What physics and humor have in common

In de serie 'Students on Science' presenteren we Engelstalige artikelen die zijn geschreven door studenten van het vak Wetenschapscommunicatie aan de UvA. Vandaag beschrijft Hilde van der Steen effectieve theorieën in de natuurkunde, die de wereld om ons heen op een contextafhankelijke manier beschrijven.

Nesting dolls. Think of theories of physics as dolls in a nesting structure: zooming in on a physical system reveals novel smaller-scale structure. A description of the smallest-scale structure is not always known. Image generated by openart.ai.

Do you know any theoretical physicists? Maybe a friend, or a niece? Have you ever had them explain some of their work to you? Perhaps you did not know whether to nod along in silent awe or laugh at the ridiculous way they use the English language: as if they are a magician trying to trick you into drawing some absurd conclusion about the material world, a conclusion that is obviously counterintuitive. An example of such a conclusion would be that every square centimeter of our world is bombarded by 65 billion tiny particles, so-called ‘neutrinos’, every second. They are passing through your body right now. Or the conclusion that matter, including solids, is mostly empty space – for more than 99%.

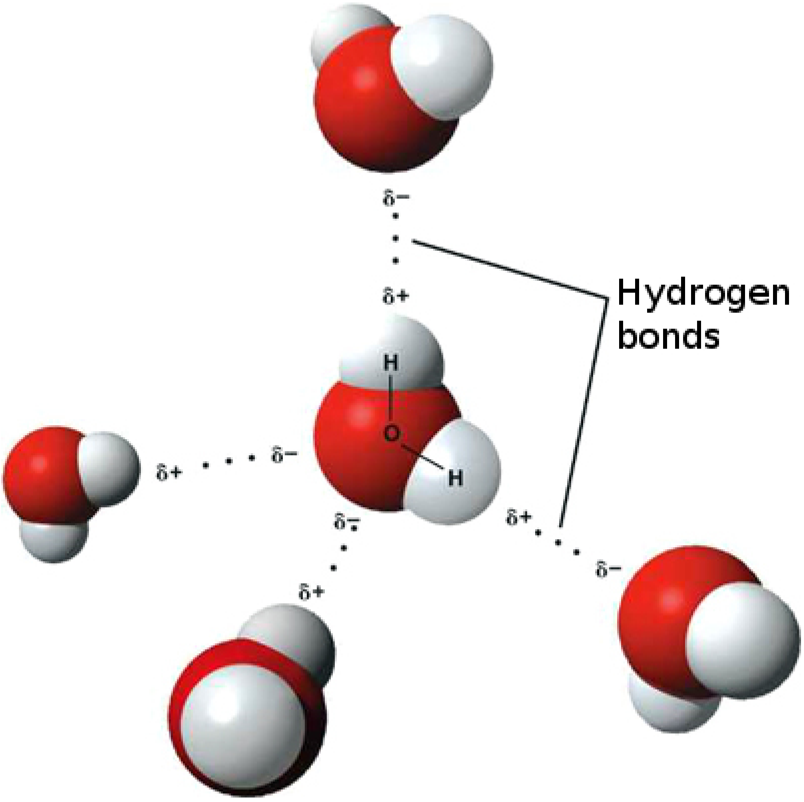
Contrary to what the language of its adepts might suggest, theoretical physics can generally be understood as a down-to-earth practice. It aims to think up *theories* to describe the universe, similar to how one would search for the funniest metaphor to mock the behavior of a friend. A class of theories in physics that strongly exhibit the idea that any theory derives its shape, purpose and meaning from its context, is that of *Effective Field Theories*. I would like to show that the underlying principle is no different from how other and everyday types of descriptions, including jokes, derive their meaning – a glimpse into a humble practice.

A theory through the lens of theoretical physics

As befits a good scientist, a theoretical physicist is possessed by finding knowledge of reality, which she casts into the shape of a theory. To start off, a theory is the main tool for reaching the scientific goal of describing and explaining observed facts and making predictions. Let us try to get a more intuitive idea of what a *theory* in theoretical physics is: say we have an aquarium-like magic box, that is of adjustable size and that we can put around any physical system that we wish to explore. The system has matter and energy in it, physical entities such as water and air, flowing at some temperature, or high-energy particles passing through. Various theories could enlighten us on its contents, depending on what aspects we are interested in and the size of the system. To name a few, we consult fluid dynamics on how ocean streams behave, and cosmology if we wish to travel back to the Big Bang. However, if we put the box around living cells, or humans, and zoom in on the relevant scale of their behavior, the theories from fundamental theoretical physics lose most of their descriptive and predictive power. That is because the scope of a theory is limited, it is only tuned to a few properties. This has everything to do with the crucial role of *scale*.

