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Microbiology, Philosophy, and Education

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Graphical abstract

Microbiology, Philosophy, and Education. 'Bacteriologists holding a bottle', a coloured lithograph by R. Huebner. Wellcome Images Library, London, wellcomeimages.org

Abstract

There are not only many links between microbiological and philosophical topics, but good educational reasons for microbiologists to explore the philosophical issues in their fields. I examine three broad issues of classification, causality, and model systems, showing how these philosophical dimensions have practical implications. I conclude with a discussion of the educational benefits for recognizing the philosophy in microbiology.

Introduction

If we think of education as a process of learning how to learn by encountering the unfamiliar – a very broad definition but at least generally true – then philosophy and microbiology can usefully be understood as providing each other with educational opportunities. Although in a formal sense, philosophy of microbiology is only a small sub-sub-field of philosophy of science (via philosophy of biology), in another sense philosophy pervades microbiology from its earliest historical beginnings until now. In what follows, I will explore some of those philosophical encounters and then suggest learning about these interactions is intrinsically educational.

Philosophy of microbiology issues

Microbiology, as all readers of this journal know, is a heterogeneous discipline that runs the full breadth of the basic to applied continuum. Evolution, ecology, molecular, industrial and medical microbiological fields abound and intersect all the time. Different problems and different aims drive these various streams forward and, increasingly, lead them to impact on non-microbiological fields. But a number of common questions, often philosophical ones, are applicable to any combination of approaches and any historical era of microbiology. Even if complete and final answers have not always been forthcoming, these questions have needed to be asked. Let me address three of the broadest questions with relevance to much microbiological practice.

1. Classification and why it matters. For example, what are species (and do we need them)?
2. How do (we know) microorganisms cause things? How have fundamental problems of specificity, stability, and inheritance shaped how microbiology has developed?
3. What is the nature of modelling, in that microbial model systems can be used to understand macroorganismal phenomena? What are the consequences of using model systems that can only partially represent more complex realities?

Classification issues

Whether one dates the beginnings of microbiology from when microorganisms were first observed in the seventeenth century (Gest 2004), or when pure culturing approaches in the late nineteenth century allowed microbiology to enter the age of experiment (Fleming 1947; Brock 1999), identification and classification have always been central to microbiology. Although the early microscopists in the mid-seventeenth century such as Antony van Leeuwenhoek and Robert Hooke may never once have named or grouped the minute life forms they observed, they did open up a new category of life: cellular life that could be observed only microscopically. This was not uncontested. For some contemporaries, such as Margaret Cavendish, the very need for microscopes meant these were not genuine observations but merely technological artefacts (1666, 1668, in O'Neill 2001).

Classification of a more fine-grained sort, of the kind that is done now in all branches of microbiology, began to gain some impetus in the eighteenth century. People such as Carl Linnaeus and Otto Friedrich Müller extrapolated from existing taxonomical frameworks for animals and plants to make room for microorganismal life (Drews 2000). Often, this involved bundling groups of microbes into plant and animal groups; only later, was the 'nature' of microorganisms deemed to mandate entirely new taxonomic categories. Christian Gottfried Ehrenberg, in the early nineteenth century, made strong statements about the similarities in all basic respects of microorganisms and macroorganisms: they all possessed organs, digestive and even nervous systems, whatever their size (Jahn 1998).

Pleomorphism, however was the enemy. Many microorganisms were observed to be highly changeable, even over a single lifetime. Some observers argued that any single microorganism could become any other: they were not fixed to one form like other life (Nägeli 1879, in Farley 1974). It was not only morphology that fluctuated in accordance with environmental conditions but specific causal properties too. A microorganism could cause one disease in one moment, then with very little effort, cause another disease the next moment (Cole and Wright 1916).

