglected as an expertise and training tool compared to other branches of biology, such as genetics and molecular biology, which are branches constantly modifying their theoretical bases and tools[55]. Apart from a few rare exceptions, it is impossible to obtain funding for "purely" descriptive projects of marine biodiversity[56]. The more systematic knowledge of life grows, the more it seems limited and superficial. At the current rate of description, it would take another 250 to 1,000 years to perform a complete inventory of marine biodiversity [KAI 11, p. 58]. But the age of discovery continues, even for the best-known species, such as fish [AUS 10, p. 3 and following], and already an extraordinary diversity is emerging.

1.1.2.2. *The living diversity*

The assessment of biodiversity is often reduced to the calculation of the number of species present in one location, which is the simplest and most accessible measurement. Yet, if diversity is easily assessed at the specific level, it corresponds less to quantitative data than to interactions at several levels: between species (interspecific level), within species (intraspecific or genetic level) and within an ecosystem in relation to others (ecosystemic level). For theoretical and methodological reasons, scientists often choose a specific angle of approach: for example, according to size (thus a distinction is made between micro- and macrodiversity) or discipline (biochemists study chemodiversity and biologists study phyletic, morphological or genetic

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[54] Data digitalization helps, *inter alia*, to regularly update them and avoid redundancies (for example synonymous species names). The CoLM thus gave rise to a digitalized World Register of Marine Species (WORMS), including information on synonyms. There are other registers for certain regions (for example European Register of Marine Species – ERMS) or certain taxa (for example algaebase for algae, fishbase for fish, etc.).

[55] "Taxonomists who are used to morphological descriptions rightly fear that the contemporary fascination for new technologies might overshadow traditional methods which are already greatly underfunded" [BRU 05]. Molecular biology is not however a rival but an ally of systematics. It corrects many errors linked to the plasticity of morphological traits.

[56] Interview of Sophie Arnaud-Haond, researcher in evolutionary biology and ecology, IFREMER, Plouzané, January 19, 2011.

diversity). They are also mostly limited to the study of the diversity of a type of environment: terrestrial, tropical, aquatic, insular, marine, biodiversity, etc.

Ex situ, scientists focus their studies on model organisms. These organisms are both natural and artificial, both products of nature and evolution and inventive products resulting from standardization processes [GAY 06, pp. 9–43]. Their use helps us to develop explanatory schemes based on an actual organism, from which experiments are conducted and from which results are generalized or extrapolated. They are exemplary organisms, as representatives in a field of research and as tool organisms allowing scientists to experiment and understand. The use of these reference models is justified by the quantity of the tools, the available genetic data on them, the ease of farming and our expertise on the vital cycles of the species selected. Their use has significantly increased over the last 30 years and the marine field is no exception[57].

Specialists agree that the marine environment is particularly rich in biological diversity. Life was allegedly born in oceans nearly 3.8 billion years ago, a duration that must be put into perspective with the 400 million

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[57] Some marine model organisms were used as demonstration support for the following Nobel Prizes: in 1913, the French physiologist Charles Robert Richet was the Medicine Nobel Prize winner, for his discovery of anaphylaxis and the formation of antibodies from extracts of the tentacles of *physalia*, which are organisms from several colonies of cnidarians forming a meta-organism found in tropical seas and sometimes near the coasts of the Aquitaine and Charente-Maritime; in 1963, Sir Alan Lloyd Hodkin, British physiologist and biophysicist, received the Medicine Nobel Prize for his work on the electrical pulse transmitted between the central nervous system and the rest of the organism – his study material was the longfin inshore squid *Loligo pealei*, the only nervous structure large enough to allow him to record ionic currents; in 2000, Eric Richard Kandel, American doctor and researcher in neurosciences, professor of biochemistry and biophysics at the Columbia University of New York, received the Medicine Nobel Prize by decoding the fundamental mechanisms of memory by studying the few neurons of the mollusk *Aplysia californica*; in 2001, British biochemist Richard Timothy Hunt received the Medicine Nobel Prize for his discoveries on the role of cyclins, which was a major contribution to the mechanisms of cellular multiplication – his study initially concerned the eggs of an urchin, the *Arbacia punctulata*; in 2008, the Japanese marine chemist and biologist Osamu Shimomura received the Chemistry Nobel Prize for the discovery of the Green Fluorescent Protein (GFP) derived from the jellyfish *Aequorea victoria*, and its development for use in cellular biology.

years of continental life [LEG 05a]. Most lineages have since remained confined in specific marine ecoregions, and only a few specimens managed to transition to the terrestrial universe and then to diversify[58]. In the marine animal world, there are 28 phylums (molluscs, echinoderms, chordates, arthropods, cnidarians, etc.), including 13 which are endemic[59]. In the plant world, the green, red and brown coexist, whereas only chlorophyll plants colonize the terrestrial environment. In the microbial world, prokaryotic unicellular organisms (bacteria, cyanobacteria, prochlorophytes, etc.) represent most of marine life and are still very little known[60].