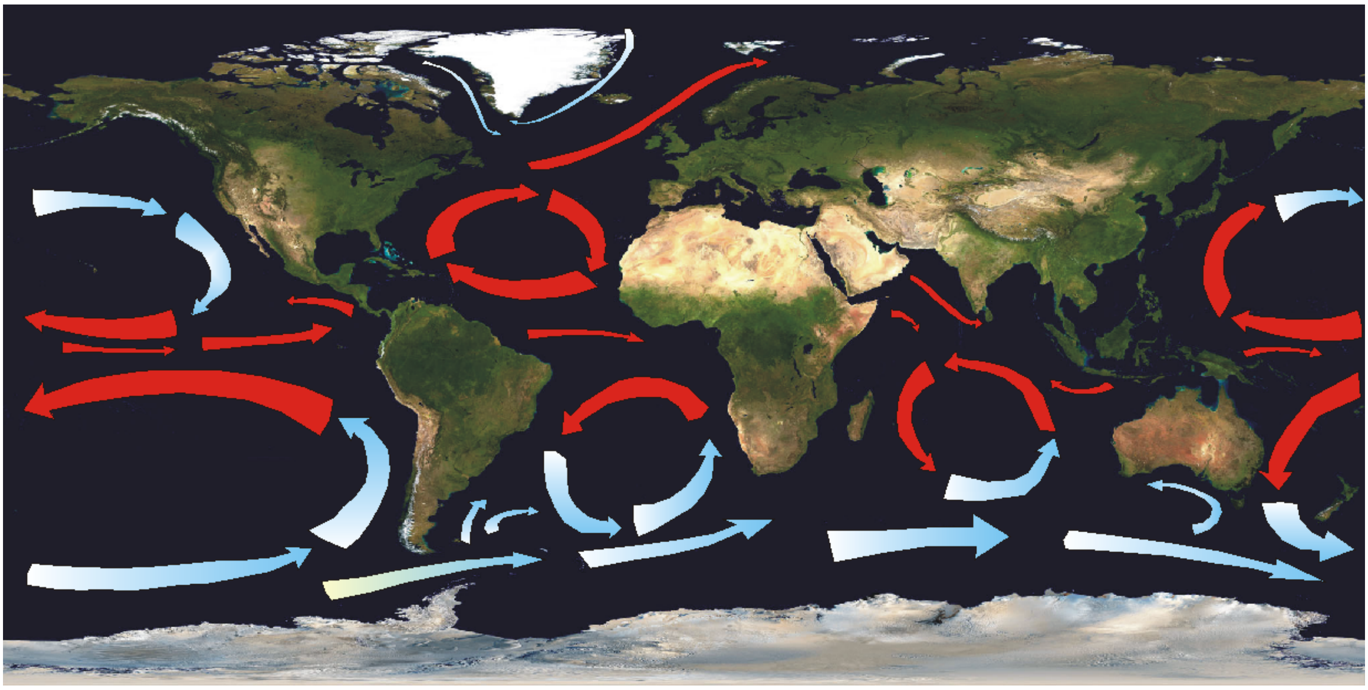
A nesting doll as a frame of frames: to be effective or to be fundamental

I already mentioned the size of the system: importantly, the *length scale* of a physical system is linked to an *energy scale.* In particular, a small length scale corresponds to a high energy scale, and vice versa – much like how a sturdy and weighty person would move sluggishly compared to a springy schoolchild. This is why a high-energy particle collider serves as a microscope on the universe. On top of that, the pivotal principle of *separation of scales* states that a description at one scale does not require knowledge of physics at smaller scales.



A water molecule. Image via Pycril.

Let's break this down by first having a look at how scales are related by reductionism. Reductionism boils down to describing a complex phenomenon in terms of its simpler or more fundamental parts. Each part has a smaller length scale than the composite system, which introduces a direction when reducing one theory to another: one might say the 'arrow' of reductionism is such that a *fundamental* high-energy (small scale!) theory explains a low-energy or *effective* theory, not the other way around. Compare this to the structure of a nesting doll: looking closer at a large system, one finds smaller-scale structures. Being 'more fundamental' in physics is like being the smaller doll in a nesting doll. In this sense, a description of electron movement in water molecules is more fundamental than a description of ocean streams. With enough computing power, one could in principle derive ocean stream behavior using the movement of water molecules. But in no way can ocean streams tell us the internal dynamics of a water molecule.



Ocean currents. The obvious scale difference between water molecules and ocean streams illustrates the importance of using the appropriate description for a system's scale: try describing the ocean streams using the water molecule dynamics, and you will most likely fail. Background image: NASA; adaptation via Wikimedia Commons.

Now, although reductionism relates large-scale theories to small-scale theories in a way, *separation of scales* tells us they are independent in another way. Sticking with the nesting-doll metaphor: separation of scales guarantees us that there is no need to know what the smaller doll looks like to find a fruitful description of the larger doll. This is redeeming to science, since the high energy scales are difficult – if not impossible – to access and the small dolls therefore often remain elusive. Separation of scales tells us why theories of physics work, even though their scope is limited.