The invention of pure culture was designed to overcome such raw fluidity. By rigorously isolating and transferring such organisms to different host environments, Robert Koch and Louis Pasteur aimed to demonstrate that specific causal effects were the properties of particular microorganisms. Those organisms and their effects could then be reliably propagated in laboratory conditions and become part of the brave new world of experimental biology (Gradmann 2000). Classification thus became microbiology's entry point into scientific inquiry. However, although the emerging discipline may have gained a place within experimental practice, it still had to prove its credentials to systematics and post-Darwinian evolutionary biology.

Once pure culture methods were available, the notion of 'species' as something specific and stable could be developed in microbiology. Ferdinand Cohn, often regarded as the true founder of microbial taxonomy (in the late nineteenth century), advised microbiologists not to get too hung up about whether microorganisms were in their nature the same as animal and plant species. Instead, he suggested they should sort things out by applying the same classification practices. If those methods worked, then the species notion applied (Cohn 1875, in Brock 1961). Cohn was thus suggesting what we might call a pragmatic species concept.

As everyone knows, the twentieth century is rife with discussion of how 'natural' the microbial entities identified by species concepts are. Given the difficulties of understanding microbial evolution, particularly bacterial, on the basis of morphological and biochemical data, some microbiologists thought the quest for 'principled' justifications of species designations might not be fulfilled (Stanier et al. 1963). But with the advent of molecular data, optimism reigned again: 'Darwin's dream' of a universal tree of species, including the smallest to the largest life forms, was thought to have been realized (Woese 1996). Now, however, lateral gene transfer and recombination undermine for some evolutionary microbiologists the very idea of having a single natural notion of species. All that can be justified is a pragmatic, contextualized designation of species, or rather, of ecological populations (Doolittle and Zhaxybayeva 2009). Interestingly, the more this is known for microorganisms, the more feedback there is into how species are conceptualized in macrorganismal biology (e.g., Shapiro et al. 2016).

Where exactly one stands on issues such as the nature of microbial species does not matter for the purposes of my discussion here. My point is that all these historical debates, obstacles and concerns are deeply philosophical. They concern not only the nature of microorganisms, but *how* that supposed nature is known, and how specific methods for producing that knowledge are justified. Many philosophers would consider these general aspects the warp and weft of philosophy: ontology and epistemology. Do microbiologists need the same philosophical terminology? Not at all. But by recognizing what's at stake, why there are disputes, and where to tread carefully, microbiologists will be better prepared to deal with issues as they arise in scientific practice.

How do (we know) microorganisms cause things?

Specificity, stability, and inheritance were all contested capacities for microorganisms. Even though Pasteur's use of Koch's postulates was meant to have established causal specificity, microbial capacities continued to confound this restraining framework. For example, variability in forms, and instability over the life of a cell (or population) were even in the twentieth century seriously problematic for microbiologists (Cole and Wright 1916; Braun 1947). Inheritance was part of the problem, because the apparent lack of a nucleus in prokaryotes meant that what guaranteed genetic continuity (and thus causal properties) in large organisms was not available for prokaryotes. Because these difficulties loomed large in the first decades of the twentieth century, the modern synthesis of evolutionary biology rejected microorganisms as just too different to be admitted (Huxley 1942). From this point of view, Charles Darwin, who had been perfectly comfortable with the idea of microorganisms evolving in exactly the same way as large organisms (Darwin 1861; see O'Malley 2009), could be interpreted as not being informed enough to exclude them.

Molecular analysis from the 1940s onwards put microorganisms on more of an equal footing – perhaps even elevating them to a superior vantage point (Demerec 1946; Lederberg 1948; Davis 2003). Molecular biological modelling was able to establish causal pathways from microbial genes to biochemical capabilities and how those causes and their effects evolved (Betz et al. 1974; Mortlock 1983; Hall 1984; Dykhuizen and Dean 1990). But these causal modelling efforts were still of isolated laboratory pure cultures, and thus not representative of the more complex interactions out in the messy world. Determining how causal effects are produced by complex microbial communities has truly come to the fore in today's microbiota research. While patterns of association have been widely revealed by environmental genome sequencing projects (metagenomics), in all sorts of ecosystems – from oceans to swamps and human bodies – associations, even in the form of statistically validated correlations, are not (as every undergraduate is told) necessarily causal relationships.

