Special issue

A brief history of genetics: Chronology, concepts, and themes

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ABSTRACT: The history of genetics, since its origin, has transcended the scientific dimension, interweaving social, cultural, and political contexts. This brief contribution aims both to offer a chronological overview of scientific achievements in the field of genetics, starting from the pivotal work of Mendel and Darwin, and to outline concepts and themes that have emerged over time. It will show how the history of genetics allows us to reflect on some peculiar dynamics of the history of scientific thought, such as the evolution of scientists' image, its relationship with society, the birth of new forms of cooperation (from the small lab to Big Science), and a constant, intense dialogue among the different social actors. All these elements still strongly characterize genetics today and investigating their historical roots will help us understand their nature and *raison d'être*.

KEYWORDS: Chronology; concepts; society; genetics; history

1. Introduction

The history of studies, hypotheses, and discoveries in the field of genetics is not only a matter of the development of science. This is true of any paradigm shift[1] or new theory, of course, but in the birth and emergence of genetic theories, the links between the evolution of scientific thought and the historical, sociological, and cultural context are particularly evident, recurrent, and ultimately worthy of attention. Obviously in this case, these links between scientific production and its contexts are nourished primarily by the proximity of the theme to the meaning of human life, its origin, and its future. The emergence of new concepts, such as "hereditary character" or "gene", at the end of the nineteenth century forced us to rethink humankind's past, its evolution, its relationship with other living forms, and its specificities. In the field of genetics, the dialogue between what has taken place and is taking place in laboratories and research centres and what lies outside them is now more intense than ever, as demonstrated by the epistemological, philosophical, ethical, political, and legal debates prompted by the new frontiers of genomic editing, biobanks, and so on.

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[1] T. KUHN, *The Structure of Scientific Revolutions*, Chicago, 1962.

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The very concept of the gene, as well as those of genetics and DNA, has become such an integral part of our culture[2] and way of thinking that various authors,[3] building on the classic article by Star and Griesemer in 1989, have referred to it as a fitting example of a "boundary object". Boundary objects are "both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. [...] They have different meanings in different social worlds, but their structure is common enough to more than one world to make them recognizable, a means of translation".[4] It is quite easy to understand why an 'object' such as the double-helix structure of deoxyribonucleic acid and a term such as *gene* easily lend themselves to this definition. This, however, is already in some way a point of arrival, something that we easily recognise in the sensitivity and reinterpretation of our contemporary world.

It is therefore interesting to look at how genes and genetics have been scientifically and socially constituted over time, starting with Mendel's research and going to the end of the twentieth century, when the Human Genome Project was launched. In the second step, we will consider how the concept of the gene has changed over time and how other concepts, such as race and eugenics, were first widespread and then became outdated. Finally, we will highlight the contexts and themes central to the development of scientific thought, for which the evolution of genetics offers numerous opportunities: for example, the birth of laboratories in the modern sense and the changes in their collaboration, or women's contributions, or the image of the scientist in his or her relationship with society.

2. From Charles Darwin to the Genome Project: A chronological overview

The roots of genetics and the study of the inheritance of traits can usually be traced back to the Englishman Charles Robert Darwin (1809–1882) and the Czech Gregor Johann Mendel (1822–1884).[5] Certainly, such themes, which can already be found in classical authors such as Aristotle or Democritus, have always accompanied the history of philosophical and scientific thought. From the early modern age onwards, reflections on the origin and evolution of species and the mechanisms of reproduction intensified considerably, producing fundamental contributions that paved the way for the many crucial steps that marked the nineteenth century. Thus, Darwin's and Mendel's theories were preceded by essential works, such as the evolutionary theory developed by Jean-Baptiste Lamarck

[2] See, for instance, D. NELKIN, M. LINDEE, *The DNA Mystique: The Gene as a Cultural Icon*, Ann Arbor, 2004.

[3] M. BUCCHI, *Science and the Media: Alternative Routes in Scientific Communication*, London/New York, 1998, pp. 30-32; H.-J. RHEINBERGER, *Gene Concepts: Fragments from the Perspective of Molecular Biology*, in P. J. BEURTON, R. FALK, H.-J. RHEINBERGER (eds.), *The Concept of the Gene in Development and Evolution: Historical and Epistemological Perspectives,* Cambridge, 2000, pp. 219-239; E. PARTHENIA SHEA, *How the Gene Got Its Groove: Figurative Language, Science, and the Rhetoric of the Real*, 2008, chap. 5.