The oceanic space is a complex assembly of interdependent, shifting three-dimensional spaces, some of which are big, and others are more restricted or characterized by sets of quite specific physical and chemical constraints [LEG 05a, p. 3]. Rare species are usually common there [AUS 10, p. 3]. Unlike the terrestrial biodiversity gradient, which indicates a maximum concentration at the equator, marine biodiversity is at its maximum under temperate latitudes. Elsewhere, the marine environment has areas with a high quantitative and qualitative density, called “biodiversity hotspots”[61] and atypical ecosystems, such as coral reefs and hydrothermal sources. The importance of heterogeneity and specificity at sea is currently the subject of active research in the field of life sciences. With 34 out of the 36 main phylums described on Earth to date, the marine world is now seen by scientists and industrialists as a significant source of genetic and

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[58] Animals (metazoans) are originally from the sea. All phylums seem to have appeared in the marine environment. However, mushrooms and multicellular plants are originally terrestrial; it is their marine forms that are derivatives [WIL 97, p. 2].

[59] Specifically, seven phylums are studied: first, sponges, then red and brown algae, then cnidarians, mollusks, echinoderms and ascidians. The terrestrial world has 11 phylums, including only one that is endemic (onychoporans) [KOR 05, p. 64].

[60] Microorganisms, representing the smallest link in the food chain, nonetheless play a major role in the economy of the great biochemical cycles and the maintenance of biodiversity. Most marine animals experience a planktonic phase in their development. Thanks to genetic analysis, the estimated marine microbial diversity was multiplied by 100 in 10 years and the number of types of different microbes, including bacteria and archaea, significantly increased [AUS 10, p. 2].

[61] “These locations were identified according to either a great total specific richness, or their richness in endemic species (or species with a limited distribution)” [SEU 97, p. 30]. According to the list made by the non-profit organization Conservation International in order to protect them, this concerns the Mediterranean Basin, New Caledonia, East Melanesian Islands, the Philippines, and more.

biochemical diversity, in particular in ecosystems and organisms with no terrestrial equivalents[62]. Systematists are aware that the importance granted to their field of study mainly comes from the services it provides by supplying a general reference system to other biologists in order to facilitate their future experimental work [BLA 02].

1.2. Life sciences: the constructed living world

Contemporary science corresponds to a radically different representation from “[the] contemplative reader ideal symbolically giving thanks to an immutable and eternal nature and its creator”[63] [HOT 97, p. 160]. While traditional vision sees nature as something given that must be accepted by humanity and into which the latter tries to become integrated, the contemporary vision of life sciences tends to turn humanity into an entity whose existence and action are imposed upon nature. Science is no longer a simple duplicate of the actual object that it describes. It is based on the idea of resonance between the actual object (the given living world), its knowledge (life sciences) and the constructed object (the scientific representation of the living world), which evolves hand in hand with theoretical and practical scientific data [MIC 97, p. 144]. The apparently clear distinction between products of nature and the artifact is increasingly ambiguous. The development of the various branches of biology (biological sciences which became life sciences) since the end of the 19th Century (see section 1.2.1) and, more recently, bio-technoscience (see section 1.2.2) have greatly contributed to the emergence of this scientific representation of a living world, which is no longer natural, but constructed.

1.2.1. *Biological sciences: the exploration of the living world*

Biological sciences are experimental sciences: first an experiment of nature, then an “artificial” experiment[64]. From the beginning of the 19th

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[62] The discovery rate of molecules of interest is five hundred times higher for marine species than for terrestrial species [KOR 05, p. 64].

[63] Translation of a French quote.

[64] “The main difference between the two types of observation is that, in the case of “artificial” experiments, one can choose the conditions and thus be able to test the factors determining the results of these experiments. In the case of the “experiments of nature”, whether it is an

Century, general biology, which had become experimental, brought humanity to the gates of the living world, to what formed the outlines of living systems (see section 1.2.1.1). A century later, genetics and molecular biology paved the way for exploration of the maze of the cellular system (see section 1.2.1.2).

1.2.1.1. *Biology: at the gates of the living world*

In its widest sense, biology is the science that focuses on the study of life and living beings. The 19th Century was a milestone in its practical and theoretical development. It became experimental[65], and fundamental concepts, such as cell theory[66], the theory of evolution[67] and Mendel's laws[68], were developed from 1850 onward. In the 20th Century, the improvement in the means of observation made it possible to progress considerably[69]. Biology was gradually divided into different branches or disciplines adopting very distinct study units.

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earthquake or the generation of an insular fauna, the task of the researcher is to infer or rebuild the conditions under which this "experiment" took place" [MAY 89, p. 42].

[65] The improvement of techniques, especially the progress of microscopy at the beginning of the 19th Century (achromatic objectives), made it possible to access tissues and cells [THE 00, p. 74 and following].

[66] In the 1830s, the German physiologist Matthias Jakob Schleiden (1804–1881) and his compatriot and botanist friend Theodor Schwann (1810–1882), established the first conceptual benchmarks of the cell theory of the living world, which made the cell the elementary unit of life. Their observations led them to outline the postulate according to which all organisms are made of cells, i.e. structurally and functionally independent units [SCH 00, p. 18].

[67] The theory of evolution put forward by Charles Darwin (1809–1882) in his book *On the Origin of Species by Means of Natural Selection, or the Preservation of Favoured Races in the Struggle for Life* (1859), states that all living beings are the result of a long series of biological transformations, called evolution. Evolution explains, from material causes, the diversity of living species and their transformation into new species. This theory is radically opposite to the fixist theory, according to which God allegedly created the Earth and all of the beings populating it.

