How physicists view the world (and biology)

(a.k.a.: What do physicists think they are doing in my subject?)

Richard G. Morris

January 2021

Abstract

The physicist's view of the world is largely shaped by so-called *effective* theories that are only valid at particular spatio-temporal scales. An example might be the use of the Navier-Stokes equations to describe the behaviour of water at the scales of, say, meters and seconds. This is entirely different to understanding its behaviour at the scale of Angstroms and nanoseconds, which requires a detailed knowledge of Van der Waals forces, and perhaps even quantum mechanics. These notes crudely summarise where biology might fit into such a patchwork of effective theories, why there are alarmingly few examples of theory and experiment working hand-in-glove like physics, and why there is hope for the future.

Taking a sanguine view of physics, as a science, is to recognise that many of its most significant achievements rely on ignoring the details, either wilfully or out of complete ignorance.

Take, for example, thermodynamics, which was a field long before being put on sound microscopic/kinetic foundations by statistical mechanics. Similarly, fluid mechanics— the description of fluids at macroscopic scales— does not require a detailed understanding of quantum mechanics or Van der Waals forces, on which it relies at the smallest of spatio-temporal scales. This is the idea of an *effective* theory.

Effective theories

An effective theory is one that is only valid at certain spatio-temporal scales.

To a physicist, the world is more or less understood via a patchwork of such theories (see Fig. 1). No one mathematical description comes close to encompassing the variety of behaviours we can see at different scales.

Spatio-temoral scales

There are no real multiscale theories in physics (despite what claims you might read in modern literature).

You might ask: why is this? Surely, if we have a detailed understanding of fundamental particles and their behaviours, then don't all other theories follow? In principle, this is true. In practice, however, it is false for all but the most trivial of systems. Broadly speaking, this is due to the so-called "many-body" problem: explicitly calculating the behaviour of a system of many interacting constituents is typically hard, and often impossible. In quantum mechanics, for example, even solving for the behaviour of three or four interacting particles is considered hard, and anything above four is considered impossible without sweeping assumptions!

Luckily, statistics comes to the rescue here. For reasons that will hopefully become apparent later in the course, as the number of constituents in a system, N, increases, most systems become increasingly characterised by their *average* behaviour, giving rise to the notions of "coarse-graining" and "emergence".

