

*Distinguished Lectures in celebration of the 150th anniversary of Charles Darwin's
"On the Origin of Species."*

The theory of evolution: 150 years afterwards*

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Resum. La introducció de la teoria d'evolució per selecció natural marca un canvi fonamental en el pensament humà. Darwin mateix va dir que era casi com confessar un assassinat. Després, les idees anteriors sobre la vida en el passat s'han anat refutant una darrere l'altra. Des de 1859 hi ha hagut altres canvis: des de la consciència del temps i espai profunds, passant pel moviment de les plaques tectòniques, fins a la ciència dels sistemes terrestres i la hipòtesi Gaia. La teoria de l'evolució naturalment s'ha modificat durant els anys amb una millor comprensió dels mecanismes de l'herència genètica i el paper de simbiosi en la selecció. Tot i que encara hi hagi un grapat de gent que la desafii amb bases religioses o pseudo-religioses, són molt pocs els que els prenen seriosament. La metodologia de l'evolució té aplicacions més enllà de la biologia, per exemple en el camp de la tecnologia. Sobretot, és una interpretació verificable de canvi continu en el desenvolupament de la vida a la Terra, que no és de cap manera contrari a la segona llei de termodinàmica. Com Thomas H. Huxley, amic i defensor de Darwin, va remarcar una vegada: havia estat ben estúpid no haver-hi pensat abans.

Paraules clau: Charles Darwin · evolució · *L'origen de les espècies* · Gaia · impacte dels humans a la Terra

Abstract. The introduction of the theory of evolution by natural selection marks a fundamental shift in human thinking. Darwin himself said it was like confessing to murder. Afterwards earlier ideas about life in the past crashed one after another. Since 1859 there have been other shifts: from awareness of deep time and space to tectonic plate movement to earth systems science and the Gaia hypothesis. Evolution theory has of course been modified over the years with greater understanding of the mechanics of genetic inheritance and the role of symbiosis in selection. Even if there is still a handful of people who challenge it on religious or crypto religious grounds, very few can now take them seriously. Evolution methodology has applications beyond biology, for example in the field of technology. Above all it is a verifiable interpretation of continuous change in the development of life on Earth, which is in no way contrary to the 2nd law of thermodynamics. As T.H. Huxley, Darwin's friend and advocate, once remarked: how stupid it was of him not to have thought of it himself.

Keywords: Charles Darwin · evolution · *On the origin of species* · Gaia · human impact on Earth

Darwin's theory of evolution: a fundamental shift in human thinking

Shifts in prevailing scientific paradigms are not easily accepted. Partly this is because most academics are better at looking at the constituent elements of problems than at seeing the connections between them and understanding how the resulting system works. The publication of *On the origin of species*, on

November 24, 1859 [1], by Charles Darwin (1809–1882) marked a fundamental shift in human thinking, one of the most significant in the intellectual history of the human species.

Until the 18th century, few had challenged the timescale of Earth history as set out in the Book of Genesis. Gradually, this came under challenge, not least from Georges Cuvier (1769–1832) and Jean-Baptiste Lamarck (1744–1829), but it was James Hutton (1726–1797) who first described in detail the immensity of Earth history, in which he saw no "vestige of a beginning" and "no prospect of an end." This was followed by Charles Lyell's (1797–1875) great work in the 1830s, and gradual acceptance of deep time with all its implications. Nonetheless, resistance continued. As Thomas Henry Huxley (1825–1895) once said, the path of geological speculation was long blocked by a thorny barrier carrying the notice: "No Thoroughfare. By Order of Moses."

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More recently, we have seen the fundamental shift in thinking caused by the theory of plate tectonics. Again, this was fiercely resisted, and Alfred Wegener (1880–1930), who first identified plate movement through continental drift, died before his ideas were generally accepted. Another, more recent example is the introduction of Gaia theory, or Earth Systems Science, which describes, in the words of James Lovelock and Lynn Margulis in 1974 [2]: “The evolution of a tightly coupled system whose constituents are the biota and their natural environment, which comprises the atmosphere, the oceans and the surface rocks.”