[4] S. L. STAR, J. R. GRIESEMER, *Institutional Ecology, 'Translations' and Boundary Objects: Amateurs and Professionals in Berkeley's Museum of Vertebrate Zoology (1907-39)*, in *Social Studies of Science*, 19 (3), 1989, p. 393.

[5] The chronological reconstruction was based in particular on the following texts: P. S. AGUTTER, D. N. WHEATLEY, *Thinking about Life: The History and Philosophy of Biology and Other Sciences*, Dordrecht, 2008; P. J. BOWLER, J. V. PICKSTONE, *The Cambridge History of Science, Vol. 6: Modern Life and Earth Sciences*, Cambridge, 2008; and the older P. ROSSI (ed.), *Storia della Scienza e della Tecnica*, Torino, 1988, vol. II, tome II; vol. III, tomes I & II. The chapters on biology are authored by B. FANTINI. Other sources are specified in the following.

(1744–1829) or the studies on hereditary traits carried out by hybridisers, cultivators, and zootechnicians through empirical research, which had already multiplied in the second half of the eighteenth century.[6] At the same time, it is undeniable that it was Darwin and Mendel who introduced the methodologies, contents, and interpretative proposals that were to play a central role in the development of knowledge in the decades that followed—although we should remember at this point that initially, Mendel's work was forgotten; it was then rediscovered at the dawn of the twentieth century, unlike Darwin's, which was immediately included in the debates of the time.

Of Darwin's important works, we recall here the indispensable *Origin of the Species*, published in 1859: a work that came out after a long gestation[7] and that was the result of the journeys that the Englishman made on board the HMS *Beagle*, during which he had the opportunity to collect an impressive amount of data on numerous animal species and fossils. Proceeding by inductive generalisation, Darwin developed a theory of evolution based on the idea of random and heritable variation, in which the action of natural selection intervenes in favour of the most suitable organism in a given environment. Darwin also made a proposal about the mechanism of inheritance of variation, called pangenesis, and formulated it in a variety of animals and plants under domestication (1868). According to this hypothesis, each part of the body produces corpuscles, the pangens, which flow into the egg cells and from there participate in the reproductive mechanism.

By contrast, Mendel based his theories on an extensive series of experiments conducted between 1856 and 1863 in Brünn, where he had joined the Augustinian monastery and taught as a substitute teacher in secondary schools. Based on crossbreeding generations of *Pisum sativum*, the common pea plant, Mendel studied the transmission and recombination of hereditary traits in offspring. In light of the crossbreeding obtained, he hypothesized the existence of two factors, one from the father and one from the mother, one of which could 'hide' the other. What is most significant about Mendel's methodology is not only the use of a quantitative and experimental approach but also, and above all, the application of mathematical and statistical calculations to the results obtained.

But why did Mendel's work go largely unnoticed? Several hypotheses have been proposed,[8] but none seems able to fully explain the substantial indifference of the scientific community of the time to the conclusions Mendel presented to the Natural Science Society in Brünn and published in its Proceedings. Whatever the reason, it was not until the beginning of the twentieth century that Hugo De Vries (1848–1935) and Carl Erich Correns (1864–1933) rediscovered the Czech monk's findings, which only then began to gain popularity and meet with experimental confirmation and general appreciation. At this point, a crucial figure in the history of genetics entered the scene: the Englishman William Bateson (1861–1926), the main advocate of Mendelian theory, who contributed greatly to its dissemination in English-speaking countries.

Through new studies, it became essential to investigate whether Mendelian factors were physical realities—and if so, where they were located—and how the transmission of a certain factor from par-

[6] A synthesis can be found in MAYR, *Storia del pensiero biologico* (ed. or. *The Growth of Biological Thought: Diversity, Evolution and Inheritance*, Cambridge, 1982), Torino, 2011, vol. I, pp. 589-599.

[7] J. VAN WYHE, *Mind the Gap: Did Darwin Avoid Publishing his Theory for Many Years?*, in *Notes and Records of the Royal Society of London*, 61 (2), 2007, pp. 177-205.

[8] See P. ROSSI, *op. cit.*, vol. II, tome II, pp. 924-928.

ents to offspring took place. The encounter between experiments in the field of agro-zootechnics, which had always looked at the transmission of traits, and research in the field of cytology, which enabled us to gain a better understanding of the structure and composition of cells, thus became important.

