Review

Darwin and Mendel: evolution and genetics

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Many studies have shown that students' understanding of evolution is low and some sort of historical approach would be necessary in order to allow students to understand the theory of evolution. It is common to present Mendelian genetics to high school students prior to Biological Evolution, having in mind historical and epistemological assumptions regarding connections between the works of Gregor Mendel and Charles Darwin. It is often said that Darwin 'lacked' a theory of heredity and, therefore, he had not been able to produce the synthetic theory of evolution himself. Thus, schools could provide a prior basis for heredity, so that students could begin to study evolution with a proper background in genetics. We intend to review some research on the history of biology, attempting to show that, even if Darwin had had notice of Mendel's works – which we think he did – he would not have changed his views on heredity. We examine this belief and its possible origins, offer some considerations about Darwin's views on heredity, including his knowledge of the 3:1 ratio, the consequences for the work on Nature of Science (NOS), and finally give five reasons to consider alternative possibilities for curriculum development.

Keywords: Darwinism; Mendelism; Evolution education; History of biology; Nature of science (NOS)

Introduction

In many countries, syllabuses first present Mendelian genetics to high school students and only subsequently address Biological Evolution, focusing on several examples of microevolution. This perspective is rooted in historical and epistemological assumptions regarding connections between the works of Gregor Mendel and Charles Darwin. Many studies have argued that students' understanding of evolution is low and some sort of historical approach would be necessary in order to allow students to understand the theory of evolution. Researchers have found 'Lamarckian' conceptions in students (but see Kamporakis and Zogza, 2007, about the inaccuracy of the characterisation of students' conceptions about evolution as Lamarckian) that would reinforce the need to revise the historical and epistemological steps leading to the modern view of evolution. There are many lines of research on the teaching and learning of biological evolution which focus on the learner's reasoning abilities (Lawson and Worsnop, 1992; Passmore and Steward, 2002, Banet and Ayuso, 2003), teacher strategies, learning materials, etc, but curriculum connections between genetics and evolution have not been investigated so far (for a review, see Hokayem and BouJaoude, 2008).

In many sources, one can read that Darwin 'lacked' a theory of heredity and that, therefore, he was not able to achieve a more sophisticated view of biological evolution. According to this stance, school could provide a prior basis on heredity, so that students – differently from Darwin, and, thus, avoiding difficulties that he faced – could begin to study evolution with a proper background in genetics. There is a widespread belief that Darwin could have made major advances toward building the synthetic theory of evolution if he had had known Mendel's work. We intend to revise some research on the history of biology, attempting to show that, even if Darwin been aware of Mendel's works – which we think he did – he would not have changed his views on heredity. In this paper, we examine this belief and its possible origins, offer some considerations about Darwin's views on heredity, including his knowledge of the 3:1 ratio, and finally give reasons for an alternative approach to curriculum development.

We want to focus on assumptions underlying the view that genetics should precede evolution in high school teaching programmes and consider whether they are either historically accurate or epistemologically pertinent. Hence, we would like to argue that curriculum studies may be a relevant topic for future research aiming at improving evolution teaching and learning.

The mismatch presented to the public

There is a widespread belief that Darwin could have carried out a wider theoretical study if he had more information about Mendelism and the laws of heredity. Darwinists of his time had to work with some unanswered questions, such as those concerning the mechanism through which biological characteristics were passed on to future generations, or the source of novel traits. The work of Mendel did not offer insights into the second question, but it did provide a background that could be used to explain how traits were passed on through generations. He explained that the crossing of plants with different characteristics does not result in mixtures of traits in the offspring; rather, traits behave in a discrete manner, not mixing with each other.

This version of the unfortunate mismatch between Darwin and Mendel can be found in a variety of sources aimed at the public, such as the American PBS network and its library: "What Darwin Didn't Know: Gregor Mendel and the Mechanism of Heredity: (…) Mendel's work helped answer these questions; unfortunately, Darwin was unaware of Mendel's work during his lifetime[.]" (PBS, 2008).