The very topic of what causation is and how it can be established is an age-old philosophical one. David Hume, in the eighteenth century, put the correlational cat among the causal pigeons by arguing that causes themselves couldn't be observed: only 'constant conjunctions', which are regularities that one has a right to expect. Causal attributions can be hung on a framework of regularities. In order to know know which regularities were of the appropriate sort, Hume wrote a little protocol called 'Rules by which to judge of causes and effects' (1739-40). Much later but in the same spirit, additional criteria for justifying causal attributions were published after repeated findings of strong associations between smoking and cancer (Bradford Hill 1965). These criteria still guide much contemporary biomedical research (Ward 2009). Some of today's microbiome researchers have noted that these guidelines from Hume, modernized via epidemiology, may be very appropriate for gaining insight into causality in microbiota interactions. By using 'epidemiological criteria for causation', top-down microbiome researchers may be able to advance their causal understanding of microbiota and disease even when mechanisms remain unknown (Knight 2013, in Ravel et al. 2014; Cho and Blaser 2012).

Bottom-up microbiome researchers are also served by philosophical approaches. Interventionist accounts of causal explanation are based on 'difference makers' (Woodward 2003). When manipulated experimentally, difference makers are shown to be central to the production of the targeted effect. This kind of approach has also been successful in microbiome research. Recent successes in identifying, for example, the microorganisms involved in suppressing *Clostridium difficile* infections, rely on specifying particular causal agents from the community of microorganisms in faecal microbiota transplants. Rather than the whole community being deemed responsible for curing the infection, experimental, mathematical and network analysis identified certain organisms possessing a secondary bile-acid synthesis pathway (Buffie et al. 2015). This pathway was thus shown to be the causal difference-maker, responsible for at least some of the effect of inhibiting *C. difficile*. It may well be the case that traditional experimentation does not capture everything that microbiome researchers want to know about microbiota activities, but causal explanation will probably continue to require this kind of bottom-up research practice, which can be justified by certain modes of philosophical reasoning about causality.

Microbiologists can work in any way they think will be effective. But when research areas are trying to make progress, and to move from descriptive to more explanatory work, it is highly worthwhile recognizing what the explanatory issues are when this is happening. Just reciting 'correlation is not causation' is not going to identify all the avenues open to further analysis and research, and sometimes good reasons may need to be given for why one approach is chosen over another.

How do findings made with microbial model systems apply to macroorganisms?

Philosophical and scientific questions about microbial model systems extend beyond microbiology itself to the rest of the biological world. The microbial model systems used so famously in early molecular biology were often vindicated on the grounds that findings made with them would be universally applicable (Demerec 1946). While this may have worked for very general understandings of gene-based inheritance and mutational change, it was less successful once more specific phenomena such as gene regulation were the focus. The operon model in prokaryotes was unable to account for most eukaryotic gene regulation (Neidhardt and Savageau 1996). Eukaryote model systems took over, at least for discovering the varieties of modes of gene regulation in eukaryotic organisms.

But many classic eukaryotic processes can still be understood generally in prokaryotic models, even though nobody is saying that prokaryotes have exactly the same features and capacities as much larger organisms. For example, social evolution, decision making, and multicellular development can all be modelled effectively in microorganisms (for discussion, see O'Malley et al. 2015). As in all models, the point of modelling with microorganisms is not to copy the phenomenon in all its detail but to represent the most basic elements of the target process in a more abstracted and simplified form (Dykhuizen and Dean 1990; Buckling et al. 2009; Jessup et al. 2004).