In fact, the existence of DNA, albeit called by different names, and of chromosomes had been known since the second half of the nineteenth century. It was the Swiss Friedrich Miescher who in 1869 isolated DNA during a series of experiments on leukocytes. Inside white blood cells, Miescher found a phosphorous-rich compound and called it nuclein, because he realised that it was in the cell nucleus. Almost twenty years later, Albrecht Kossel (1853–1927), Nobel Prize winner in 1910, showed that nuclein was composed of a protein part and a non-protein part (nucleic acid). Proceeding with the analysis of nucleic acids, he identified adenine, cytosine, guanine, thymine, and uracil. At the time, however, it was certainly not possible to hypothesise that DNA was involved in the mechanisms of the transmission of hereditary traits.

The same applies to chromosomes. They were discovered in 1878 by Walther Flemming (1843–1905), who also studied the process of cell division, called mitosis, and they were named by Heinrich Wilhelm Gottfried von Waldeyer Hartz (1836–1921). Their link to the transmission of hereditary traits became evident only years later. Incidentally, until 1955, the exact number of chromosomes in the human karyotype was not known; it became clear thanks to the work of Joe-Hin Tjio (1919–2001) and Albert Levan (1905–1988), both trained plant cytologists.

William A. Cannon (1870–1958) and Walter Sutton (1877–1916) were among the first to imagine that Mendelian factors were physically located on these threadlike structures. Their collaboration at the Zoological Station of Naples with Theodor Boveri (1862–1915) was essential because Boveri had already achieved important results. In 1902, Sutton, working on the chromosomes of *Brachystola magna* (grasshopper), realised that the number of chromosomes was halved during meiosis and that each spermatozoon or egg cell therefore received only one chromosome per pair. In his article 'The Chromosomes in Heredity', published in the *Biological Bulletin* in 1903,[9] Sutton demonstrated the substantial consistency of his results with Mendel's conclusions and suggested that chromosomes were the physical basis of Mendel's laws of heredity.

This was the beginning of intense research activity into chromosomes and the localisation of Mendelian factors, attracting the interest of many scholars and research groups. It is precisely in this crucial step, epistemological even more than experimental, that we identify the end of formal genetics and the beginning of what can be called chromosome genetics. Of the many advances made in the decades that followed, we should at least mention the work of Nettie M. Stevens (1861–1912), who identified the male Y chromosome. The discovery was published in the famous 1905 *Studies in spermatogenesis with especial reference to the accessory chromosome*[10] and followed the results of Erwin C. McClung (1870–1946), who had traced sex determination to the X chromosome alone.

[9] W. SUTTON, *The Chromosomes in Heredity*, in *Biological Bulletin*, 4 (5), 1903, pp. 231-251.

[10] N. M. STEVENS, *Studies in Spermatogenesis with Especial Reference to the "Accessory Chromosome"*, Washington, D.C., 1905, Vol I. *Cfr*. S. G. BRUSH, *Nettie M. Stevens and the Discovery of Sex Determination by Chromosomes*, in *Isis*, 69, 1978, pp. 162-172.

A strong impetus for these new lines of research came also from Thomas H. Morgan (1866–1945), 1933 winner of the Nobel Prize for Medicine, and his research group, which concentrated their experiments on *Drosophila melanogaster* (fruit fly). Initially, Morgan was inclined towards an epigenetic theory. He was also sceptical of Sutton's studies and more prone to believe that the cytoplasm, and not the nucleus (and therefore the chromosomes), played a major role in heredity. After studying the white-eye mutation on *Drosophila* and analysing its transmission to offspring, Morgan completely revised his position. He argued that genes were physically located on chromosomes, and he explained that certain 'Mendelian factors' recombined during meiosis according to the theories of a Belgian cytologist, Frans Alfons Janssens (1865–1924), who in 1904 was the first to describe the crossing-over phenomenon. Janssens had noted how, during meiosis, members of chromosome pairs roll over each other, facilitating the exchange of strand segments. The more two factors usually associated (e.g. wings and eye colour) end up splitting, the further apart their positions on the chromosomes must be. This was the basis for the first mapping attempts by Morgan's group in the following years, in particular by Alfred H. Sturtevant (1891–1970).