[68] In 1865, the Czech monk and botanist Johann Gregor Mendel (1822–1884) presented laws on transmission from generation to generation and the mutation of distinguishing traits, after a series of experiments on pea hybridization (he studied the transmission over generations of many simple traits with alternative versions: peas that are smooth, wrinkled, etc.).

[69] After WWII, the introduction of the electronic microscope helped to obtain magnifications by 50,000 to 70,000. Cells were also examined with ultraviolet or polarized light and the use of vital dyes became widespread [THE 00, p. 110].

In general biology, species and organisms are referents at the macroscopic level, and the cell and its components are referents at the microscopic level[70]. Molecular biology tries to understand the operating mechanisms of the cell at the molecular level. Microbiological study concerns microorganisms, an extremely diversified group of microscopic unicellular organisms that are distributed over the three domains of the living world: bacteria, archaea and eukaryotes. For the statistician, the individual considered is a set with one or more common traits, i.e. a population. In the paleontological approach of the living world, the American Stephen Jay Gould (1941–2002) considered a species as “an evolutionary individual”, unlike Charles Darwin who referred to the organism [GOU 97, p. 90]. At the level above the species, the ecosystem becomes the referent[71]. The reality it describes goes beyond the living world[72]. “The ecosystemic relationship is not an external relationship between two closed entities; it is an integrative relationship between two open systems, in which each of them is an integral part of the other while forming a whole”[73] [MOR 73, p. 32]. The living world, as it is understood by biologists, is multiple and evolutionary.

It was not until the publication of the *General System Theory* by a biologist of Austrian origin, Ludwig von Bertalanffy (1901–1972), in 1968 that the functioning of living systems was theorized [VON 68]. The systemic vision is different from the prevailing scientific mechanistic-minded vision[74].

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[70] The concept of species is controversial. From Linné to the end of the 19th Century, the species was a set of morphologically similar individuals reproducing in the same way from one generation to the next. Nowadays, the most common understanding is that of German biologist Ernst Mayr (1904–2005), according to which a species is a population whose individuals can effectively and potentially interbreed, and produce viable and fecund offspring in natural conditions [MAY 42, p. 119 and following].

[71] The term was used for the first time in 1935 by British botanist Sir Arthur George Tansley (1871–1955) to refer to the basic unit of nature [TAN 35, pp. 284–307].

[72] It includes a biocoenosis composed of a set of associated species that develop an interdependence network, and a biotope which groups together all of the non-living original factors, called abiotic factors. It is much more than a simple living environment. In a way, the ecosystem can be compared to a living organism. Its giant cycles activate the entire mineral and living worlds [DER 75, p. 22].

[73] Translation of a French quote.

[74] This model conceals the assumptions represented by reductionism, realism, materialism and dualism. According to the reductionist assumption, any situation can be included by reducing it to a sum of its simplest parts. Realism implies that there is a knowable reality

In contrast, the systemic vision considered the world as a vast dynamic system to which humans belong. Interdependency replaced reductionism. The notion of a given reality independent from humans lost its relevance. Materialism is replaced with an integrating vision in a consistent whole, the current state of things, the known laws and the possible futures[75]. Biological systems, from cells to ecosystems, are considered as complex systems[76]. To explain them, biology turns to multiple explanatory schemes of a traditional mechanistic, Darwinian or even non-causal nature[77], which French philosopher and sociologist Edgar Morin (1921–) called the "dialogic principle"[78]. Life sciences are now confronted with a peculiar theoretical situation: contingency. Biological systems are open, off-balance, nonlinear systems, which results in emergence and threshold characteristics, and makes them difficult to predict[79].

1.2.1.2. *Genetics and molecular biology: to the farthest reaches of matter*

The 20th Century corresponded to an acceleration of discoveries concerning the intimate operating mechanisms of living beings. Genetics was born in the 1900s, although clever experimenters had already paved its

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independent from humankind. Materialism and dualism assume the joint existence of the world of tangible things and the world of ideas.

[75] "It is in fact about studying a phenomenon no longer in an analytical way, according to the method outlined by Descartes, by striving to reduce it to its simplest components, but in a "holistic" way, by trying to immediately understand it in its entirety and in relation to its environment" [VIV 94, p. 80].

[76] Complex systems, such as biological systems, have a more or less significant number of components interacting with each other and their environment. They can adapt to distortions and restore the conditions of their operation. As they are interweaved and prioritized, they have some autonomy. Each parameter, even if is insignificant, can have an essential influence on the behavior of the whole (the butterfly effect) [DER 75, pp. 106–108].

[77] "They are not eternal and immutable explanatory schemes, but intelligibility principles which exist today in life sciences, in one or a few specific forms" [MOR 05, p. 190].

[78] According to Morin "complex thinking is mainly the thought integrating uncertainty and which is able to perceive organization; which is able to link, contextualize, globalize, but at the same time recognize what is singular and tangible" [MOR 96].

