The universe under a microscope

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The beauty of a living thing is not the atoms that go into it, but the way those atoms are put together. Information distilled over four billion years of biological evolution. Incidentally, all the organisms on the Earth are made essentially of that stuff. An eyedropper full of that liquid could be used to make a caterpillar or a petunia if only we knew how to put the components together.

– Carl Sagan

It may seem strange to begin a prognostication for microbiology with a quote from an astronomer, but the two topics are more closely linked than appears at first glance. For starters, both fields were revolutionized around the same time, in the 17th century, with drastic improvements to the telescope and the compound microscope. These two simple human technologies were not invented to discover the unknown, but instead to look more closely at things we could already see with the naked eye. Their unintended consequence, however, was an unveiling of hidden worlds within and between everything we thought to exist. Indeed, new optical devices revealed that invisible organisms, like celestial bodies, are so ubiquitous that they far outnumber the visible in terms of abundance. They exist in essentially every environment we have dared to look, including the surfaces of other organisms.

A more profound connection between the study of microorganisms and that of the cosmos, however, is ideological rather than technological and relates to a decidedly human interest: origins. The origins of life and the Earth are interwoven and have been pondered for millennia. As the quote above indicates, we have a good idea what these things are made of. Atoms, born in exploding stars, are the building blocks of everything we can describe, including all the molecules of living beings as well as the planet where they reside. Yet, the ever-expanding parts list of nucleic acids, proteins and lipids that comprise organisms does not offer a satisfying explanation of how organisms are constructed, let alone what it means to be alive. A wall of complexity has been reached in the practice of biology, and current efforts to scale that wall are largely directed towards reconstruction of all the parts from a sea of information. In order to glimpse the beauty of life, our immediate future will revolve around trying to discover and define all the connections between all the parts in all different circumstances.

A foundational principle during this transition to the future will be the emphasis on process over mechanistic materialism. When compared with the almost eternal processes of evolution and life, the matter it is made of seems somewhat hollow, transient and ephemeral. What is it about life that seems so different, so uniquely distinct from the other matter it interacts with? The crystal ball says the answer lies in microbiology. Despite the chatter about their simplicity and diminutive stature, microbes are every bit as advanced and evolved as all other extant organisms on the planet. Like us, they have evolved over an immense period of time. Unlike us, there is no indication that they will ever be completely extinguished. Their capacity for survival and adaptation far exceeds any level we could ever possess. Perhaps that ability should be our new definition of what it means to be advanced. The bustling activity of microbes supports and constrains the existence of larger forms of life, while their diversity and informational splendour is redefining the concept of species. For psychological and historical reasons, we continue to place ourselves atop an imagined evolutionary pyramid when in reality microorganisms own the Earth and we are just visitors.

It will turn out that microbes are not simple automatons subject to environmental cues. Much like us, they actively construct and destroy their environment. Moreover, they are not just individualistic reproductive machines; they exist, as we do, for each other. The discoveries of microbial quorum sensing, aggregation into biofilms and concentration on organic particles are just the beginning of the new microbial ecology. In between birth and death, microbes define value and meaning with degrees of better and worse, leading to a survival that is full of significance. Unlike the inanimate rocks and gases and fluids of Earth, microbes are not indifferent to the ceaseless fluctuations of environmental physics and chemistry.

To understand these communities, we will focus on studying microbial interactions. Environmental samples will be analysed to an extraordinary level of detail, offering high-level analyses as compared with the surveys of the past. Clades of previously uncultivable microbes will be recognized as co-dependent with other such organisms.
Synthetic communities and directed selection in the laboratory will elucidate how co-production emerges from interaction. Rather than a hierarchy of one autonomous agent acting as a sole cause for a cascade of events, the nature of causality will lay in the recursive, nonlinear dynamics of complex biological systems. Larger and larger tiers of organization will be seen to arise from the bottom-up, but this organization then produces new principles and rules that exert influence on the system from the top-down as well. In this sense, the phylogeny of microbes will turn out to be less important than their ecology.

The most difficult part of this bold and new microbiology will be the same challenge as always: the immensity of scale. Microorganisms are tiny, yet their impact is enormous. It is fashionable to make proclamations about the effects of the intestinal microbiome on human health, and the global microbiome to geochemical cycles, but we do not yet know how our observations of the smallest scales transfer up to the largest. That microbes are connected to ecosystems and planetary chemistry is certain, but quantifying this contribution in a meaningful and predictive manner is a daunting task that will require integration of many types of research, as well as new ideas on both the variant and invariant properties of organization across vast scales.

Technological advancements will continue to improve our understanding of microbes, both as individuals and community members. Single-cell analysis is becoming more accessible. In particular, the relationships between genotype and phenotype, as well as microbial ecosystems with their participants, will be clarified by the combination of flow cytometry with high-throughput –omics. In the past, our knowledge of microbes was limited to the types we could culture, but these technologies can now be applied to environmental samples, and we are no longer limited by what we can grow in the laboratory. Secret microbial worlds in new locales are being discerned regularly, and the discoveries are showing no signs of deceleration. Like the seminal findings on stars, plants and animals, simply being able to observe the dynamics of entities in native situations is incredibly powerful.

Computational advancements amplify analytical technologies, allowing us to glean more useful information from our measuring instruments. Improving algorithms and high-performance computing will decipher relationships among variables in data sets too large for our minds to comprehend. Conceptual and fundamental insights will come from the application of nonlinear mathematics to evolutionary biological systems, where simulations can help us distinguish the possible and probable from the impossible and unlikely. But as with the history of most science, the dramatic breakthroughs will progress from clever experimentation and thoughtful scrutiny of the findings. Testing hypotheses, generating evidence and forming persuasive, cogent arguments will forever be the core of the microbiologists’ toolkit.

Precise and tractable laboratory experiments will augment the complexity and reality of studies in the field. A synergy will form whereby new discoveries catalyse improved understanding not just of how life works, but how the universe works as well. Rather than being relegated to a technological discipline of engineering, environmental microbiology will pave a path towards a new paradigm of science. Ultimately, the successful biology of the future will transform other fields of science, the humanities and the philosophy of our place in the cosmos.

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