The established variability of genes and the phenomena of recombination intensified the interest in mutations, which also led to a challenging methodological question: How can we systematically study a phenomenon that is in itself random and unpredictable? Attempts were made to induce mutations in the laboratory. One of the scientists who worked hardest on this problem came from Morgan's group: Hermann Joseph Muller (1890–1967), Nobel Prize winner in Medicine in 1946, who demonstrated how the use of massive doses of X-rays could induce mutations in egg and sperm cells.[11] Muller also claimed, unlike many of his colleagues, that the mutations induced by this method were the same as those that occur naturally.[12] It was only later that scientists began to use chemical mutagens.

Mutational studies are another fundamental line of research intertwined with the hypotheses about the genes' role in controlling and regulating metabolic reactions. One of the earliest examples predates Muller's findings: Between 1902 and 1908, Archibald Garrod (1857–1936) observed that certain metabolic diseases, such as alkaptonuria, albinism, cystinuria, and pentosuria, are transmitted according to Mendel's laws, therefore assuming that their cause was a mutation in a hereditary factor. They are in fact all diseases caused by the lack of a specific enzyme. Garrod's hypotheses became relevant again in the 1940s, when George Beadle (1903–1989) and Edward Tatum (1909–1975) devised the famous "one gene–one enzyme" formulation (which later became "one gene–one polypeptide chain", in which, as we know, a triplet of bases codes for an amino acid) and inferred that the two main functions of genes were self-replication and the production of enzymes.

In the 1930s, the analysis of human chromosomes[13], which had hitherto been little studied, was made possible by the development of cytogenetic techniques, paving the way for human genetics

[11] H. J. MULLER, *Artificial Transmutation of the Gene*, in *Science*, 66, 1927, pp. 84-87; ID., *The Problem of Genic Modification*, in *Proceedings of the 5th International Congress* 1, 1928, pp. 234-260.

[12] H. J. MULLER, *Artificial Transmutation of the Gene*, pp. 84-87.

[13] There is no room here to talk about the evolutionary synthesis, which saw Darwinian evolutionism and Mendelian theory merge into a study of populations that accounted for the most recent results in the field of genetics and the tools of statistics. John Haldane (1892-1964), Sewall Wright (1889-1988), and Ronald Fisher (1890-1962) are regarded as its initiators. For a historical reconstruction signed by one of the protagonists of the debate, see E. MAYR, *op. cit.*, vol. II.

and the intensification of discoveries of genetically based diseases. In the 1940s, it was the turn of thalassaemia, whose genetic origin was demonstrated by two Italian researchers, Ida Bianco (1917–2006) and her husband Ezio Silvestroni (1905–1990), and by James V. Neel (1915–2000), who went on to study sickle-cell anaemia. As is well known, it was Linus Pauling (1901–1994), later awarded the Nobel Prize for Chemistry and Peace, who in 1949 investigated the physical properties of haemoglobin in the case of anaemia and finally confirmed the link between genes and protein synthesis. In the following decade, attention expanded to diseases caused by chromosomal abnormalities. In 1959, for example, Jérôme Lejeune (1926–1994), counting on the valuable collaboration of Marthe Gautier (1925–), a specialist in the analysis of cell cultures (and using Tjio and Levan's cytological technique), observed that Down's syndrome was linked not to the absence of a chromosome but to the presence of an extra chromosome.

In the meantime, the so-called Phage Group, an informal collaborative network comprising, among others, the physicist Max Delbrück (1906–1981), Alfred D. Hershey (1908–1997), and Salvador Luria (1912–1991), tackled a new problem that had become central, namely, whether genetic material was carried by proteins or by DNA, both of which were present in the nucleus. The experiments were carried out using a bacteriophage whose phosphorus parts had been radioactively charged, and the results gathered evidence that it was DNA that contained the hereditary information. They found that the virus released not proteins but only DNA into the bacterium to "colonise" it. This discovery earned Delbrück, Hershey, and Luria the Nobel Prize for Medicine in 1969.[14]

Increasing research into the properties of deoxyribonucleic acid led to the discovery of its double-helix structure in 1953. This work, carried out by James Watson (1928–) and Francis Crick (1916–2004), would never have been possible without the studies of Maurice Wilkins (1916–2004) and Rosalind Franklin (1920–1958). At this point, it was necessary to explain not only the mechanisms of DNA self-replication but also how protein synthesis was controlled. The identification of messenger RNA was not long in coming. Finally, in a 1961 article published in *Nature*,[15] Crick, together with Leslie Barnett (1920–2002), Sydney Brenner (1927–2019), and Richard Watts-Tobin (1934–), set out to decipher the genetic code: the sequence of bases was to be read in triplets, since each triplet (or codon) encodes an amino acid.