The genesis of evolutionary ideas

Darwin himself inherited the mindset of his age, and this is evident in the work that led to the publication of *The Voyage of the Beagle* (Fig. 1). He was influenced by the ideas of his grandfather Erasmus Darwin (1731–1802) and especially by those of Thomas Malthus (1766–1834), who in 1803 set out the principle that population growth would sooner or later outstrip the growth of resources, with the eventual result of overpopulation and insufficient supply. On his return from his expedition on the Beagle, which lasted almost 5 years (from December, 27, 1831 to October 2, 1836), Darwin had the time and financial independence to pursue his research interests as he so wished. He may have been influenced by Robert Chambers' anonymous work of 1844, in which Chambers proposed a universal law of development not unlike the eventual theory of evolution by natural selection (only the 12th edition, posthu-

mous, published in 1884, revealed the author's name). The trouble was that Chambers' book, *The Vestiges of the Natural History of Creation*, contained bad ideas as well as good ones, and although widely read was scarcely regarded as serious scholarship. For his part, Darwin was aware from the beginning that his ideas about evolution would be highly controversial; he therefore undertook a program of detailed work on barnacles, climbing plants, beetles, and, in the end, worms to establish his thesis beyond reasonable criticism. When he eventually produced *On the origin of species*, he admitted that it was like committing murder.

Darwin was precipitated into publication of *On the origin of species* because Alfred Russel Wallace (1823–1913) had come up with similar ideas and had written to Darwin in 1856 to explain some of his thinking. In February 1858, Wallace completed his work on the subject and sent a letter about it to Darwin. In a meeting at the Linnaean Society in London, in July of that year, Darwin's and Wallace's papers were first made public, even though they received scant notice [3]. The publication of *On the origin of species* the following year not only changed the direction of human thinking about life on Earth, but also provoked criticism and controversy, which expanded beyond the scientific community both in Britain and abroad (Fig. 2).

Accuracy of Darwin's theory

From the current perspective, it seems almost extraordinary how much Darwin (and Wallace in some respects) got right. In

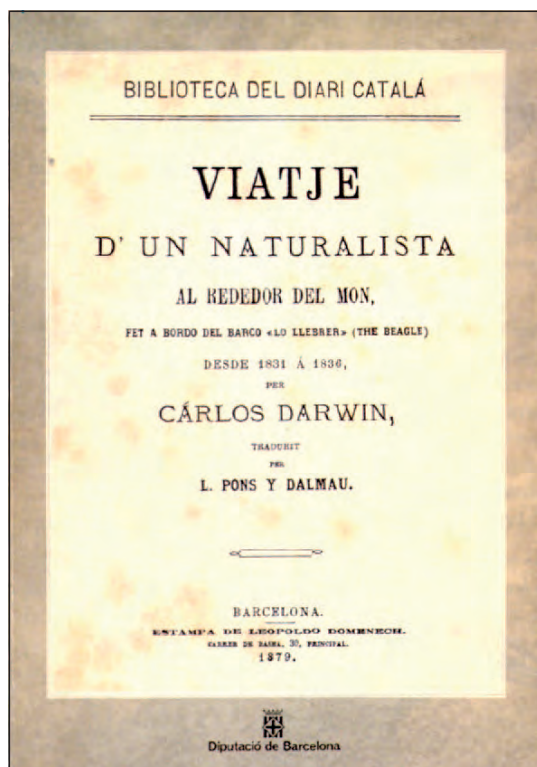


Fig. 1. Cover of the book *Viatje d'un naturalista al rededor del mon, fet a bordo del barco "Lo Llebrer" (The Beagle)*, by Charles Darwin, published in Catalan in Barcelona in 1879.



