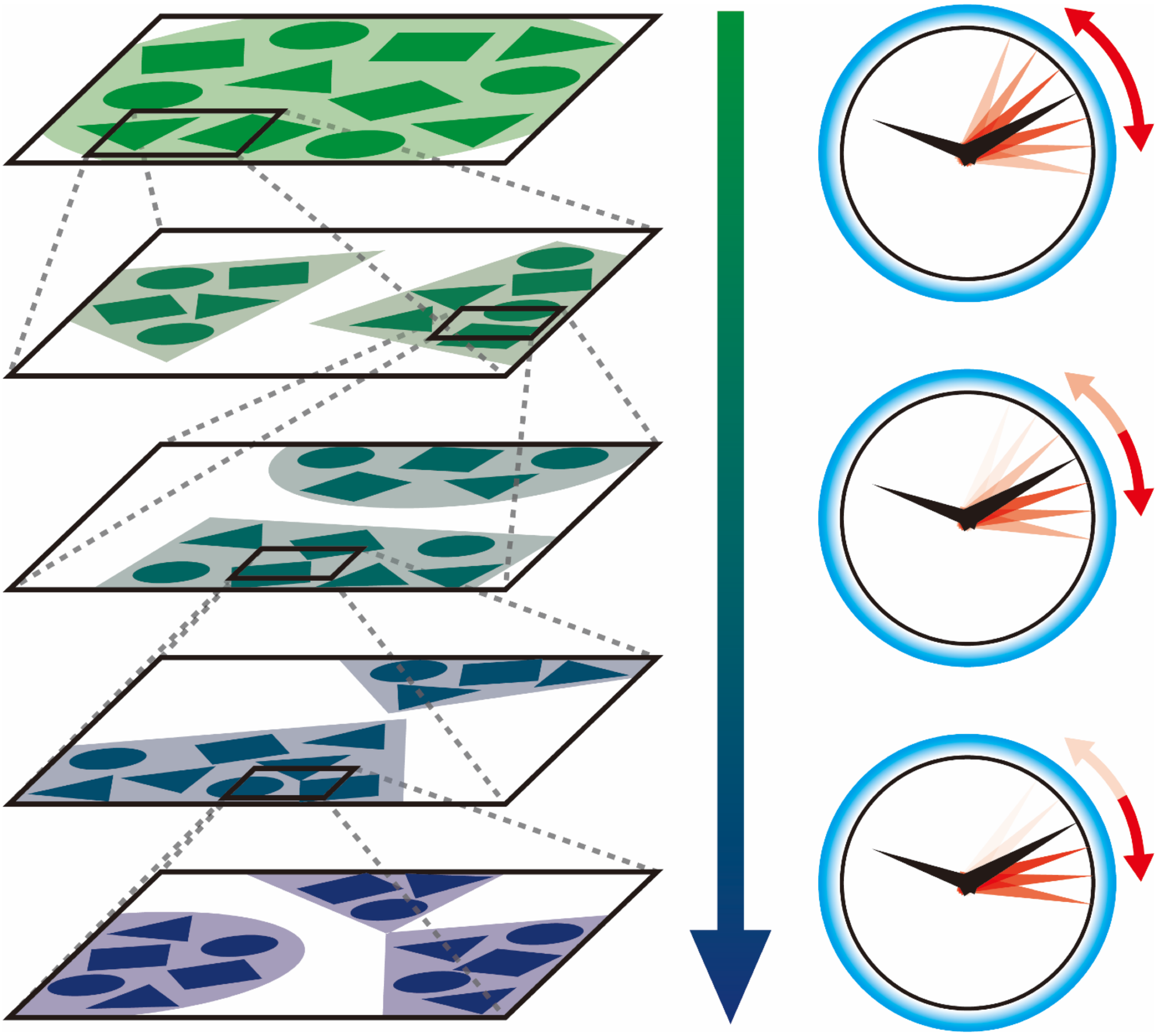
Irreversibility: a key to our complex, multi-layered world

Naruo Ohga



Our world has a broad hierarchy of physical layers, from microscopic to macroscopic. At the most microscopic layer, or the ‘lowest’ layer, are the atoms, while at the highest layer are a variety of complex phenomena such as living organisms. These two extremes are connected by various middle layers. For example, a human body consists of organs, which consist of cells, which consist of protein molecules, which consist of atoms. Such layered structure is the source of rich phenomena observed in our scale. A lower layer constitutes the behavior of the successive higher layer, while the higher layer imposes the lower layer to behave consistently with the laws of the higher layer. The ladder of such interplays forms our multi-layered world.