[79] Biological systems are a counterexample of reductionism and linear determinism. They fall under the field of contingency. The laws that can be formalized with the knowledge of these phenomena now reflect possibilities and no longer certainties [DER 75, pp. 106–108].

way in the 19th Century[80]. As the science of heredity, it studies the hereditary traits of individuals, their transmission over generations and their variations. In 1903, Dutch botanist Hugo de Vries (1848–1935) described the appearance of sudden and hereditary variations, which he called "mutations"[81]. In 1909, heredity particles were referred to as "genes" by Danish botanist Wilhelm Johannsen (1857–1927). Following the chromosomal theory of heredity of American embryologist and geneticist Thomas Hunt Morgan[82], the gene, a purely conceptual tool, became an objective element referring to a small segment of chromosome. It is defined in the form of a triple unit: the function unit (it determines a trait), the mutation unit (it is likely to undergo modifications) and the recombination unit (it can change chromatid fragments).

In 1938, the American and Canadian geneticists Oswald Avery (1877–1955), Colin Munro Mac Leod (1909–1972) and Maclyn Mac Carthy (1911–2005) showed that DNA was the carrier of genetic information. Three years later, American geneticists George Wells Beadle (1903–1989) and Edward Lawrie Tatum (1909–1975) confirmed that it was indeed genes that controlled the synthesis of enzymes and that each protein was coded by a different gene. "One gene encodes a protein" became one of the dogmas of genetics. In his 1944 book entitled *What Is Life? The Physical Aspect of the Living Cell*, Erwin Schrödinger (1887–1961), a physicist of Austrian origin, developed an extremely rich thesis at the biological and philosophical levels. He described genetic material as requiring both stability and regularity, likening it to an "aperiodic crystal" representing the multiplicity of its potential traits [SCH 44].

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[80] In the 19th Century, hybridization experiments on mice and plants paved the way for genetics as a scientific discipline, but the greatest contribution was that of the Czech monk and botanist Johann Gregor Mendel (1822–1884), who developed the laws of inheritance in 1865. These laws imply the existence of autonomous elements, "heredity particles", which are transmitted from generation to generation and can mutate, namely change state [MEN 07, pp. 371–419].

[81] The role of sexual chromosomes in the determination of sexual traits was highlighted. Mendel's laws and the notion of mutation were extended from the plant world to the animal world.

[82] The experiments conducted on the drosophila by Thomas Hunt Morgan and his team at the University of Colombia from 1910, helped to show that each chromosome carries a determined number of genes (Mendelian units), which are organized into a linear series on the chromosome, and helped to draw approximate maps of them.

The year 1953 was a turning point in the history of genetics and the beginning of molecular biology, also called genetic engineering[83]. From X-ray images[84], the Anglo-Saxon geneticists James Dewey Watson (1928–), Francis Crick (1916–2004) and Maurice Wilkins (1916–2004) described the structure of the gene carrier molecule, deoxyribonucleic acid (DNA)[85]. The order of the four DNA nucleobases (adenine (A), cytosine (C), guanine (G) or thymine (T)) determines the genetic information. Living beings have an information system included in a linear sequence coding for proteins. The universality of the DNA molecule, code and functioning allows scientists to consider that a gene from any species can be integrated into and operate in any other species, whatever its taxonomic origin. In 1968, American biochemist Marshall Warren Nirenberg (1927–2010) and Indian biologist Har Gobind Khorona (1922–) deciphered the genetic code of the 20 amino acids whose combination forms proteins. The basic scheme of molecular biology and genetics was in place: a gene, a messenger ribonucleic acid (RNA), a protein. Therefore, the synthesis of proteins is assimilated to an information transfer mechanism. The development and functioning of organisms are the result of a genetic program, which provides a mechanistic explanation of living processes[86].

From the 1970s, molecular biology facilitated the achievement of numerous technological feats and became an essential tool of modern biology[87]. The dogma “one gene encodes a protein” that causes traits, if effective for bacteria, turned out to be too simplistic for complex organisms. In 1977, American biochemist Phillip Allen Sharp (1944–) observed that

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[83] The term “molecular biology” refers to all techniques used for handling nucleic acids (DNA, RNA), also called genetic engineering techniques. It also refers to the scientific discipline at the crossroad of genetics, biochemistry and physics, whose subject is the understanding of cell operating mechanisms at the molecular level.

[84] These X-ray images were the result of the work of British molecular biologist Rosalind Elsie Franklin (1920–1958) who was not, however, directly associated with the discovery of DNA and unfairly did not receive the Nobel Prize.

[85] The latter obtained the Medicine Nobel Prize in 1962.

[86] “The discovery of genetic code, which is key to the correspondence between the structure of DNA and that of proteins, makes it possible […] for the first time to effectively introduce the notion of information in biology, a so-called genetic information” [ATL 99, p. 14].

[87] However, molecular biology cannot be reduced to a set of techniques, separated from the knowledge of nature that these techniques help to acquire: “[It] is a scientific revolution, a new vision of the living world, which the development of a set of techniques made efficient and operational” [MOR 95, p. 15].

genes of superior organisms were fragmented into sequences encoding proteins (exons) and others apparently unnecessary (introns). A so-called “splicing” procedure removes RNA from non-coding elements. Yet, the way in which non-coding elements are removed and the way in which coding elements are reassembled can vary. A gene encodes different proteins. DNA, RNAs and proteins are constantly interacting and do not act in a linear way. It is not only the number of genes that makes it complex, but the way in which their expression is regulated[88].