Fig. 2. Label of Catalan anisette Anís del Mono (literally, Monkey's Anisette) that reproduces a figure, half ape half human, holding a piece of paper that says: “It is the best. Science said it, and I am not lying.” There has been much controversy about the meaning of the animal represented in the label. Vicente Bosch, owner of the distillery where the anisette was produced, might have wanted to honor Darwin and his theory of evolution. However, it is also speculated that Bosch wanted to ridicule Darwin and science, with the face of the ape thus representing that of Darwin. The figure of the “monkey” became very popular, and the anisette was a great success in its time, and many decades after. The famous painter Ramon Casas (1866–1932), a friend of Picasso and other painters in Barcelona in those times, won a contest to choose the best poster to advertise the anisette.

their works, there was the theory of natural selection itself; there was the notion that, however diversified species might become over thousands or millions of years, they came from a single stock or tree; there was recognition of the selective extinction of species in different circumstances, thereby showing living organisms as a patchwork of possible forms; there was the need for deep time, in which evolution could take place (although how much deep time remained a matter of controversy); there was the dispersal of species related to their geographical circumstances (later well illustrated by plate tectonics); there was the role of sexual selection to explain dif-

ferentiation between the sexes; there was recognition of the co-evolution of species and what Darwin called "the economy of nature," or the biological processes we now describe as ecology; and there was the gradual evolution of living organisms similar to the gradual character of geological change over time. In this scenario, the role of an interventionist and capricious God in creating species from time to time, and of course maintaining them, was unnecessary. When early geologists found marine reptile fossils, the conventional wisdom then was that if only they looked hard enough they would find these same species alive somewhere else on Earth.



Fig. 3. Darwin's finches. Contribution of naturalist illustrator Carles Puche to the Darwin Year 2009.

Darwin was not and could not possibly have been aware of the many aspects of biology that research has revealed throughout the last 150 years. Nevertheless, what has been learnt since, in particular about the mechanisms of mutation and genetic inheritance arising from the work of Mendel and his successors, fits amazingly well with Darwin's original thesis. This is the case with respect to the discovery of DNA, the sequencing of the human genome, and, more recently, the identification of jumping genes, or transposons, between very different species. There has also been a modification of Darwin's ideas about selection, in demonstrations of cooperation between species and what has been called symbiogenesis (or the evolutionary effects of mutual dependence between organisms). Then there are the vagaries of evolution. How organic structures that play a given role evolve and eventually play another one: for example, how gills in fish eventually became the bones of the human ear. These discoveries, and surely those to come, have enriched the theory of evolution rather than qualified it. Darwin was truly an extraordinary pioneer, and every word he wrote has had lasting value.

There was particular opposition to Darwin's conception of deep time. Although many people abandoned biblical chronology, the age of the Earth remained a matter of high controversy. When Darwin and Huxley died, in 1882 and 1895, respectively, the conventional view was that the cooling of the Earth did not permit an age of more than 100 million years. Lord Kelvin (William Thomson, 1824–1907), one of the scientific sages of that epoch, maintained that it was closer to 24 million years. It was not until the discovery of radioactivity, by Antoine Henri Becquerel in 1896, and its application to the age of the Earth, by Ernest Rutherford in 1904, that the immensity of deep time could be accepted. Nowadays, the age of the Earth is roughly estimated to be 4550 million years, as was established by Clair Patterson in 1956 [4]. The timing of the beginning of life is still controversial but may have been around 900 million years later.

The enduring character of change

The character of change, as outlined by Lyell and his successors, was also a matter of controversy, with those who believed in uniformitarianism and others in catastrophism. The truth lies between them. In the second half of the 20th century, Stephen Jay Gould (1941–2002) introduced the idea of punctuated equilibrium, in which gradual change was punctuated by episodes in which the evolution of species moved rapidly in response to a variety of ecological circumstances. In addition, there seemed to be a contradiction between the second law of thermodynamics and entropy on one side, and the increasing complexity and elaboration of species on the other. Once it had been accepted that the second law of thermodynamics only operated within closed systems and that entropy carried the implication of the dispersal rather than the disappearance of energy, this objection lost its force.

The enduring character of change is an essential element in Darwin's theory of evolution (Fig. 3). This goes back to Heraclitus and the early Greek philosophers. Just as the environment

changes, so do living organisms and the relationships between them. This brings me to a few words about Gaia theory, which in many ways supplements our understanding of evolution.

The theory arose from James Lovelock's observation that the vital difference between the Earth and Mars was the chemical instability of the Earth's atmosphere, and that this instability was nonetheless constant within limits over billions of years. What established those limits? The answer was the role of living organisms, originally bacteria and later algae, operating through photosynthesis to help regulate the environment on the Earth's surface. In short there was a dynamic relationship between the physical and biological elements, each contributing to the other, a sort of symbiosis most clearly identifiable when seen from space.