In the years that followed, the steps forward were countless and decisive. It would be too complex to go through all the stages: for example, the 1977 discovery of the existence of introns and exons, and therefore of the presence of non-coding DNA; the first steps in biotechnology; and the localisation in 1983 of the first polymorphic marker linked to a genetic disease, that relating to Huntington's chorea, found on chromosome 4.[16]

The growth of increasingly precise and complex knowledge led to the Human Genome Project in the late 1980s. Given the considerable costs involved in the project, the first of its kind in the life sciences, there was much criticism and discussion. In fact, the complete sequencing of the human genome

[14] The reasons can be found at www.nobelprize.org/prizes/medicine/1969/summary/, last accessed 20 January 2021.

[15] F. Crick, L. Barnett, S. Brenner, R. Watts-Tobin, *General Nature of the Genetic Code for Proteins*, in *Nature*, 192, 1961, pp. 1227-1232.

[16] J. F. Gusella et al., *A polymorphic DNA marker genetically linked to Huntington's disease*, in *Nature*, 306, 1983, pp. 234-238.

definitively opened up a new phase in the history of genetics, of which we are today only seeing the first effects, centred on the possibility of intervening directly on genes, for example, to prevent or cure diseases by modifying DNA.

3. Evolving concepts

This brief, non-exhaustive chronological reconstruction shows how the history of genetics is marked by the birth and sequence of new concepts, whose meanings constantly change, intertwining with philosophical, historical, sociological, and cultural issues. Obviously, the concept of the gene is central, but it is not the only one to deserve attention. Other concepts, such as heredity, 'race', eugenics, and epigenetics, have played and continue to play an important role, demonstrating once again how and to what extent research into DNA, the evolution of species, and the mechanisms of cellular reproduction have catalysed, in the past as well as today, reflections and debates in the world of research and in society in equal measure.

As many contributions have shown,[17] the concept of the gene has taken on profoundly different meanings in the history of genetics, in relation both to the periods when studies on heredity were carried out and to the epistemological approach of the researchers dealing with it over time.

The term *gene* was introduced[18] in 1908 by Wilhelm Johannsen (1857–1927), a Danish botanist, and soon replaced a series of words that had been used to that point, from Mendel's *Merkmal*—'character', 'factor'—to the *Anlage*—'unit'—of the Dutchman De Vries, and the *Unit-character* proposed by Bateson. The problem lay in the semantic confusion that these terms failed to resolve: they could refer either to the visible characteristic or to the corresponding hereditary basis. It was for this reason that Johannsen introduced the clear distinction between 'phenotype' and 'genotype'. The term *gene* recalled *pangene*, which Darwin and De Vries had used to refer to hereditary particles. This lexical change was crucial and brought with it questions not only of semantics but also of epistemology, science, and philosophy. The first problem emerging with renewed clarity was about the relationship between gene and characteristic, the chemical and biological mechanisms relating them, and, above all, the nature of the gene itself. If phenotypic characteristic was the empirically 'seen', how was the gene to be understood? Was it a material reality or, rather, a unit of calculation? The *formal approach*, the term used to refer to the pre-molecular or classical phase of the history of genetics,[19] did not concern itself with what a gene actually and chemically was. Johannsen himself was not interested in answering the question, as this passage from his fundamental text *Elemente der exakten Erblichkeitslehre*[20] shows: "The word gene is completely free from any hypothesis; it only ex-

[17] For an in-depth discussion: E.F. KELLER, *The Century of the Gene*, Cambridge, 2000; P. J. BEURTON, R. FALK, H.-J. RHEINBERGER, *The Concept of the Gene in Development and Evolution: Historical and Epistemological Perspectives,* Cambridge, 2000; P. PORTIN, *The Concept of the Gene: Short History and Present Status*, in *The Quarterly Review of Biology*, 68 (2), 1993, pp. 173-223; E. A. CARLSON, *Defining the Gene: An Evolving Concept*, in *American Journal of Human Genetics*, 49, 1991, pp. 475-487.

[18] Curiously, William Bateson had already used the term *genetics* in a private letter four years earlier, but it did not become widespread until after Johannsen introduced *gene*.

[19] P. PORTIN, *op. cit.*, pp. 175-179.