Many biology textbooks also convey this view, as we can see in the following example:

> Just a few years after Darwin published *The Origin of Species*, Gregor Mendel wrote a groundbreaking paper of inheritance in pea plants. In that paper, Mendel proposed a particulate model of inheritance, which stated that organisms transmit discrete heritable units (now called genes) to their offspring. Although Darwin never learned about genes, Mendel's paper set the stage for understanding the genetic differences on which evolution is based. (Campbell and Reece, 2008, p 469)

Another version appeared in a biology textbook in which the novelty of Mendel's work is presented, not in terms of experimental design, but rather in the fact that Mendel would have been the first to count down the offspring of crossings. He would have repeated previous experiments carried out in England, and, for the first time, would have had the idea of counting the different forms of the offspring:

> (…) This was the same experimental design that Knight and others had used much earlier. But Mendel went an important step further: he counted the numbers of offspring exhibiting each trait in each succeeding generation. No one had ever done that before. (Raven, Johnson, Losos and Singer, 2004, p. 245)

This version is not restricted to lay or school audiences, but can also be found among academics. For instance, Ernst Mayr (1991) stated that "Darwin never heard of Mendel's work and was never able to solve the problem" (p 109). More recently, another version of the same idea appeared, in which it is said that an 'uncut' copy of a Mendel's paper was found in Darwin's archives, but had not been read; moreover, it added that if Darwin had read it carefully "evolutionary biology would have been anticipated at least in three decades" (Rose, [1998]2000, p 43). But the history of the evolutionary synthesis is a convoluted one (Bowler, 2003) and an historical perspective can show that it is not feasible that Darwin could build or even pave the way to some synthetic approach merely from a reading of Mendel's paper. Things are not that simple. Nevertheless, the myth that he could have done so thrives in school teaching.

Historical background

It is possible to trace the origin of this idea of a mismatch between Darwin and Mendel. It can be found as early as 1902 in William Bateson's influential book *Mendel's Principles of Heredity: A Defense*. In this book, Bateson wrote: "Had Mendel's work come into the hands of Darwin, it is not too much to say that the history of the development of evolutionary philosophy would have been very different from that which we have witnessed" (p 39). In a later edition of the book (Bateson, 1909), he not only repeated the phrase (p 31), but added another similar statement: "I rest easy in the certainty that had Mendel's paper come into his [Darwin's] hands, those passages [about the views of evolutionary progress through blending] would have been immediately revised" (p 19).

To understand this claim, one needs to situate it in the context of Bateson's debates with the biometricians (Olby, 1989; Bowler, 2003). Biometry was founded by Darwin's cousin, Francis Galton, and originated from the application of statistical techniques to the analysis of the range of variation in populations and the effect of selection on that range. The idea was to apply statistics to the study of animal populations so as to provide direct evidence for the operation of natural selection. One of the main consequences of this approach was an emphasis on the central role of continuous variation in the evolutionary process.

Despite the fact that Galton was initially a strong enthusiast of Darwin's theory of inheritance (pangenesis), he proposed a 'law of ancestral inheritance' some years later. Darwin thought that cells of every part of the body would "throw off atoms or gemmules", with information for the construction of that part. Gemmules would aggregate by mutual affinity, forming either buds or the sexual elements. When different forms were crossed, characters should blend, as the result of the mixture of different gemmules. However, one form could be **prepotent** "due to some advantage in the number, vigour, or affinity of its gemmules", and the other would be **latent**. In the next generation, gemmules would appear to have acquired (or lost) vigour, as they could be more (or less) prepotent. After some generations, there would be a 'reversion' to the parental stock, or the latent gemmules would face extinction. It was a clear model of 'soft inheritance', as Mayr (1982) has called it, as hereditary particles would change continuously. Darwin called his hereditary views a "provisional hypothesis of pangenesis", a "theory of pangenesis", but also "doctrine" (Darwin, 1868).

According to Galton an individual would derive half of its hereditary traits from each parent, one-quarter from its four grandparents, and so on. Galton thought that selection could not produce permanent changes in a population because of what he called 'regression', i.e. that in each generation variants would regress toward the mean value for the species as a whole (Galton, 1886). Regression entailed that natural selection would never produce a permanent change in a population (Mackenzie, 1984; Heyde and Senete, 2001; Bowler, 2003). Consequently, Galton was led to an idea at odds with Darwin's theory, since he accepted that new species could appear by saltation, and Darwin emphasised, in turn, that evolution was always a gradual process, as he famously stated in his claim that "nature makes no leaps" (*Natura non facit saltum*).

Bateson's claim about what would happen if Darwin had read Mendel can be seen as an attempt to bring Darwin to his side of the debate. If Darwin had known Mendel's work, he would support his position, and not that of Galton and his followers. Despite the popularity of this view, the fact that we now see, retrospectively, Mendelism and Darwinism as complementary theories does not mean that the potential for their synthesis could be apparent either for Darwin or for the early geneticists and biometricians. Mendelian genetics and Darwinism were taken to be opposing or rival theories at the beginning of the twentieth century. Early geneticists were strongly influenced by the idea of saltative evolution. The very "rediscovery" of Mendel's laws in 1900 was partly prompted by enthusiasm for evolution by saltation. Mutations were taken at first to create new species instantaneously, and adaptation and natural selection were not regarded as so relevant as they are nowadays (Olby, 1989; Bowler, 2003).