At the turn of the 21st Century, the genome sequencing of a few model species, especially the human species as well as a few marine species, was completed[89]. Isolated study of a gene or group of genes involved in a single biochemical circuit was no longer sufficient. The genome had to be handled in its entirety, by considering the interactions within it and with the environment [WAT 03, p. 181]. Besides genetic determinism, a new school, “epigenetics”, emerged. It stepped back from the “everything is genetic” perspective [ATL 99] to focus on the whole formed by the cell[90]. From the point of view of this emerging school or discipline, DNA did not explain everything. Epigenetics studies how the environment and individual history influence the expression of genes and all of the modifications that can be transmitted from one generation to another.

Today, we know that each gene encodes numerous proteins and that, on the reverse, there are DNA portions that will not be transcribed or will be

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[88] In humans, for example, almost 150,000 genetic messages derived from only 22,000 known genes [COR 10a, p. 62].

[89] “We call genomes, all of the genetic instructions of an organism contained in the nuclei of each cell” [WAT 03, p. 181]. Sequencing consists not only of determining the order of genome bases, but also in identifying the groupings likely to be genes. Considering the chaotic architecture of the genome, locating a gene is a complex endeavor [WAT 03, p. 181]. The Human Genome project, which started in 1989, made the sequencing of a human genome possible in 2003 (approximately 20,000 to 25,000 genes). The genome sequencing of model organisms, such as the marine nematode *Caenorhabditis elegans* in 1998 or the mouse in 2002, also contributed to rapid progress in the field of genomics.

[90] British development biologist Conrad Hal Waddington (1905–1975) introduced the term “epigenetics” at the beginning of the 1940s, to name the branch of biology studying the cause–effect relationship between genes and their products, revealing the phenotype. In the 20th Century, the common definition of epigenetics was the study of hereditary changes in gene function, occurring without modifying the DNA sequence [WAD 57].

transcribed in RNA without producing proteins. These DNA portions are included in regions that geneticists previously called “rubbish DNA”, but which however represent in some species a significant part of their DNA, and turn out to be active[91]. However, by overfocusing on DNA, scientists forgot the thousands of molecules contained in cells and their potential interactions. It is necessary to realign our vision back to the time when genetics was not limited to DNA [ATL 99]. Once more, it is a question of learning where the traits are located which make genetic resources such coveted objects. If it is not an element, the gene(s), that harbors these traits, it will be the whole: the cell, the organism and its genome. Consequently, the notion of genetic resources cannot be limited to only genes and their functions.

1.2.2. *Bio-technosciences: the instrumentalization of the living world*

The end of the second millennium was marked by a scientific context favorable to an instrumental understanding of intellectual activity. The search for a better understanding of nature was closely linked to the transformation of the world and the improvement of living conditions [BLA 02]. The ontological questions about nature and the origin of life were followed by more pragmatic inquiries on the useful and controllable characteristics of living systems. Science, which used to focus on the passive study and representation of a given actual world, became technoscience, because it created worlds from reality [HOT 97, p. 160]. According to French sociologist, anthropologist and philosopher Bruno Latour (1947–), technoscience refers to “science in action”, and no longer the science of observation [LAT 87]. Bio-technosciences concern the living world and specifically refers to biotechnologies. They show the disappearance of the opposition between nature and artifice [HOT 97, p. 161], as demonstrated by biochemistry (see section 1.2.2.1). Furthermore, they symbolize the transformation of the living world into an artifact, as illustrated by genetic engineering and synthetic biology (see section 1.2.2.2).

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[91] RNAs induced by these DNA portions have a function as significant as the genes themselves. They allegedly activate or deactivate the latter according to circumstances and the environment. As gene regulators, along with other molecules (histones, methyl labels, etc.), they are currently recognized actors of epigenetics.

1.2.2.1. *Biochemistry: the connection between living and inert worlds*

Behind the diversity of forms and the variety of properties, a composition and functioning unit emerges [JAC 09, p. 281]. Biochemistry deals with the living world from the perspective of the chemistry of its structure and functions, and the chemistry of the expression and transmission of genetic information. Living organisms are compared to complex assemblies of inert molecules, including some, such as nucleic acids (DNA, RNA) and proteins, which are typical of the living world. “Thus, a domain is defined which, on the one hand, overlaps with chemistry, since the substances of beings are composed of universal matter components, and which, on the other hand, meets biology [organic chemistry] since these substances are radically different from those studied in mineral chemistry”[92] [JAC 09, p. 107].

Up until the first half of the 19th Century[93], chemists confined themselves to identifying and analyzing the great variety of the compounds of the living world, and classifying them according to their size (micro- or macromolecules), nature (sugars, fat, etc.) and their role (metabolic or plastic) [JAC 09, p. 108]. Thanks to synthesis, they started to imitate nature, not only by reproducing its compounds, but also by creating new bodies[94]. In the middle of the 19th Century, the subjective concept of “life force”[95] that significantly slowed the progress of biochemistry, was replaced with that of energy. Scholars argued that “[…] the chemical effects of life are due to

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[92] Translation of a French quote.