[20] W. JOHANNSEN, *Elemente der exakten Erblichkeitslehre*, Jena, 1909.

presses the established fact, that at least many properties of an organism are conditioned by special, separable, and thus independent 'conditions', 'foundations', 'dispositions'".[21] In the third edition of 1926, Johannsen emphasised the concrete dimension of the gene[22]—"Genes are realities, not hypothetical conceptions"—but then concluded that genes are "entities of calculation, expressions of realities of unknown nature".[23] Despite the possible apparent contradictions, it is quite clear that for Johannsen, it was important to state that genes exist, that "they are there". It was less important to establish "what they are" because that is not functional in explaining the mechanisms of heredity.

Already the cytogenetic phase implied a change since with Sutton and then the studies of Morgan and his research group, interest shifted to chromosomes,[24] their constitution, and the possible location of genes. Regarding this period, Hermann Muller's text, read at a conference in 1926, remains fundamental. The American geneticist reiterated his opinion that the gene was *the* basis of life and not just *a* basis of life. Incidentally, Muller argued for the key role of mutations and, more than anything else, their inheritance, maintaining that mutations and inheritance were key components of the same mechanism, not separate processes.[25]

A further breakthrough occurred with the entry into the molecular phase—which Portin calls *neo-classical*—and thus with the identification of the double-helix structure of DNA and the coding mechanisms of polypeptide chains. The years that followed 1953 strongly put the concept of the gene as a unit of information to the test. Consider, for example, the 1976 discovery of introns, demonstrating the existence of non-coding—and therefore apparently unused and unusable material—within each gene. Other examples include all the subsequent experiments that led to intervention directly on the gene to modify it. The more the gene was investigated, the more its concept became complex and difficult to handle. The words of Portin, who wrote thirty years ago, are very effective in this respect:

> [Due to] the discoveries of repeated genes, split genes, nested genes, overlapping genes, transposable genes, alter-native splicing, multiple and complex promoters, enhancers and silencers, downstream signals, internal control signals, proteolytic cleavage of translation products and other types of protein processing, editing of primary transcripts, the special case of immunoglobin genes, and the detailed analysis of gene complexes […], our comprehension of the nature of the gene entered a dramatic new phase. Paradoxically, in spite of the new, sometimes overwhelming, concreteness of our comprehension of the gene as a result of DNA technology, we seem to be left with a rather abstract and generalized concept of the gene that has quite different significances in different contexts.[26]

[21] Translation by N. ROLL-HANSEN, *Commentary: Wilhelm Johannsen and the problem of heredity at the turn of the 19th century*, in *International Journal of Epidemiology*, 43(4), 2014, pp. 1007-1013.
[22] W. JOHANNSEN, *Elemente der exakten Erblichkeitslehre,* Jena, 1926[3].
[23] N. ROLL-HANSEN, *op. cit.*, p. 1011.
[24] E. A. CARLSON, *The Drosophila Group: The Transition from the Mendelian Unit to the Individual Gene*, in *Journal of the History of Biology*, 7 (1), 1974, pp. 31-48.
[25] E. A. CARLSON, *The Drosophila Group: The Transition from the Mendelian Unit to the Individual Gene*, *op. cit.*, p. 31. See H. J. MULLER, *Variation Due to Change in the Individual Gene*, in *The American Naturalist*, 56 (642), 1922, pp. 32-50.
[26] P. PORTIN, *op. cit.*, p. 174.

It is precisely this last passage, in which Portin maintains that the concept of the gene "has quite different meanings in different contexts", that brings us back to the contemporary idea of the gene as a "boundary object" that crosses spheres and contexts and takes on renewed semantic values over time. In particular, we should emphasise how today the 'gene' is not an exclusive preserve of scientific language, belonging plastically to social, cultural, legal, political, and economic reality.

Moreover, it is typical of the history of genetics, as we said, to cross heterogeneous dimensions that go beyond the purely scientific. Another concept clearly demonstrates this: namely, the concept of eugenics.[27]