Looking back it is strange how uncongenial the observation was to the practitioners of the conventional wisdom, particularly biologists, when it was put forward in its present form over a quarter of a century ago. Unfamiliar ways of looking at the familiar, or any rearrangement of the intellectual furniture, tend to arouse emotional opposition beyond rational argument: thus opposition to Darwin's theory of evolution by natural selection, of Wegener's ideas on continental drift and tectonic plate movement, and more recently of cometary or asteroid impacts from space.

The robustness of Gaia over 3600 million years is both impressive and reassuring. She has survived the great extinctions imposed from outside the Earth, and the great catastrophes from within it. This has required a remarkable resilience whereby physical and biological mechanisms have adapted to new circumstances. Nonetheless or perhaps as a consequence, Gaia has no particular tenderness for humans. We are no more than a small, be it immodest, part of Gaia. Only in the last tick of the clock of geological time did humans make their appearance, and only in the last fraction of it did they make any impact on the Earth system as a whole.

We now realize how vulnerable our planet is to human depredations. A periodic visitor from outer space would find more change in the last 200 years than in the preceding 2000, and more change in the last 20 years than in the preceding 200. The association between humans and their environment, including the micro-world in and around them, has changed at every change of human evolution: from vegetarians to meat eaters, from hunter gatherers to farmers, and from country dwellers to city dwellers. But the most radical divide started at the beginning of the industrial revolution in Britain, in the late 18th century. Until then, the effects of human activity had been local, or at worse regional, rather than global, as they are now.

The eminent biologist E. O. Wilson has laid out some of these changes in his book *The Creation*. In his words: "We have, all by our bipedal, wobbly-headed selves, altered Earth's atmosphere and climate away from the norm. We have spread thousands of toxic chemicals worldwide, appropriated 40 percent of the solar energy available for photosynthesis, converted almost all of the easily arable land, dammed most of the rivers, raised the planet sea level, and now, in a manner likely to get everyone's attention like nothing else before it, we are close to running out of fresh water. A collateral effect of all this genetic

activity is the continuing extinction of wild ecosystems, along with the species that compose them. This also happened to be the only human impact that is irreversible.” [5]

Impact of human activities on the evolution of life

All the civilizations of the past pushed evolution in different directions by clearing land for cultivation, introducing plants and animals from elsewhere, and causing a variety of changes. Modern industrial societies have caused disturbances of various categories, which, as implied in the quote from Wilson, are interlinked and will have an impact also in the future evolution of life on Earth. Let us examine a few of them.

Population increase. The human population has grown from around 1000 million at the time of Malthus, at the end of the 18th century, to over 2000 million in 1930, and is now close to 7000 million. Currently, it is increasing by over 80 million people every year. More than half of them live in cities, which are themselves like organisms, drawing in resources and emitting wastes.

Lack of resources. More humans need more space and more resources. Soil degradation is widespread, and deserts are advancing. Such degradation is currently estimated to affect some 10% of the world’s current agricultural area. Although more and more land, whatever its quality, is used for human purposes, the increase in food supplies has not kept pace with the increasing population. Applications of biotechnology, itself with several dubious aspects, can never hope to meet the likely shortfalls. In the meantime, industrial contamination of various kinds has greatly increased. To run our complex societies, we need copious amounts of energy, at present overwhelmingly derived from dwindling resources of fossil fuels laid down hundreds of millions of years ago.

Increasing wastes and pollution. Overpopulation leads also to mounting problems of waste disposal, including the toxic products of industry. In addition, there has been increasing pollution of water, both fresh and salt. No resource is more essential than fresh water, the demand for which doubles every 21 years and seems to be accelerating. The chemistry of the atmosphere has also changed due to human activities. Acidification from industry has affected wide areas of both land and sea. The levels of greenhouse gases are increasing at a rate that is already changing the average world temperature, resulting in large variations in climate and local weather as well as sea levels. Carbon levels in the atmosphere are now the highest they have been in the last 650,000 years, and they continue to rise. We face not only climate change but also climate destabilization.

