Reconsidering the meaning of concepts in biology education

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Abstract
Concepts have a central and important place in biology, therefore, it is important that their meanings are precise. However, such precision does not always exist, even in the case of such fundamental biological concepts as "gene". A quick look at textbooks reveals that different meanings may be attributed to the same concept, even within the same textbook, without explicitly discussing the differences of those meanings. This can be misleading, and mask important conceptual differences. Therefore, the differences between the various meanings of the same concept should be discussed and explained in order for conceptual understanding to be achieved. Taking the "gene" concept as example, I explain the conceptual problems that emerge from the conceptual polysemy usually found in biology education. I conclude with suggestions for teaching and learning biology concepts.

Keywords
Concepts; conceptual understanding; genes; philosophy of science; history of science.

The meaning(s) of scientific concepts

As with all human knowledge, scientific knowledge is structured by concepts that provide systematic representations of entities and phenomena through which explanations, predictions and understanding are possible (Nersessian, 2008, p. 186). Nevertheless, representation is not the only function of concepts, as they may also contribute to advancing research (MacLeod, 2012). It is therefore more accurate to state that scientific concepts have important representational and heuristic roles in the acquisition and justification of scientific knowledge because they both represent entities, properties, and processes in nature, and also make their investigation possible (Arabatzis, 2019). Any kind of discourse about science has to involve concepts, the meaning of which ought to be precise. Otherwise, it is possible for misunderstandings to arise among professional scientists working in different fields. Precision is even more important when it comes to science education and the public representation of science, as non-experts may be confused when they encounter different meanings of the same concept. However, such precision does not always exist; polysemy can be found even in the case of fundamental biological concepts, such as "gene". Different meanings can actually co-exist, because they apply under different conditions. As the various meanings of the "gene" concept have been studied in detail, both historically and currently, this concept serves here as an example in order to illustrate the conceptual variation that is possible and the potential problems when this variation appears to exhibit inconsistencies.

The gene concept in biology

The "gene" concept is a central concept in biology, the meaning of which changed significantly during the 20th century. The gene concepts used during the period described as classical genetics – starting from 1909 when the "gene" concept was coined until about the late 1940s – were not specific about the material or structure of genes. Broadly speaking, these concepts could be defined like this: "A factor in the cells of an embryo that made them produce an adult organism with a particular phenotypic trait." This is the gene concept used in Mendelian and population genetics, which we call here the classical gene concept. During the period of classical genetics, it made no difference whether scientists knew what a gene was made of: considering them as parts of chromosomes was good enough. What mattered was that the "gene" was a very useful

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tool for research, with enormous heuristic value for the study of the inheritance of traits. But in the 1950s a new, molecular "gene" concept emerged, which in the end could be defined like this: "A particular DNA or RNAsegment that encodes a particular RNA molecule (that may or may not further produce a protein molecule), which in turn affects a phenotypic trait." According to this molecular gene concept, genes were made of DNA and were also considered to contain information about specific molecular products (Kampourakis 2017; Rheinberger and Müller-Wille, 2017). Thus, different "gene" concepts have come to dominate scientific discourse on heredity over different periods and several meanings have co-existed.

One might wonder at this point why the gene concept of classical genetics could not simply be reduced to the molecular gene concept. The reason is that whereas there is always one molecular gene, there can be different classical genes in the sense described above. To give one example, there is an allele of the gene *Lmbr1/LMBR1* (limb development membrane protein 1) that results in abnormal limb development in both mice and humans. This is a classical gene, in the sense of Mendelian or population genetics, and its variation within a group or population can be studied. However, the respective molecular gene that is actually implicated in limb development, the sonic hedgehog (*Shh*), is located around 850 000 nucleotides away on the same chromosome. What happens is that a sequence within *Lmbr1* regulates the expression of Shh in the developing limb. The respective protein acts as a signal for the patterning of the digits in a posterior to anterior direction. It is therefore possible for an individual to have abnormal limbs without any change in the *Shh* sequence, which is the molecular gene implicated in limb development, and which could also be considered as the classical gene. A change might occur in *Lmbr1*, which is not the molecular gene. As a mutation in *Lmbr1* produces abnormal limb development, it could also be considered as the classical gene related to this character. In short, the classical and the molecular gene in this case are clearly distinct, and they do not necessarily overlap. Whereas there is only one molecular gene, the *Shh*, there can be two classical genes: either the *Lmbr1* or the *Shh* (Kampourakis, 2017).