It was clear that Bateson wanted to show that the Mendelian model was not anti-Darwinian in an evolutionary sense, presenting a general model which could absorb much of what the critics were pointing out against it (Martins, 2002). He added a note at the end of the translation of Mendel's *Pisum* and *Phaseolus* paper which appeared in his book, saying that Mendel's concluding paragraphs seemed to support the idea that the general mutability of natural species might be doubtful, though the hybrids produced showed that one species could be definitely 'transformed' into the other (Bateson, 1902, p 95). It was clear that both Gregor Mendel and Charles Darwin knew that hybrid (in)stability would throw some light into the question of the mutability of species (see Bowler, 2003).

Historically sound evidence

For the purposes of this article, these accounts of the possible implications of a contact between Darwin and Mendel are important in two respects. On the one hand, they present the work of the two scientists as fully compatible in their original form, and suggest that they were not originally merged as a matter of pure chance. On the other hand, they convey a certain view of science and scientific work which have been criticised in the context of science education. The soundness of these ideas is, therefore, an important issue to consider, particularly because they reach many different instances, such as school textbooks, the media, and scientific works.

Andrew Sclater (2006) wrote an excellent summary of the different published versions of these accounts as well as about the sound evidence available on the subject. The 'uncut' version of Mendel's work (Rose, [1998] 2000, p 43) was, in fact, a copy of a book that contained a summary of Mendel's experiments. Darwin had passed it on to George Romanes, who had asked him to suggest references for a short text on hybridism. Darwin simply sent him a recent book, saying that he had not had the time to read it. However, Sclater comments that Darwin indeed entered into contact at least once with a secondary source where the work of Mendel was discussed in some detail.

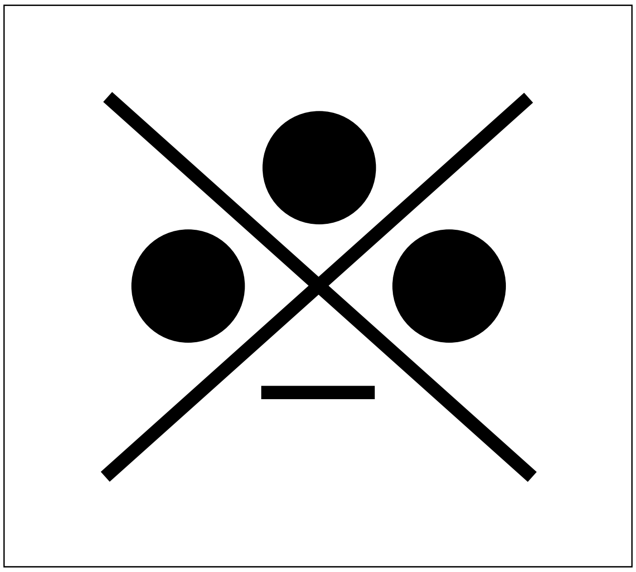
Peter Vorzimmer (1968) stated that Darwin had been aware of Mendel's work, contrary to what has frequently been asserted since the beginning of the 20^{th} century. He added that Darwin had direct contact with Nägeli, a well known botanist with whom Mendel was frequently in touch, and Hermann Hoffmann, who also knew Mendel's results well. In addition, he stated that Darwin also knew the works of Köelreuter and Knight, the latter being one of the most distinguished horticulturists of his time in England, having established that peas could breed true. Vorzimmer also called attention to the entry #112 in Darwin's Reprint Collection, which was called *Untersuchungen zur Bestimmung des Wertes von Spezies und Varietät* ("An Investigation into the Quality of Species and Varieties"), a long paper by Hermann Hoffmann. This was an extensive review of experiments with hybrids, including a critique of Darwin's recently published theory of pangenesis. Vorzimmer also mentioned that Hoffmann's paper contained a summary of Mendel's work and, thus, concluded that Darwin was aware of Mendel's results. Moreover, he stated that, in the section where Mendel's work was detailed, Darwin was cited four times, which certainly attracted Darwin's attention (Vorzimmer, 1968).