[93] The first drafts of chemical studies on living matter started in the 18th Century. At the beginning of the 19th Century, various substances were extracted from plants and animals (quinine, strychnine, etc.).

[94] To perform the synthesis of a chemical compound means to obtain this compound from other compounds by means of chemical reactions. In 1828, German chemist Friedrich Whöler (1800–1882) accidentally performed the synthesis of urea. This experiment showed that there was no longer any obstacle between the living world and the inert world. This accidental discovery was fundamental, since it demonstrated that it was possible to produce in a laboratory, under controlled conditions and from inorganic compounds, a compound known to be produced only by biological organisms.

[95] According to the vitalist thesis, the living world cannot be reduced to physical–chemical laws. It considers life as matter animated by a principle, “the life force”, which was allegedly added to matter laws for living beings. According to this understanding, this force allegedly breathes life into matter.

ordinary chemical forces […]”[96] [JAC 09, p. 251][97]. Numerous organic molecules were synthesized *in vitro* and the principle of catalysis by enzymes was discovered[98].

In the first half of the 20th Century, the improvement of the means of investigation made it possible to analyze increasingly small, complex or fragile molecules. The ensuing discoveries were numerous and major. In 1913, the German biologist Peter Michaelis (1900–1975) explained the dynamics of the enzymatic action[99]. The first link between a gene and an enzyme was presumed by British doctor Archibald Edward Garrod (1857–1936) in 1909 and confirmed in 1941. Genes control the synthesis of enzymes and each protein is encoded by a different gene. Genetics overlapped biochemistry and protein filled the gap between gene and trait.

In 1928, the bacterial transformation studied by English doctor and bacteriologist Frederick Griffith (1879–1941), aided progress in the identification of the chemical carrier of heredity. This biological process suggested that there was a “transforming factor” of an unknown nature in cells, which was likely to be durably integrated into the gene pool of other bacteria. The response was provided 10 years later by the Anglo-Saxon geneticists Oswald Avery (1877–1955), Colin Munro MacLeod (1909–1972) and Maclyn MacCarthy (1911–2005). It was DNA. In 1953, the Americans James Watson and Francis Crick, together with Briton Rosalind Elsie Franklin (1920–1958), determined the structure of the molecule composing genes and DNA, and thus furthered understanding of the molecular mechanisms of heredity[100].

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[96] Translation of a French quote.

[97] The German biologist Ernst Haeckel (1834–1919) concluded that, unlike the vitalist thesis, the laws of physics and chemistry were applicable to both the organic and inorganic worlds, and were therefore not heterogeneous. Life was nothing more than a physical–chemical phenomenon.

[98] “The catalytic force is that some bodies can, through their presence alone […], awaken chemical affinities, which would otherwise stay inactive at the temperature considered” [JAC 09, p. 112].

[99] Enzymes are proteins made by the cells of living organisms. They are specialized proteins, each for a specific action: to provoke, prevent or accelerate chemical reactions; to rearrange molecules; to add or, on the contrary, remove components. There are numerous types of enzymes. Not all of them have yet been discovered.

[100] A few years earlier, the American biochemist, of Austrian origin, Erwin Chargaff (1905–2002) published work on the four nucleic bases (ATCG) of DNA, which were decisive for the creation of a model of the DNA structure by James Watson and Francis Crick.

In the 1960s, French researchers in biology and in biochemistry François Jacob (1920–), André Lwoff (1902–1994) and Jacques Monod (1910–1976) made another major discovery. They explained how DNA was structured into codons to program the synthesis of proteins, coding redundancy, the mutation mechanism and the presence of a chemical mechanism coding the beginning and end of reading, like on a magnetic tape [GRO 86, p. 144]. However, "as rewarding as it is to be able to add a chemical analysis to the traditional genetic theory, it does not mean in any way that genetics was [therefore] limited to chemistry" [MAY 89, p. 70].

At the same time, marine biochemistry experienced its first developments in pharmacochemistry and pharmacology [FAU 00]. The first drugs of marine origin date back to the 1960s by means of the discovery of two compounds: spongothymidine and spongouridine, extracted from the Caribbean sponge *Tethya crypta*. "Both the diversity of marine forms and the adaptation of the latter to an atypical marine environment and/or extreme conditions (hydrothermal areas, seabed sediments, hypersaline lagoons, cold seeps of continental margins, Arctic and Antarctic continents, microbial mats, etc.) open new perspectives for the development of new bioactive molecules, enzymes, polymers, secondary metabolites, as well as the implementation of new industrial processes" [GUE 05b, p. 39].

Three methods are now available to obtain products in quantity: the extraction from macro- or microorganisms[101], total synthesis[102] and hemisynthesis[103]. More than 50% of marine bioactive substances have

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It showed that DNA, thanks to its bases, was likely to contain genetic information; that there was a correspondence between adenine and thymine, cytosine and guanine, (C/G or A/T) molecules and that this ratio was the same in all of the species studied.

[101] "Numerous active ingredients are still extracted from plants, even from microorganisms, because even if their synthesis is possible, it remains a scientific feat in a laboratory and it is not necessarily economically viable. Biological resources are still often required as raw materials used in the production of the drug" [MOR 07, p. 31].