Loss of biodiversity. Humans are causing extinctions of other organisms at many times the normal rate. Indeed, the rate of extinction is reminiscent of what happened when the dinosaurs came to an end, some 65 million years ago. Yet we remain ig-

norant of our own ignorance. The rising damage to the natural resources on which we, like all species, depend is immeasurable. There is no conceivable substitute for such resources. At present, there is a creeping impoverishment of the biosphere. And what about the effects on humans themselves? How much is human nature or behavior a product of evolutionary change or of the learned environment?

What kind of evolution?

In his book *The Meaning of the 21st Century*, James Martin distinguished what he has described as primary, secondary and tertiary evolution. He suggests that: “[p]rimary evolution is the mutation and natural selection of species—a glacially slow process [...] Secondary evolution refers to an intelligent species learning how to create its own form of evolution. It invents an artificial world of machines, chemical plants, software, computer networks, transport, manufacturing processes, and so on. It learns how to manipulate DNA [...] Tertiary evolution refers to something which is just beginning on Earth. An intelligent species learns to automate evolution itself.”

The idea of automated evolution represents a vast acceleration of change. James Martin writes that with the machines we envisage today, it could be a billion times faster: “Furthermore it will be incomparably more efficient. Darwinian evolution is described as being random, purposeless, dumb and Godless. Automated evolution is targeted, purposeful, intelligent, and has humans directing it and changing its fitness functions on the basis of results. In Darwinian evolution, the algorithm stays the same. In automated evolution, researchers will be constantly looking for better techniques and better theory. The techniques of evolvability will themselves evolve.”

In his fantasy *The Time Machine*, published in 1895, H.G. Wells (1866–1946) foresaw a genetic division of humanity into Eloi (or the master class) and Morlocks (or the servant class) in perpetual struggle against each other. At present, we do not have to go so far. On the one hand, humans may thereby be liberated from many current drudgeries. Soon houses may be able to clean themselves, robots may produce meals on demand, cars may drive under remote instruction; even the evolution of desirable characteristics could be automated. All this seems unimaginable when so many still have to trudge miles to collect fuelwood and water. On the other hand, humans could well become dangerously vulnerable to technological breakdown and thereby lose an essential measure of self-sufficiency. Already, our dependence on computers to run our complex systems, and on electronic information transfer to carry out our daily activities, whether small or large, is having alarming effects.

The future is around the corner

For the longer term, I hesitate to speculate. Are we a degenerate species because we have contrived that so many of us survive, thereby frustrating the processes of natural selection? Or can we safely proceed with secondary and even tertiary evolution?

Peter Ward once wrote: "The future stretches before us not as one long dark tunnel but as a series of vignettes of variable clarity, like a long avenue punctuated by street lights of differing luminosity." Cities will rise and fall. Tectonic plate movement will shift the relationship between land and sea. Changes in oxygen levels in the atmosphere may affect the viability of current forms of life. In any case, plant and animal species will continue to change in shape and function. Humans may be no exception. Given the evolutionary significance of our brains and the current hazards of childbirth, we might imagine a sort of human marsupial in which women gave birth earlier in the reproductive process and developed a kind of pouch.

Supposing our species fell victim to some natural disaster, as other species have so often done in the past. I wonder how long it would take for the Earth to recover from the human impact. How soon would our cities fall apart, the soils regenerate, the animals and plants we have favored find a more normal place in the natural environment, the waters and seas become clearer, the chemistry of the air return to what it was before we polluted it? Driven by evolution, life itself, from the bottom of the seas to the top of the atmosphere, is so robust that the human experience could become no more than a short and certainly

peculiar episode in the history of life on Earth. As the 17th century philosopher Thomas Hobbes said, as he approached death, "I am about to take my last voyage, a great leap in the dark." That is true of all living species, not least ourselves, now and for ever.

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Sir Crispin Tickell is a British diplomat, environmentalist and academic. He graduated from Christ Church Oxford with first class honours in Modern History. He is internationally respected as having a strong grasp of science policy issues, and over the course of his career, and despite his non-scientific background, has received numerous honorary doctorates (honoris causa) from British and overseas universities in Law, Civil Law, and Science. He has been decorated as a Knight of Grand Cross of

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