It is likely that Darwin would have been especially interested in Hoffmann's paper, since it contained a critique of his views on heredity set out in his book *Variations of Animals and Plants Under Domestication* (Darwin, 1868). Olby and Gautrey (1968) also noted that it was long known that Hoffmann's work was mentioned by Darwin himself in his later book *Effects of Cross and Self Fertilization in the Vegetable Kingdom* (Darwin, 1876). This clearly means that Darwin thought it relevant for his reflections on heredity. However, Darwin mentions only Mendel's experiments on *Phaseolus* reported in Hoffmann's work. Olby and Gautrey (1968) wrote that, taking into account that the written marginalia in Darwin's handwriting could only be found as far as page 78 in Hoffmann's work: "It is doubtful, therefore, that Darwin ever read the reports on *Geum* and *Pisum*, but simply jumped from page 78 to the *Schlussrèsümè* on pp 169-171." (p 10).

This conjecture about a 'jump', in which Darwin skipped Mendel's results on *Pisum*, reinforces the idea that, had Darwin known Mendel's results on *Pisum*, there would have been a complete change in the subsequent events. One of the authors of this article (Bizzo) examined Hoffmann's brochure kept in Darwin's Reprint Collection in the Manuscripts Room of Cambridge University Library. It was possible to confirm, with the help of experts who were working there at that time, that the marginal handwriting was actually Darwin's. However, there is marginalia further on in the brochure, near the report on *Pisum* results. It is not writing, but an X, in pencil, with three dots and a trace in the inner space near each angle, which was taken as a reference to the already well known 3:1 ratio (Figure 1). Further on, another cross shows four traces which could possibly be a reference to the first generation of crossing, indicating that Darwin might have had his own interpretation of Mendel's results (Bizzo, 1999). This indicates that the report on *Pisum* could have been actually read by Darwin, but did not make him change his mind on the whole subject of heredity. He already knew those ratios and had an explanation for them, in terms of gemmule prepotence (related to what is now called gene dominance) and reversion to the parent stock, a phenomenon of striking importance in the context of pangenesis. In fact, when Hoffmann describes the work of Mendel on peas, he says he found that: "hybrids possess the inclination to revert to the parent [species] stock". In other words, not even Hoffmann had recognised the opposing views of Mendel and Darwin in explaining those 25% odd hybrids' offspring!

Darwin himself had performed experiments, for instance with *Anthirrinum majus* (snapdragon), having found the 3:1 ratio. It is possible that he did not read Hoffmann's work

Figure 1. Mark left by Darwin in his reprint of Hoffmann's paper. When he read the description of Mendel's results he had already reached (and published) results of F1 and F2, on a 3:1 basis.



before 1874 (Olby and Gautrey, 1968). This means that when Darwin read the report of Mendel's work, he might have been revising his *Variations of Animals and Plants under Domestication*, since the second edition appeared in 1875. In 1868, in the first edition of his book on Variations, Darwin reported his results with peloric[1] and normal snapdragon, in which he found 100% of one parental form in the first generation. Then, he added:

> The crossed plants, which perfectly resembled the common snapdragon, were allowed to sow themselves and, out of a hundred and twenty-seven seedlings, eighty-eight proved to be common snapdragons, two were in an intermediate condition between the peloric and normal state and thirty-seven were perfectly peloric, having reverted to the structure of their one grandparent. (Darwin, 1868, pp 70-71)

These results, which he recognises had already been reported by others, showed that the first generation exhibited just one type of the parental forms (common snapdragon), but in the second generation there was a 'reversion' to the latent form (radial flower) in 29% (37/127) of cases, in comparison with the other 70% (88/127). Hence, Darwin was well aware of this tendency in the second generation, and added:

> (…) the tendency to pelorism, appearing to gain strength by the intermission of a generation, prevailed to a large extent in the second set of seedlings. How it is possible for a character to gain strength by the intermission of a generation, will be considered in the chapter on pangenesis. (Darwin, 1868, p 71)

The explanation for these results appeared in the last chapter of his book, on Pangenesis, in which he argues that the 'prepotency' of particles change according to the circumstances, from generation to generation. The appearance of radial flowers, he argued, was a direct reflex of changing the plant to soil with a different fertility. In other words, Darwin was working within a model of 'soft inheritance'. Mendel, instead, had clearly worked within a hard inheritance model.