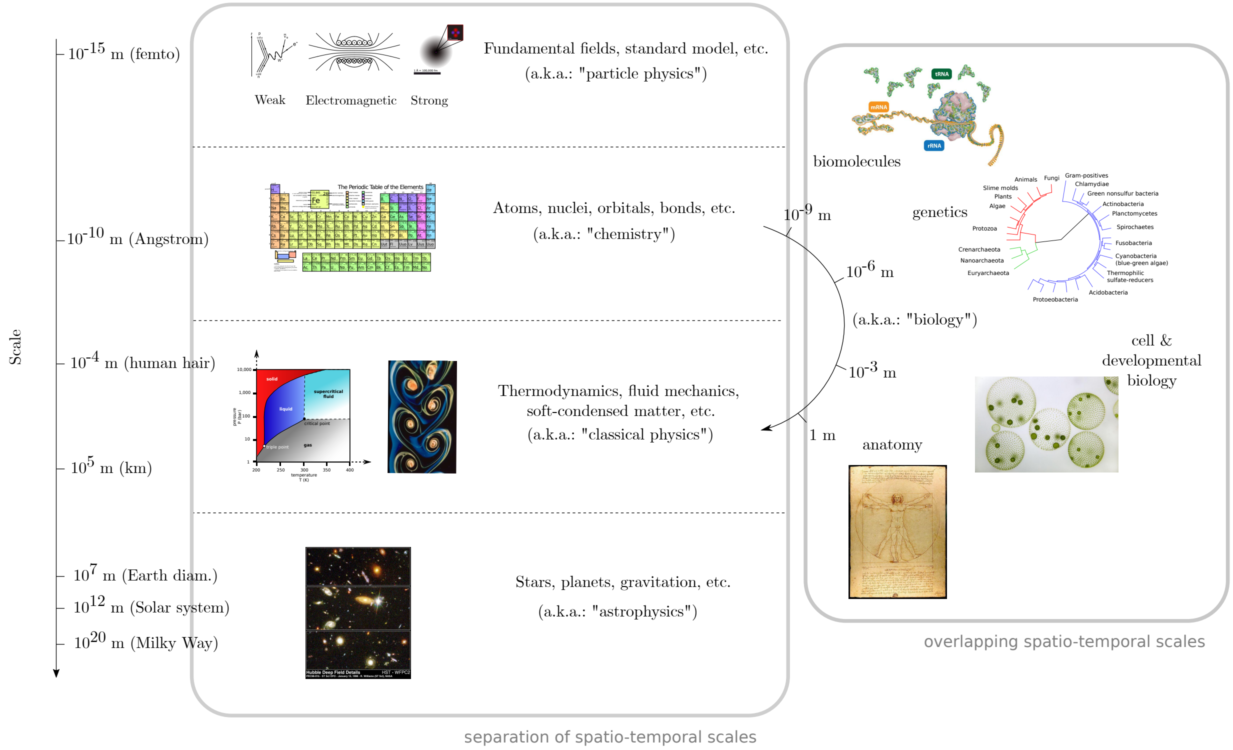

Figure 1: **Effective theories and biology**. A non-exhaustive schematic illustrating that many aspects of physics are *effective* theories. That is, they can be understood without knowing the details of theories at smaller scales. (Notable exceptions to this idea include hard-condensed matter physics and cosmology, which are not shown). Generally speaking, effective theories work because there are many orders of magnitude in scale (both spatial and temporal) between the constituents and the collective. In biology, however, these lines become blurred. For example, certain bio-polymers and filaments have similar length-scales to cells themselves. Similarly, the morphology of certain tissues change on a time-scale similar to those characteristic of the overall organism. Such overlapping spatio-temporal scales prevent the decomposition of living systems into a hierarchy of effective theories.

Coarse-graining & emergence

Coarse-graining is the idea that, as N becomes very large, the many-body problem is rescued by statistics, and systems are increasingly well characterised by their mean, or average, behaviour.

Emergence is the idea that coarse-graining gives rise to unique, or at least, unpredictable behaviours. That is, the collective is distinct from the individual.

In this light, it is not entirely surprising that we end up with an understanding of the world that is split between distinctly different scales, with not much in-between.

So, where does biology fit into all of this? Well, much of biology occurs in the "in-between". At all scales, biology is essentially a science of interacting constituents. To see why we don't have good effective theories for biology, it is helpful to consider a single yeast cell. Each yeast cell has roughly $\sim 4.2 \times 10^6$ proteins, which is a lot[1]. However, these proteins are associated with a proteome whose size is roughly 5×10^3, implying that, on average, each protein has only circa. 800 copies. This leads us to highlight two issues that are broadly symptomatic of the field.

[1] To all Douglas Adams fans: the question to which the answer is "42" is therefore: "How many hundreds of thousands of proteins are there in a single yeast cell?"

Biology

The statistics in biology are, almost without exception, sufficiently poor that data is very noisy. Coarse-grained theories are typically only a poor approximation of the real world.

Biology is complex: the many different flavours, and overlapping spatio-temporal scales of interacting components not only compounds the issue of poor statistics, but it makes reductionism hard.

Concerning the latter point, complexity is a significant barrier to understanding biological systems quantitatively. For example, the properties of the cell cortex cannot be discerned from the collective properties of an inert actin meshwork alone, but require knowledge of the signalling pathways that control polymerisation/depolymerisation, not to mention myosin motors, their hydrolysis by ATP, and the forces that they exert on the network. All of the requisite components operate at overlapping scales, making it impossible to decompose the system into hierarchy of effective theories.

Finally, there is one further feature of biological systems that sets them apart from those of classical physics, and it concerns the fact that living systems are far-from-equilibrium.

Being away from equilibrium is, in itself, not as special as is often made out. Existing effective theories of classical physics encompass the notion of being away from equilibrium. The difference is *how* biological systems are forced (that is, how the energy is added).

In conventional classical physics, it is often said that forcing comes from the boundary. For example, consider a fluid being stirred by a spoon, or a gas being compressed by a piston. The force is applied by a macroscopic object, external to the fluid itself. If the forcing stops, dissipative processes then govern how the system relaxes back to equilibrium. That is, the added momentum (and/or energy) is eventually "shared out" amongst degrees of freedom at smaller and smaller scales.

In biology, the opposite is true, which leads to the notion of "activity", or "active matter".

Activity

An active system is one where energy and momentum are added on microscopic scales, and manifest at macroscopic scales due to collective interactions.

Understanding active descriptions of biological systems is a current frontier of theoretical biology, the heart of which goes back to the idea of overlapping scales.

So, given these challenges, is there any hope that biology might someday work hand-in-glove with theory, much like the effective theories of physics? Of course there is! Think how far science has come in last century or so, and then imagine where it might take us in the future. For example, a little over a century ago, science (J. J. Thompson in particular) was just getting to grips with the existence of electrons, now we have iPhones that work by virtue of circa. 8 billion transistors, each of which is predicated on solid-state quantum physics!

In conclusion, physics, as it currently stands, is certainly very far from a panacea. However, systematically, over a century-long endeavour, there is hope that the life sciences might transcend the restrictive labels of traditional disciplines and develop into a fully integrative science with theory and experiment working hand-in-hand.