The gene concept in biology education

The conceptual variation of the "gene" concept in textbooks has been the focus of several studies. For instance, a study investigating the presentation of the "gene" concept in 13 Swedish upper secondary school textbooks found that they exhibited a wide range of variation in the meaning of the "gene" concept. A "gene" was depicted in 17% of the cases as "an abstract entity without structure", in 18% of the cases as "a particle on the chromosome", in 53% of the cases as "a DNA segment", and in 12% of the cases as "one or several DNA segments with various purposes" (Gericke & Hagberg, 2010). In another study of 4 Finnish textbooks, a "gene" was depicted in 11% of the cases as "an abstract entity without structure", in 31% of the cases as "a particle on the chromosome", and in 58% of the cases as "a DNA segment"; however, no instances of "one or several DNA segments with various purposes" were found (Aivelo & Uitto, 2015). Textbooks may also present hybrid "gene" concepts that indiscriminately mix up features related to different historical "gene" concepts. The presence of such hybrid "gene" concepts was investigated in 18 Brazilian high-school textbooks. It was found that different gene concepts, such as the "classical molecular gene" concept and the "informational gene" concept were simultaneously present in 39% of the units of analysis (Carvalho Santos et al., 2012). A more inclusive, comparative study of 38 biology textbooks from 6 countries (including Sweden and Brazil, as well as Australia, Canada, the UK and the USA) confirmed the prevalence of multiple and hybrid "gene" concepts in textbooks (Gericke et al. 2014). Although these findings are interesting in their own, it is very significant that this conceptual variation is rarely discussed explicitly or explained. This can have important implications for science education and communication because the different meanings are often considered equivalent even though they may not be.

A quick look at textbooks shows the problem. In order to see whether these different meanings of the same concepts, and the differences between them, are explicitly discussed and explained in textbooks, we looked at a convenient sample of six international biology textbooks about how “gene” and “adaptation” concepts are defined. We must note that our aim is not to suggest that textbooks are not well written and that they overlook conceptual variation; rather it is to discuss the conceptual problems that might occur if textbook authors do not discuss and explain the conceptual variation that exists (Kampourakis and Stern, 2018). On the one hand, both classical and molecular gene concepts co-exist in the same textbook. If classical and molecular concepts are used interchangeably without explaining the differences between them, it is possible for students and the public to perceive that these are synonymous and that they can be reduced to each other. However, as shown with the example of limb development above, this is not necessarily the case. Therefore, the distinction between classical and molecular gene concepts is important and should be made clear in both education and public communication. Variations in a DNA sequence other than the one directly implicated in the development of a trait might affect the latter. Therefore, even though a single molecular gene may exist, it is possible for several different classical genes also to exist.

Conclusions

Scientific concepts provide systematic mental representations of entities and phenomena that frame the discourse among scientists and influence the direction that research takes. They are also very important for science education and communication, in order for non-experts to understand the findings of scientific research and the conclusions drawn from these. Therefore, it is important that the meanings of scientific concepts are made clear whenever these are used. However, because concepts are historical entities whose meanings evolve over time, different meanings of the same concept may come to co-exist in scientific discourse. Therefore, it is necessary that the different meanings of the same concept are discussed and the different contexts in which each of this applies or not are explained. This will have important implications because insofar as this conceptual variation remains implicit and undiscussed, it may negatively affect conceptual understanding. To achieve this, it is necessary to draw on the relevant scholarship from history and philosophy of science.

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