The second edition of Darwin's *Variations of Animals and Plants under Domestication*, which appeared in 1875, brought a small but important change, among others, in the chapter on inheritance. The phrase "It is therefore not surprising that every one hitherto has been baffled in drawing up general rules on the subject of prepotency" (Darwin, 1868, p. 71), which meant that no one had already dared to put forward a general theory to heredity, changed to "It is therefore not surprising that <u>no</u> one hitherto has <u>succeeded</u> in drawing up general rules on the subject of prepotency" (Darwin, 1875, p 47, emphasis added). This may mean that he was aware of some propositions which, by the way, were not limited to Mendel's, but judged them as not being successful in explaining the matter of prepotence/dominance.

This leads us to the conclusion that the argument that Darwin had never heard of Mendel and that had he done so he would have changed his views on heredity, are simply wrong and should not inform curriculum developers. As Sclater (2006) argued:

> The scientific community was extremely slow in realising the significance of Mendel's work, probably because he himself was not capable of fully explaining the difference between his clear-cut findings with peas and his less easily interpreted results from crosses in other genera. Hence, even if Darwin had studied the results of Mendel's work, he may well have failed to appreciate their significance. The fact remains that Mendel's name does not appear in Darwin's published work, or in his correspondence. Indeed, as has recently been argued, it is quite likely that Darwin would have had difficulty accepting Mendel's work, which appeared to ascribe variation to the results of hybridization rather than natural selection. (p 192)

It is not our intention here to enter into these general discussions about the fate of Mendel's work. Our intentions are more modest. It is clear to us that, contrary to Bateson's expectations and no matter how other naturalists appreciated Mendel's work, Darwin could not be capable of seeing how the ideas encapsulated in Mendel's paper might fit together with his own theories. He had his own approach to heredity, the theory of pangenesis, which was very different from Mendel's account. To the extent that he took Mendel to be working on the origin of species, this would be an alternative approach to his theory of natural selection. Mendel and Darwin were simply working within different theoretical frameworks.

Genetics and evolution at school

Curriculum design relies on some assumptions related to the building of complexity. Simple concepts, especially those which help to understand more complex ones, are anticipated in each syllabus, so that a progressive approach can be provided. Evolution is frequently placed at the end of the school year, if not in the last year of high school (Tidon and Lewontin, 2004). This is the case in the Brazilian curriculum, but it is common in many different places too. No doubt several different justifications can be raised to account for this state of affairs, but at least one of them relies on epistemological grounds.

The argument runs as follows: Darwin lacked the theoretical framework of Mendelian genetics and, therefore, was not able to develop the so-called evolutionary synthesis, something which eventually became possible in the 1930s. School would then offer an epistemological bypass to students, showing Mendel's work as directly connected with Darwin's. Hence, when students begin to study evolution, they would have already achieved what Darwin lacked in his time, namely Mendelian genetics. The school environment would be therefore presented as a 'fast lane' in terms of curriculum design aiming at understanding biological evolution. We believe that this argument is a fallacious one, with no sound evidence in either historical or cognitive psychological grounds. Five arguments can be presented in order to justify alternative approaches for high school biology.

1. School biology: historically accurate?

The first aspect to be considered refers to the version of scientific knowledge we offer to students at school. 'School biology' can be seen as a version of knowledge shaped by different social agents and found in textbooks and syllabuses. This body of knowledge has been built especially for school and its primary aim is to be suitable for the learner. This means that there are reasons to avoid a strict historical reconstruction; although we strongly support the use of history of science in science teaching, one cannot lose sight of the fact

[1] The modern terms would be zygomorph and radial flowers.

that a course on the basics of biology is not a course on history of biology. We should avoid, however, wrong approaches to both history and science. Obviously, this does not mean that we should teach all the theories of the past, including those which are no longer accepted. For instance, there is no reason to teach pangenesis in detail at the high school level, something which could seriously threaten a proper understanding of modern biology. However, it does not follow that we should say to the public that Darwin had never reflected on the subject of heredity, or say, as Bateson did, that it was unfortunate Mendel's work never reached Darwin's hands.

2. Why should high school students learn evolution?

There are several lines of reasoning to justify the teaching of evolution at high school level. One can use, for instance, one of the following avenues:

(a) To simply and straightforwardly say that evolutionary theory is the fundamental cornerstone to all life science, and thus it should undoubtedly be learnt by high school biology students.

(b) To argue for the relevance of evolution to informed decision-making about socio-scientific issues related to, for instance, genetic engineering, antibiotic resistance, conservation, agriculture, etc (Sadler, 2005; Meyer and El-Hani, 2005).

(c) To discuss the ethical consequences of the fact that evolutionary thinking situates human beings within the living world, not outside and above it and, thus, the important consequences to the way we conceive of our relationship with the remainder of the organisms and the environmental crisis following from how we structured this relationship.