[102] Total synthesis is the preparation of molecules from simple molecules, usually without using biological processes; "but increasingly, the isolated natural molecule is used as a 'prototype' of the commercialized drug, which is then produced through chemical synthesis. The natural resource then disappears from the manufacturing process of the drug" [MOR 07, p. 31].

[103] Hemisynthesis is the preparation of molecules based on natural molecules that already possess the molecule concerned. It is a compromise between the first and the second methods. "It is the case of some essential oils, containing simple molecules used as a basis for the

biological activity in the field of antitumor drugs, 10% in the field of antifungal drugs and the rest at the level of the immunomodulation, antibiotics, anti-inflammatory drugs, enzyme inhibitors or substances acting on the cardiovascular or nervous system. Few of them will result in a drug, because the molecule must be active, stable, non-toxic and available [GUE 05b, p. 41]. A second wave of complex molecules is being developed in various therapeutic fields: cancer, AIDS, inflammation, nervous system, etc. These molecules were discovered following the implementation of automated high-throughput screening of large collections of extracts on cellular targets discovered by means of genomics [NEW 07, DEB XX][104]. The production pathway, by means of biotechnology of active molecules, remains promising at the economic level, either through aquaculture in the natural environment of the producing organisms (sponges, ascidians, gorgons, algae) or through biotechnological processes (fermentation, photobioreactor), especially for microorganisms (cyanobacteria, mushrooms, bacteria) [GUE 05b, p. 44]. To date, marine biotechnologies are still a new science[105].

1.2.2.2. *Genetic engineering and synthetic biology: the transformation of the living world into an artifact*

In the 20 years following the discovery of the double-helix structure, the functioning and regulation of genes were understood. At the beginning of the 1970s, all of the enzymes required for the recombinant DNA technique were gathered, and this made it possible to move on from study to action[106]. Transgenesis made it possible to physically isolate a gene, by cutting on either side the DNA molecules concerned by the gene, and to integrate it into

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syntheses of consumer products or, for example, Taxotere derived from the yew tree. Obtaining these natural precursors is therefore like obtaining other raw materials for the industry, generally with a large-scale cultivation" [MOR 07, p. 33].

[104] The expression "high-throughput screening" (HTS) refers to the techniques aimed at studying and identifying, in chemical libraries and target libraries, molecules with new properties that are biologically active. The high-throughput refers to the use of IT and bioinformatics to accelerate the testing phase of molecules. Other new techniques, such as ultracentrifugation, electrophoresis and chromatography, are also used.

[105] In 2005, less than 5% of these organisms had been the subject of the study of their chemical and biochemical properties [GUE 05 b, p. 50].

[106] In molecular biology, the term "recombinant DNA" refers to the intermingling of chromosomal segments at a reduced scale and results in the recombination of two DNA segments into a single composed molecule [WAT 03, p. 110]. For an exhaustive presentation of genetic engineering techniques, see [TAG 03].

the genome of another organism, in order to compensate for or modify its hereditary genetic deficiencies[107]. Humanity was now capable of creating chimeras, and this made the living world, partially or fully, an artifact. Its creativity had no limit and could not be anticipated. For the first time, the *a priori* trust in research was spectacularly and dramatically questioned, as it was traditionally conducted without concern for its potential uses, or the risks for humankind and the environment in the background [ATL 99, p. 185]. In February 1975, a moratorium requesting the voluntary interruption of any research applying recombinant DNA technique to the living world was decided upon and then lifted[108]. The end of the 1970s was the beginning of gene isolation, characterization and cloning for industrial purposes. Researchers developed a set of techniques called biotechnologies, which made it possible to handle and reorganize the genes of various living organisms. Biotechnologies associated engineering work with life sciences to make new products and processes. Biotechnological industry was born[109].

In the 1980s, radical changes in the relationship between science and industry took place. “Biologists [started] to become aware that the socio-economic dimension of their work, and the slightly puritanical reservation of the beginning tinged with an obvious ecological concern [was] replaced by […] an attitude of perfect businessmen” [GRO 86, p. 193]. What kind of relationship should be established between universities, laboratories, teachers and the world of biotechnological companies? Should we be wary of or accept, to use the expression of James Watson, a “productive

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[107] The principle of genetic engineering is based on the transfer of a foreign gene into a cell in culture or in a tissue (somatic or germinal) to obtain the expression of a new property linked to the gene thus transferred, for example transferring tomato genes into the fish species *carasssius auratus* to increase its vitamin E content. This implies three operations: recombining, cloning and expressing [GRO 86, p. 180].

[108] Researchers from all around the globe met in private in Asilomar (State of California, USA) to decide upon it. No consensus was reached. The lifting of the moratorium came hand in hand with the implementation of conditions on precaution and reinforced security (GMO containment, no use of organisms that are dangerous for humankind or capable of reproducing in animals) [WAT 03, p. 120]. In 1976, the American National Institutes of Health (NIH), followed by other national institutes, adopted normative measures (rules of compulsory notification and minimum containment) [GRO 86, pp. 186–187].