Understanding the interplay among layers remains to be a big challenge in science. The difficulty is that different layers have different characters and call for separate theories. This difference makes it hard to develop a theory unifying several layers. For example, a heart and the cells are distinct objects, and a theory of cells is quite different from a theory of the heart as a whole. Therefore, science usually deals with only a single cell, focusing on the cellular layer, or considers the function of the heart at the higher layer. In both cases, the interplay between these layers is ignored. This is how most science deals with the world, and we still do not know enough how to understand many layers in a unified manner.

In the past 20 years, physicists have discovered a potential key quantity to understand the multi-layered nature of the world: irreversibility. The concept itself is simple. A process is said to be irreversible when it is much more likely than its reversed process. Let's say you drop a glass of water and break it. This process is irreversible because its reversed process is improbable, in which the glass fragments and the spilled water spontaneously fly up to form a glass of water in your hands. With this concept in mind, physicists have defined irreversibility as an exact quantity. The irreversibility of a process is the ratio between the probability of the process and the probability of its reverse process. The irreversibility is large if the process is much more likely than its reversed one.

Despite the simplicity of the definition, irreversibility has an essential relationship with the hierarchy of layers [1]. We will observe more irreversibility when we look at a process from a lower layer. Consider, for example, lifting your arm slowly. This process is not irreversible on our daily layer because the reversed process, lowering your arm slowly, is also possible. However, if we look closely inside your body, we will observe the consumption of nutrients to shrink your muscle. The consumption is irreversible because the nutrition would not be spontaneously produced inside your body. This relationship between irreversibility and the hierarchy of layers is universal. Indeed, with the above mathematical definition of irreversibility, it has been rigorously proven that a closer observation increases irreversibility.

The advantage of irreversibility is that it is a universal quantity across layers. It can be applied to any layer, thanks to its simple definition. Therefore, it can overcome the difference in characters among layers and will be a key concept in investigating the interplay of layers in the physical world.

This relationship between irreversibility and the hierarchy of the world has, so far, not been fully recognized or utilized. The relationship is known only in a small branch of physics called stochastic thermodynamics, and the application is just getting started for simple imaginary systems [2]. Nevertheless, this concept will certainly be soon recognized in other areas of science and applied to complex real-world phenomena in, say, 20 years.

We can imagine extracting a variety of information from the irreversibility of a system. We can, for example, calculate the irreversibility at each layer and compare it across layers. If the difference in irreversibility between two layers is almost zero, the lower layer is just obeying the higher layer. On the other hand, if the difference is large, the lower layer exhibits more irreversibility than required from the higher layer. In the latter case, the irreversibility is 'hidden' in the lower layer. Such hidden irreversibility may contribute to a richer behavior of the whole system.

Furthermore, we can examine the correspondence of the irreversibility observed at different layers. All the irreversibility in a higher layer should have its source in the lower layer. Therefore, we can investigate which irreversibility in a lower layer constitutes which in the higher layer. This analysis will uncover how the behavior of the lower layer comprises that of the higher layer.

One of the promising targets of such investigation is living organisms. Living organisms are full of irreversibility. All lives eat food and convert it into energy, while they cannot conversely transform energy into food. If this irreversible process halts, the organism dies. In other words, the rich phenomena of living systems all arise from irreversibility.

Therefore, we can analyze the entire organism as an irreversible system. By examining the irreversibility at each layer, we will know which layer just obeys the higher layer and which layer hides irreversibility. We will also uncover how the behavior of a lower layer, say cells, comprises the behavior of a higher layer, say organs, from the viewpoint of irreversibility.

Irreversibility will be one of the key concepts for understanding this world. It pierces the complex hierarchy of layers like a straight warp, allowing us to ride on it and climb up and down among the layers. In a couple of decades, this new concept will significantly advance our understanding of the complex, multi-layered world, including living systems.

References:

[1] M. Esposito, Stochastic thermodynamics under coarse graining, Phys. Rev, E **85**, 041125 (2012).

[2] L. Cocconi, G. Salbreux, and G. Pruessner, Scaling of entropy production under coarse graining in active disordered media, Phys. Rev. E, **105**, L042601 (2022).

Disclaimer (Not a part of the essay. Delete this when publishing on the FoPM website.):

I followed the essay guideline to spare about one-third of the word count for each of (1) what was discovered, (2) why it is important, and (3) the impact I think it could have on the future of science and/or society. However, I did not write these points in this order. The first section (separated by a blank line) is intended for (2). The second section starts from (1) and ends in (2). The third section is devoted to (3). The fourth section (the single paragraph) does not belong to any of the three.