(d) Along the same line of reasoning, to emphasise the relevance of evolution to a critical appraisal of 'speciesism' (Singer, 2009), i.e. the act of placing higher moral or ethical value on one species (typically ours) over others, which also has quite important consequences for environmental and animal rights issues.

(e) To address the relationship between an understanding of evolution and students' epistemological views, since to conceive of human perceptual and cognitive systems as 'evolved' is a way of recognising that human knowledge is tentative, an important issue regarding students' views about the nature of knowledge, and, more specifically, science (Lederman and O'Malley, 1990; McComas, 2000).

(f) To consider how we can build a more consistent and thorough understanding of our health and disease if we see medicine from a Darwinian perspective (Nesse and Williams, 1996).

(g) The very origins of biology as a science, as an integrated field of knowledge about living systems and processes, are related to evolutionary thinking (Meyer and El-Hani, 2005).

These perspectives are not exhaustive, since yet others can be considered (see Alters and Alters, 2001, especially Chapter 5 "Why Should Students Learn Evolution").

3. Genetics and evolution: mind the gap!

Darwinian evolution seen as a consequence of Mendelian genetics is a particular reconstruction of the epistemological journey of some ideas of (at least) two thinkers. This version is not the only one possible and certainly not the most accurate from the historical point of view. Moreover, it may not be the easiest way to achieve a proper understanding of modern biology but, on the contrary, can even make it more difficult to do so. Mendelian genetics includes the concept of hard inheritance, broadly speaking, a model of how hereditary particles travel unaltered through generations, and this may not come to terms with evolutionary perspectives at first sight. Mendel himself, in the last paragraphs of his 1865 paper, doubted the possibility of species 'transformation' beyond certain limits, namely combinations of pre-existing variations in the parental stocks.

One has to consider that students may not have the possibility of thinking over the compatibility of a model of hard inheritance and the sources of random variation available to natural selection, genetic drift and gene flow. It took several decades to combine Mendelian and Darwinian perspectives in a single, comprehensive theory, and it is not likely that this process can be rebuilt in detail in the school setting. If this is the case, it is likely that a curriculum design which takes Genetics as a requisite to Evolution can be of no help in the proper development of student understanding of biological evolution.

This does not mean that Mendel's work is of no importance to basic education. Students often bring ideas of 'soft inheritance', which can be, by the way, very similar to Darwin's original ones. A proper understanding of both Genetics and Evolution should enhance students' perception of hereditary phenomena not only on biomolecular grounds but also about macroprocesses. It is probable that Genetics will be taught in different ways in the near future, as new phenomena have been discovered and changed traditional views about concepts which seemed very simple, such as the 'gene', for instance (El-Hani, 2007). Mendel plays a central role in the history of the discovery of the modern basis of Genetics.

However, it is necessary to recognise that conflicts may arise in students' minds. Modern science can make students understand the connection between these two classes of phenomena which are at the same time conservative and innovative. Curriculum developers should admit that evolution could have a more extensive presence in schools, and could be presented to students prior to the findings of Mendel. In addition, genetics should be seen as a group of contents which may not help students' understanding of evolution. On the contrary, they may see contradictions between them. Biology teachers should encourage students to present their views and show that Darwinian scientists were also sceptical about Mendelian genetics at the beginning of 20th century.

4. Genetics, microevolution and geological time

Evolutionary biology concerns two related domains of phenomena: microevolution and macroevolution. In the first domain, we can focus, for instance, on molecular biology and genetics, while in the second palaeontology plays a major role. Most K-12 curricula have an unbalanced bias toward microevolution (Dodick and Orion, 2003; Dodick, 2007) and, even at the university level, palaeontology is not typically regarded as a core area for biologists. There is a tendency to reduce the presence of palaeontology in biology teachers' initial preparation courses in Brazilian universities, and there is a growing importance given to molecular biology. A possible explanation for this is the focus on natural selection and how variability is maintained in populations.

This leads directly to the links between evolution and genetics, and raises a relevant question: if curriculum developers look for an historical approach, showing the work of Darwin in some detail, what is to be done with his writings about pangenesis? In addition, popularly known examples of evolution, such as industrial melanism in peppered moths and antibiotic resistance in bacteria, are examples of microevolution which can hardly be paralleled with examples taken from the original work of Darwin. This brings a tension to the curriculum, since adopting an historical perspective would make us tend to value original writings, but they are in the end replaced by modern ones. In fact, if a student opens *Origin of Species* or *Variations*, he or she will be probably dazed with the examples found there.