Why should a low-energy, large-scale theory that ignores smaller-scale structure be called 'effective'? The description at low energies should be considered an approximation of the underlying more fundamental theory. Low-energy variables are sneakily informed about the more fundamental theory since they are averages of smaller-scale dynamics, sweeping the microscopic details of what happens at those scales under the carpet. For example, using the dynamics of ocean streams, we try to compute the sea water temperature near the shore in July and find 24 degrees Celsius. Temperature, however, is the average kinetic energy of the water molecules. Even though it ignores variations in water molecule movement, the ocean stream description is valid and operative, which is why it is called 'effective': it works.

Now that we have an idea of what an ‘effective theory’ is, we can try to grasp how this idea is reflected in the case of ‘Effective Field Theories’ (EFTs). They are a class of theories that is central in theoretical physics. In the case of particle physics, for example, they describe how particles with a specific amount of energy interact or ‘bounce off’ each other when they collide, like marbles hitting one another. Each theory works best for a specific range of particle energies, creating a spectrum of theories for the same physical system. When we are interested in the large scale/low energy behavior of the particles, we do not consult the high-energy theory. Analogously, we do not bother to include the movement of electrons in water molecules when mapping ocean streams, and we shouldn’t. It will soon become apparent why this class of theories is particularly interesting.

Effective yet ‘fundamental’

But first, wait- really? A theory is an *approximation*? Isn’t that dull, and non-exact? Effective Field Theories are approximations, indeed – albeit very *precise* ones. (The proton mass, for instance, is predicted by a theory called *lattice quantum chromodynamics* (QCD) up to 3 digits.) Instead of producing ballpark estimates, an EFT is a description that approaches reality or completeness, without reaching it.

Perhaps being approximate is also perfectly normal, since approximations are the only thing we have. That is to say, *the* fundamental theory in theoretical physics, which would not be an EFT since it is not an approximation of something deeper, is not known, and not even known to exist. No theory that we know of explains all other theories. Rather, all underlying theories we have, such as the one that would include all the electron movements, are also EFTs, and therefore at best approximations of an even deeper and more fundamental theory.

Although EFTs might often be considered the next best tool available to do physics for want of a truly fundamental theory, is the principle of EFTs itself not a more fundamental principle in any sensible description-generating business? And here I mean ‘fundamental’ in the usual sense of being the central principle on which something is based. So, just like “approximations” are in fact very precise, I would maintain that “effective” descriptions are in fact most fundamental.

To support this view, note that the right *context* is what makes an effective description so meaningful. Just like EFTs are valid and therefore meaningful at the right length/energy scale, any good description should be valid and meaningful when tested against reality in the appropriate context. To further explore this idea, let us try to find in what other guises we can recognize effective descriptions.

A familiar concept: the precision of jokes

What can we say about jokes, for example? What makes a good punchline? There's the element of timing, wording. Mostly, as soon as the moment has passed, you wouldn't want to repeat your darling joke for that one friend who didn't pay attention. The moment that the joke was relevant has passed, its meaning is just not the same in a different context that occurs a moment later. A good joke also *reveals* something about the way things are. It attempts to seize the moment to make a snapshot of reality. A joke that is spot-on is an incredibly precise creative utterance. It is a reality-revealing, informative, meaningful and illuminating tool. Doesn't that smell of theories? Put dryly, a joke is also an effective description since it works in the appropriate context.

As such, I would argue that effective descriptions are not limited to science. Rather, they are ubiquitous. If you start spotting them, they reveal themselves in innumerable places. Some examples from daily life apart from jokes include letters, poems, artworks, songs, and text messages; they all try to cut to the heart of something, yet they are very distinct and diverse in their shapes and perspectives. They carry meaning in their context, which is given by a sender and a recipient, a medium, a time and a place. They are related (for they can be translated into each other – a poem can describe a painting, for example), yet independent (in the right context, they are operative by themselves).

Within the walls of science, active theory-relating is at the heart of interdisciplinary science, which attempts to integrate descriptions from different disciplines. Even beyond the walls of science, the meaning of a description can be interpreted and related starting from its context. The business of interpreting and relating keeps us busy, it's what we do, in our attempt to navigate the myriad contexts that the world confronts us with. Similar to how physicists keep searching for the One Grand Unified theory, a philosopher might wonder whether the relatedness of descriptions implies there lies actual truth at the heart somewhere; whether our theories and descriptions are shadows of the real world.

Until the day that the Theory of Everything is found, wouldn't it be most sensible to think of theories in Theoretical Physics as pragmatic, operative descriptions that no longer carry meaning or truth when disconnected from their context? A theory of physics applied at the wrong length or energy scale, is as effective as telling an inside joke to an outsider.

Effective, yet fundamental, therefore ordinary

Rather than nailing down the way the world behaves once and for all, science is centered around making effective descriptions – operative approximations – of the world in which we live and about which we wonder. Physics is no exception. Except, perhaps, that it observes the world at bizarre length (and therefore energy) scales. Although this makes theoretical physics at times a mysterious world – and not just to people unfamiliar with it – it is not magic. Its starting point is the familiar pursuit of statements that are true and effective in a given context. Admittedly, that might still be an airy formulation. Let’s put it this way. What do we aim for? Everything, and the truth. What do we do? Whatever works best.