Well before the sad and well-known drifts of the Nazi and Fascist regimes, the term *eugenics* was coined in 1883 by Francis Galton (1822–1911),[28] who would later define it as "the study of the agencies under social control that may improve or impair the racial qualities of future generations either physically or mentally".[29] At the beginning of the twentieth century, eugenics programmes multiplied, together with the number of conferences, societies, and journals. Examples include the American Eugenics Record Office, the English Eugenics Society dedicated to popularisation, and the Eugenics Review.[30] The basic idea was to "improve" the human species by eliminating phenomena such as alcoholism, crime, 'moral degeneration', and even innate eroticism. The basic assumption of the programme was that all these behaviours were phenotypical traits determined solely and exclusively by a single gene (the environment or situations of degradation were not taken into account). It would therefore be easy to eliminate them, for example, by means of targeted sterilisation campaigns. Scientists of the calibre of Muller or Morgan adhered to this idea, and across the USA in the 1930s, a series of forced sterilisations were carried out. Opposition to the concept of eugenics became very strong in scientific circles, and fierce criticism arose because of factors including Hitler's rise to power, together with the Nazis' use of these theories, and the gradual awareness of the lack of scientific basis for the concept (it was soon discovered that each phenotypic characteristic was in fact determined by several genes). So, the term was no longer used, except in a negative sense, and the first human genetics programmes promoted at first the protection of the human gene pool and its variability as a guarantee of the survival of the species.[31]

A similar path and fate were met by the concept of race. The discoveries about the extreme variability of human DNA and the evolution of the human species demonstrated its scientific unreliability and definitively confirmed the impossibility of implementing a discrete and objective classification on a genetic basis.[32] The concept of race was so criticised by scientists that this criticism, combined with political events and social and cultural changes of the second half of the twentieth century, made necessary and imperative a broader reappraisal of the term.

[27] See A. Bashford, P. Levine (eds.), *The Oxford Handbook of the History of Eugenics*, Oxford, 2010, and also F. Cassata, *Molti, sani e forti. L'eugenetica in Italia*, Torino, 2006.

[28] F. Galton, *Inquiries into Human Faculty and its Development,* London, 1883.

[29] F. Galton, *Memories of my Life*, London, 1908, p. 321.

[30] L. Bland, L. A Hall, *Eugenics in Britain: The View from the Metropole*, in A. Bashford, P. Levine (eds.), *op. cit.*, pp. 213-227.

[31] B. Fantini, in P. Rossi, *op. cit.*, 1988, Vol. III, tome II, p. 793.

[32] L. L. Cavalli-Sforza, P. Menozzi, A. Piazza, *The History and Geography of Human Genes*, Princeton, 1994, pp. 16-20.

So these terms were decisively abandoned, but others were not. Let us mention at least one that was introduced in 1942 and continues to be used today. This is the concept of epigenetics, a recent branch of genetics studying how the environment influences gene expression without altering DNA sequences.

4. Conclusions: Contexts, actors, dynamics

The history of genetics is an incredible magnifying glass, allowing us to take a close look at science and how it works and has worked over the last century. If we look at the places and actors of gene studies, we find not only a sequence of hypotheses, discoveries, and methodologies but also a rich overview of contexts, places, and sociocultural dynamics.

Let us begin by looking at the two scientists who, as we said, are generally referred to as those who gave the decisive impetus to the research on evolution and the heredity of traits developed during the twentieth century: Mendel and Darwin. Their biographies and intellectual paths, in many different ways, open a window on what it meant to be a "man of science" in the second half of the nineteenth century. Mendel was the son of a farmer, and to continue his studies, he entered a monastery, where his appointment as abbot effectively prevented him from continuing his scientific work. Darwin, on the other hand, came from a wealthy family; the son of a doctor and grandson of a natural philosopher, he could support his travels and research without financial worries. For both of them, being a scientist was not a profession; it was an occupation developed according to their own inclinations and interests without any income. This point is crucial for the history of scientific thought as well as for the evolution of the figure of the scientist, especially in relationship with society.[33] Only during the twentieth century, due to the progressive institutionalisation of science and the production of knowledge, does the figure of the professional scientist emerge as one who researches no longer for (only) mere vocation but (also) for work, earning a living. This is a paradigmatic change, giving rise to new areas of knowledge and provoking new questions and reflections by social actors. It is therefore no coincidence that Craig Venter's (1946–) decision to found Celera Genomics as a private response to the Human Genome Project has catalysed growing debate and reflection on the lawfulness and morality of his conduct.[34] This scientist-entrepreneur personifies the highest point of this ongoing tension. On the one hand, there is the ancient perception of the scientist as a morally upstanding figure, who carries out his or her studies with complete economic disinterest. On the other hand, the professional scientist emerges, pursuing profit as a 'side effect' and using scientific research as a genuine entrepreneurial activity.