Most importantly, the emphasis on microevolution tends to confer less importance to the study of evolution on a grand scale, the origin of taxonomic groups, evolutionary trends, adaptive radiation, and extinction. This means that genetics and molecular biology tend to have an unbalanced presence in the curriculum, as compared with palaeontology for instance. Students are introduced to natural selection from the beginning of the unit in evolutionary biology, and have to construct abstract models of populations, instead of visualising changes in an individual organism and then connecting them with population-level changes. As Jeff Dodick (2007) stated: "(…) starting a teaching unit in evolutionary biology with microevolution, and specially Natural Selection, has difficulties" (p 246). The subject of macroevolution, and particularly an operative concept of geological time, is essential to develop a sound understanding of evolutionary biology (Dodick, 2007.

5. Biological evolution at the end: too late or too much?

A curriculum design which locates evolution as the last part of high school biology may lead to ineffective results. Some teachers and curriculum developers take for granted that knowledge of biological diversity, molecular biology and genetics is essential to the understanding of evolution. This leads to a cumulative perspective, in which contents taken to be relevant to the understanding of evolution are added in a stepwise manner. The basic fact is that everything is relevant to evolution! However, there are some constraints which have to be considered, especially if one considers the time span of high school biology. Left to the end of basic education, evolution tends to be improperly addressed and, moreover, is not used to make sense of its own products, such as biological diversity (often taught as a parade of different taxa with no underlying process bringing them together). Also, a study of the geological aspects of our planet, including the idea of geological time, could instead be taken at the very beginning and could help to construct a broader picture of the environment in two dimensions, namely space and time.

For Darwin himself, the understanding of geological time was crucial and occurred while he was still on the *Beagle*. It has been suggested that Darwin unlocked the door of geological time around April 1835 when he was in the Andes, more than three years before he had read Malthus and thought about natural selection (and pangenesis). This may be relevant to the school curriculum. Therefore, moving the subject of evolution to a different stage in the curriculum might benefit broader approaches, tackling macroevolution, as well as avoiding or at least reducing more specific questions about gene patterns in populations and generations. In other words, the subject could thus become more coherent and adequate to the learner.

6. Avoiding whiggish[1] science

There is no sense in hiding the fact that Darwin had a model of heredity which has been rapidly abandoned by the scientific community. If this is mentioned, it will bring a more realistic tone to the understanding of the scientific enterprise. Notice that a 'wrong' model of heredity (or no model of heredity, as some say) may not prevent a proper model of evolution. In fact, this was the case with Darwin, who developed a 'right' model of evolution while having a 'wrong' model for heredity. This was not surprising, since the idea of natural selection just requires that abundant variation be present in a population, something that could not be denied already in Darwin's day. To build a model of natural selection, it does not really matter what are the origins of variation. This amounts to a separate, albeit important, research question.

This is yet another way of showing that the idea that a course in Genetics prior to Evolutionary Biology is necessary *per se* can be wrong from an historical and epistemological perspective. This can also be the case at the high school level today. Nevertheless, our claim is not cast in terms of learning efficiency, but rather as regards the question of the image of science that we bring to students. They should see brilliant scientists having all sorts of ideas, including some that proved to be wrong. This does not bring scientists to a lesser place on the stage of science. On the contrary, this may show students what science is really about.

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References

Alters B J and Alters S M (2001) *Defending Evolution*. Sudbury (MA): Jones and Bartlett Publishers.

Bateson W (1902) *Mendel's principles of heredity: A Defence*. London: Cambridge University Press.

Bateson W (1909) *Mendel's principles of heredity*, Cambridge: Cambridge University Press.

Banet E and Ayuso G (2003) Teaching biological inheritance and evolution of living beings in secondary school. *International Journal of Science Education,* 25, 373-407

Bizzo N (1999) On the different interpretations of the historical and logical development of the scientific understanding of evolution. In: Toward Scientific Literacy, *Proceedings of the IV HPSST Conference*, Faculty of Education, University of Calgary, pp 99-112.

Bowler P J (2003) *Evolution: The History of an Idea* (3rd Ed). Berkeley: University of California Press.

Campbell N A and Reece J B (2008) *Biology* (8th Ed), Pearson Benjamin Cummings, San Francisco.

[1]The term refers to the tendency to adjust the history of science to present day understandings, leaving aside what we consider as "wrong" ideas in the work of scientists of the past that are highly regarded today, or to diminish or neglect the importance of the works of scientists not committed to theories currently accepted. The term derives from the influential book *The Whig Interpretation of History*, by H. Butterfield (1931).