Understanding what a model is and how modelling works, whether mathematical, computational or material (which is where organismal systems fit), is a major topic in philosophy of science (Weisberg 2013; Godfrey-Smith 2006). Philosophers suggest that material models function as effectively as mathematical and diagrammatic models, by leaving out non-relevant details and making unrealistic but useful assumptions. For example, microbial model systems with unrealistically limited interactions, such as two bacterial consumers and one phage predator, can attain a stable state mathematically and experimentally (e.g., Levin et al. 1977). Such models may be unrealistic but they say something that is generally important and true about modes of interaction and their stability. They also show how it is important to combine different modelling strategies to gain more robust results, and how 'simpler' microorganisms can effectively represent more complicated larger organisms. Closer philosophical examination of the tradeoffs between generality, realism and precision (Weisberg 2013; Odenbaugh 2003; Levins 1966) could encourage microbiology students and experts to analyse where their own model systems fall along these axes, and whether and how particular simplifications achieve the desired scientific aims.

Giving microbiology students a basic philosophical background in what models are and how they work, including when the models are material organismal systems, can help students and other research trainees understand different modelling practices, the aims in general of modelling, and some of the historical successes of microbial model systems in particular.

From philosophy to education

The point of thinking about the philosophical issues running through any science is not to suggest that everyone needs to go to philosophy classes, but to show that understanding the science itself can be greatly enriched and clarified for students by raising these general issues. They can work as glue to connect different aspects of microbiology and its research methods. Acknowledging philosophical undercurrents can allow students to grasp general issues more readily, and transfer knowledge gained from one situation to another. Recognizing unresolved philosophical conflicts can prevent confusion when students encounter contradictory approaches or claims in what they are taught. And thinking philosophically can give students resources for clear thinking, careful argumentation and appropriate treatment of difficult topics. Developing these kinds of capabilities is arguably what a thorough education is about.

It is not necessarily the case that philosophers themselves have to teach these philosophical aspects of the science to microbiology students. However, many universities probably have departments or units that are homes to historians and philosophers of science, who – even if their expertise is not microbiology – can work on these issues with a variety of scientists-in-training. Other options are for microbiologists themselves to draw from the philosophical literature with the aim of enhancing the scientific education of their students. Many microbiologists dabble in or even plunge into the history and philosophy of their fields, and this work often has practical payoffs. Acknowledging that some issues in science are intrinsically philosophical, and thus may never be resolved by more data (but can perhaps be better managed by careful conceptual analysis and reasoned argument), is an important realization for emerging scientists to attain. And understanding how a discipline or field has been shaped or at least pervaded by philosophical issues throughout its existence can bring home the historical legacies of the science in deep and interesting ways.

Most of what I have discussed so far is about ‘basic’ microbiology. As I noted at the beginning of this essay, however, much microbiology is ‘applied’, meaning it is put to use to enable industrial, medical and other social achievements. Can philosophy help here, as an educational tool? I think so. Many social debates are also philosophical, such as those about what is natural and what is somehow not. For example, genetic modification of microorganisms for biotechnological purposes has rarely generated strong reactions, unlike very similar modifications made to larger organisms. Thinking philosophically about what microorganisms are, and whether the issues are exclusively macroorganismal, can contribute to the depth and scope of the debate and open it to broader discussion (and perhaps deflate overblown conclusions). Philosophical positions on environmental, biomedical, and research ethics are central to instruction about any microbiological methodologies, whether they are used in applied or basic contexts. Applied microbiology might, in fact, have the most to gain from philosophical resources as new technologies are taken up and discussed publicly.

Conclusion

The process of communicating the depth and breadth of microbiological research to students is not always easy in an era of disciplinary specialization and methodological focus. But finding some common threads, at least a few of which are philosophical, can enhance learning experiences and facilitate overall training. A well-rounded education is not necessarily the aim of every microbiology programme these days, but there can be many opportunities in any class, training situation, or textbook to raise at least a few underlying issues and see if this inspires students and gives them additional resources in the long journey toward becoming a full-fledged microbiologist.

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