[33] On the images of the scientist throughout the history of science, see the fundamental works by Shapin, in particular S. SHAPIN, *The Way We Trust Now: The Authority of Science and the Character of the Scientist*, in P. HOODBHOY, D. GLASER, S. SHAPIN (eds.), *Trust Me, I'm a Scientist*, London, 2004, pp. 42-63; S. SHAPIN, *The Man of Science*, in L. DASTON, K. PARK (eds.), *The Cambridge History of Science. Vol. 3: Early Modern Science*, Cambridge, 2006, pp. 179-191; S. SHAPIN, *Figures de scientifiques*, in *Histoire des sciences et des savoirs, Vol. 3: Le siècle des technosciences (depuis 1914)*, Paris, 2015, pp. 27-45.

[34] For instance, S. SHAPIN, *Figures de scientifiques*, pp. 27-45; J. WITKOWSKI, *A life worth writing about*, in *Nature*, 449, 2007, pp. 785-786.

Furthermore, when the subject of the research is the genome, and therefore the very essence of human life, intense ethical, legal, and philosophical questions arise, summed up by this question: Who owns the genome?[35]

Another trend in the history of genetics relates to the birth of the laboratory in the modern sense. Consider Mendel and Darwin; surely, they were part of a network of contacts fundamental to their training and to the reception of their work. But it is clear that the two men of science worked on their research largely alone. We have to go forward in time to find more extensive, continuous, and even institutionalised collaborations and arrive at the first genuine research groups in the life sciences. One of the earliest, and also best known and most important, laboratories in the history of genetics is undoubtedly the one set up around the figure of Morgan, also known as the 'Drosophila Group', with reference to the animal model used, or the 'Fly Group', after the name of the room where the researchers met. Here, in the Zoology Department of Columbia University, biologists such as Muller, Sturtevant, and Calvin B. Bridges (1889–1938)[36] worked together. Another example is the famous Phage Group, an informal group that revolved around the figure of Delbrück rather than a real laboratory, in which the meeting of scientists from different backgrounds played a key role. This group gave rise to the Phage Course, a summer school at the Cold Spring Harbor Laboratory, which was fundamental to the training of numerous researchers.

It is even more interesting to note that, from the laboratory's limited and restricted size, the range of action has increasingly expanded, first with the intensification of collaborations between different research institutes, and then with the launch of the Human Genome Project,[37] a proper window on the Big Science that characterises our century and finds its counterpart in other fields in the Large Hadron Collider (LHC) of CERN in Geneva or in the International Space Station. The International Human Genome Sequencing Consortium has come to involve not only the USA and the UK but also Germany, Japan, China, and France.[38]

Finally, it should not be forgotten that the history of genetics, like the whole of the history of scientific knowledge, is also crowded with female figures that the historical memory has given us with difficulty despite the fundamental contributions they have made. The most famous is certainly Rosalind Franklin, but she is not the only one. Think of Nettie Maria Stevens, who discovered the Y chromosome; Barbara McClintock, winner of the Nobel Prize for Medicine and Physiology in 1983, who in the 1950s discovered transposons (genetic elements that can move); or Martha Chase, who performed the crucial experiment with bacteriophages that led to the identification of DNA as the carrier of genetic material: the experiment is now known as the Hershey-Chase experiment, yet Chase's collaboration with the Phage Group is rarely mentioned.

[35] M. ANGRIST, R. M. COOK-DEEGAN, *Who Owns the Genome?*, in *The New Atlantis*, 11, 2006, pp. 87-96.

[36] See E. A. CARLSON, *The Drosophila Group: The Transition from the Mendelian Unit to the Individual Gene*, *op. cit*. On the relevance of specific laboratory dynamics in the construction of scientific knowledge, see B. LATOUR, S. WOOLGAR, *Laboratory Life*: *The Construction of Scientific Facts*, Beverly Hills, 1979; B. LATOUR, *Science in Action: How to Follow Scientists and Engineers Through Society*, Cambridge, 1987.

[37] The bibliography is very rich. See, for example, H. ZWART, *Human Genome Project: History and Assessment*, in *International Encyclopedia of Social & Behavioral Sciences*, Oxford, 2015, 2 ed., pp. 311-317.

[38] www.genome.gov/human-genome-project. Last visited on 18 January 2021.

All these dynamics, which the history of genetics highlights, are a window on the broader panorama of the development of scientific thought. Genetics is undoubtedly a privileged place of observation. It tells us a great deal about our past and our present and will continue to do so for those who look back in the future.

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