Darwin C R (1868) *Variations of Animals and Plants Under Domestication*. London: John Murray. [idem, ibidem, second edition 1875].

Darwin C R (1876) *The effects of Cross and Self Fertilization in the Vegetable Kingdom*. London: John Murray.

Dodick J (2007) Understanding evolutionary change within the framework of geological time. *McGill Journal of Education,* 42(2), 245-264.

Dodick J T Orion N (2003) Introducing evolution to non-biology majors via the fossil record: a case study from the Israeli high school system. *The American Biology Teacher,* 65, 185-190.

El-Hani C N (2007) Between the cross and the sword: the crisis of the gene concept. *Genetics and Molecular Biology* 30(2), 297-307.

Galton F (1886) Regression towards mediocrity in hereditary stature. *The Journal of the Anthropological Institute,* 15, 246-263.

Heyde C C and Senete E (Eds) (2001) *Statisticians of the Century*. New York, Springer.

Hokayem H and BouJaoude S (2008) College students' perceptions of the theory of evolution. *Journal of Research in Science Teaching,* 45(4), 395-419.

Kamporakis K and Zogza V (2007) Students' preconceptions about evolution: How accurate is the characterization as 'Lamarckian' when considering the history of evolutionary thought. *Science & Education*, 16. 393-422.

Lawson A and Worsnop W (1992) Learning about evolution and rejection a belief in special creatrion. Effects of reflective reasoning skill, prior knowledge, prior belief, and religious commitment. *Journal of Research in Science Teaching,* 29, 143-166.

Lederman N G and O'Malley M (1990) Students' perceptions of tentativeness in science: Development, use and sources of change. *Science Education*, 74, 225-239.

Mackenzie D (1984) *Statistics in Britain, 1865-1930: the Social Construction of Scientific Knowledge*. Edinburgh University Press, Edinburgh.

Martins L A C P (2002) Bateson e o programa de pesquisa mendeliano. *Episteme,* 14, 27-55.

Mayr E (1982) *The growth of biological thought*. Cambridge-MA: Harvard University Press.

Mayr E (1991) *One Long Argument: Charles Darwin and the Genesis of Modern Evolutionary Thought*. Cambridge-MA: Harvard University Press.

McComas W F (2000) The principal elements of the nature of science: Dispelling the myths in science education. in: McComas W F (Ed) *The Nature of Science in Science Education*, pp 53-70. Dordrecht, Kluwer.

Mendel G J (1965) *Experiments in Plant Hybridization*. Cambridge-MA: Harvard University Press.

Meyer D and El-Hani C N (2005) *Evolução: O Sentido da Biologia*. São Paulo, UNESP.

Nesse R M and Williams G C (1996) *Why We Get Sick: The New Science of Darwinian Medicine*. New York-NY, Vintage.

Olby R (1989) The dimensions of scientific controversy: The biometric-Mendelian debate. *The British Journal for the History of Science*, 22, 299-320.

Olby R and Gautrey P (1968) Eleven references to Mendel before 1900. *Annals of Science,* 24, 7-20.

Passmore and Steward (2002) A modeling approach to teaching evolutionary biology. *Journal of Research in Science Teaching,* 39, 185-204.

PBS (2001) *What Darwin Didn't Know: Gregor Mendel and the Mechanism of Heredity*. Available at: www.pbs.org/wgbh/evolution/library/06/1/l_061_01.html. Accessed on 9 August 2008.

Raven P G, Johnson J, Losos and Singer S (2004) *Biology*. McGraw Hill, New York.

Rose M R (2000) *O Espectro de Darwin: A Teoria da Evolução e suas Implicações no Mundo Moderno*. Rio de Janeiro: Jorge Zahar. [originally published in 1998 as Darwin's Spectre (Evolutionary Biology in Modern World), Princeton University Press, Princeton, NJ].

Sadler T D (2005) Evolutionary theory as a guide to socioscientific decision-making. *Journal of Biological Education*, 39, p.68-72.

Sclater A (2006) The extent of Charles Darwin's knowledge of Mendel. *Journal of Biosciences,* 31, 191-193.

Singer P (2001) *Animal Liberation*. New York-NY, Harper Perennial.

Tidon R and Lewontin R C (2004) Teaching evolutionary biology. *Genetics and Molecular Biology,* 27, 124-131.

Vorzimmer P (1968) Darwin and Mendel: The Historical Connection, *Isis* 59(1), 77-82.

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