[109] It was in 1976 that the first biotechnological company, Genentech, was created in the USA, followed by numerous others. Their objective was to manufacture on an industrial scale proteins whose usefulness was proven: insulin, the growth hormone HGH, EPO, etc. [WAT 03, p. 134 and following].

symbiosis" between the public and private sectors? [WAT 03, p. 136]. American universities implemented codes of ethics to avoid conflicts of interest, while encouraging researchers to privilege commercial objectives. Some researchers turned into real entrepreneurs and, in order to protect their interests, engaged in the creation of biotechnological companies and the systematic patent applications for their innovations. The scope that was then opening was tremendous. Very diverse activity sectors were involved: industrial, agronomic, pharmaceutical, biomedical, cosmetic, environmental, etc. In the biomedical field, for example, it became possible to purify and manufacture on an industrial scale molecules relevant to human and animal health, to diagnose genetic diseases, and to use genetic therapy techniques based on gene transfer to correct some hereditary deficiencies. Since the 1990s, we can also note a gradual separation between "traditional" biotechnologies based on cell biology and the cultivation of microorganisms and tissues, and "contemporary" biotechnologies based on molecular biology and genetic engineering. As these two paths simultaneously developed, they each created new specializations and new jobs [KOR 05, pp. 583–584][110].

In the field of marine biology, the application of genetic engineering techniques only dates back 20 years or so [THA 08, p. 234]. According to French professor in pharmacology Jean-Michel Kornprobst, there are three fields of current application of marine biotechnologies: the nutritional field, the biomedical field and the environmental field [KOR 05, p. 588]. Eligible marine organisms are mainly microorganisms, due to the amazing diversity of organisms (bacteria, mushrooms, yeasts, dinoflagellates, cyanobacteria, etc.), lineages and genomes, as well as the possibility of quickly cultivating them on a large scale. Future fields of application are, on the other hand, linked to genomics, synthetic biology and bioinformatics. They present problems related to the collection and management of massive quantities of data.

At the dawn of the third millennium, synthetic biology heralds a new era: the "*folle aventure des architectes et des bricoleurs du vivant*" ("mad adventure of the architects and tinkers of the living world") has started [DER 10]. It intends to implant entire custom-made genomes by means of

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110 The future seems inextricably linked to the development of genetic engineering. The only practical results in this field concern fish, in particular the production of transgenic species with rapid growth.

chemical synthesis into cells partially or fully emptied of their own genes[111]. The demarcation between nature and artifice disappears. Biologists are no longer content with describing existing genes, isolating them and then implanting them. They can design, make and recombine genes of interest, which are completely artificial, for industrial applications, and create “genetically enhanced organisms”[112].

In July 2010, the controversial American biologist and businessman John Craig Venter published, together with 23 researchers from the John Craig Venter Institute (JCVI), a description of the first cells with synthetic genomes[113] in the journal *Science*. The purpose of these cells, called *Mycoplasma mycoides JCVI-syn1.0*, was to be used as cell factories for the production of chemical compounds on demand[114]. Thirteen applications for patent families linked to the self-replication of synthetic bacterial cells were presented by Synthetic Genomics Inc., a private partner company of JCVI. Those cells raise a number of questions from the ecological, practical, legal and ethical points of view. Four main fields of application are promising:

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[111] The top-down approach modifies a natural biological system in order to obtain a simpler system, for example choosing a bacterium and removing some of its genes while keeping only the minimum necessary for its survival in a laboratory. The bottom-up approach consists of creating building blocks with well-defined functions and assembling them to make customized biological systems; for more information, see [BEN 11].

[112] Synthetic biology exceeds the capacities of transgenesis. With generic engineering, it is about adding or removing “natural” genes in a carrier organism and making hypotheses to deduct results from them, which eventually leads to industrial applications. The objective is reversed. The first goal is the product. For more information, see: doc. UNEP/CBD/COP/DEC/XII/24, October 17, 2014; [AIG 09]; [BLO 14].

[113] These cells were created by transplanting the “digitalized genomic information” in a bacterium of the Mycoplasma species *capricolum* deprived of its own genome. The new cells have the expected phenotypic properties and are able to continuously self-replicate [GIB 10, pp. 52–56].

[114] In order to obtain this result, 15 years of research and approximately 40 million USD of investment were necessary. In the 1990s, John Craig Venter and his team at the John Craig Venter Institute (JCVI) were already leading the race for deciphering the human genome. They made the headlines when they wanted to patent this discovery. In 2003, they had already synthesized a small virus infecting bacteria and, in 2008, the small genome of a bacterium called *Mycoplasma laboratorium*. For more information, see J. Craig Venter’s Website: www.jcvi.org.

– energy, with the production of biofuels from microalgae or through photosynthesis[115] ;

– pharmacy, thanks to living organisms transformed into drug factories;

– chemistry, *via* the synthesis of complex molecules or new materials;

– the detection of harmful substances, as well as decontamination, by creating sentinel organisms and depolluting organisms.

The demarcation between nature and artifice becomes blurred. Scientists even think of assisting evolution to conserve biodiversity. The living world, which used to be inherently considered as natural, is entirely projected in the humanized sphere of the artefact. Complex, it becomes an object of use, as illustrated by the marine genetic diversity and the resources it holds.

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[115] For example, J. Craig Venter is considering the production, by means of synthetic biology, of photosynthetic algae (cyanobacteria) capable of "hyper-producing" ethanol from CO_2, or of producing hydrogen intended for powering the fuel cells, which will equip new-generation hybrid cars [DER 10, p. 98].