Indian Academy of Sciences Conference Series (2019) 2:1
DOI: 10.29195/iascs.02.01.0017

Description of nature: A single law or many laws?

MAHENDRA K. VERMA

Department of Physics, I. I. T. Kanpur, Kanpur 208 016, India
*Corresponding author. E-mail: mkv@iitk.ac.in

Abstract. In this short paper we explore whether nature can be described by a single law in the reductionist paradigm, or it is to be described by a set of laws based on multiscale perspectives.

Keywords. Reductionism; history of science; multiscale physics; nature of laws; turbulence.

PACS Nos 01.65+g; 94.05.Lk

1. Introduction

Science aims to describe nature in the simplest and most comprehensive manner. This has been a guiding principle from age immemorial. In the early phase of modern science, Galileo and Newton formulated the laws of motion. Another important milestone is Newton's law of universal gravitation that describes the gravitational attraction among all bodies. Using law of gravitation, Newton explained many phenomena on the surface of the Earth, motion of the Moon around the Earth and motion of the planets around the Sun [1]. Later, quantum theory was discovered that proved to be a very important tool for describing interactions in the microscopic world.

In the last 150 years, the basic laws have become more compact and powerful. Maxwell combined the electric forces with magnetic ones. Salam, Weinberg and Glashow [2] integrated the electromagnetic force with weak nuclear. Then, in a standard model [2], strong nuclear force was combined with the former two forces. Gravity is yet to be united with the other three fundamental forces. In addition, quantum field theory successfully unifies relativity and quantum mechanics.

There have been advances in the construction of unified frameworks in other areas of sciences as well. For example, theory of critical phenomena explains all kinds of transitions in a single framework. The equations of thermodynamics and fluid dynamics describe almost all of the fluid flows and thermal systems. Amazingly, many natural and laboratory phenomena could be explained using the aforementioned theories.

Among many researchers, the above advances have led to a belief that all phenomena in the universe could be explained using fundamental forces and interactions among elementary particles. Some physicists call such elusive theory, Theory of Everything (TOE) [2]. However, not everyone agrees with this hypothesis. Many physicists believe that 'More is different' [3, 4] and 'Whole is more than its parts'. For example, Wilson [5] showed that the physics of phase transition is governed by interactions among large scale fluctuations. Thus, phase transition is an emergent phenomena. In this article, we shall advance a hypothesis that laws of nature at different scales are different [3, 4], and that often, these laws cannot be derived using microscopic forces and structures.

Before we start to compare the hypothesis of a single law and that of many laws, we make an important remark. At present, constitutive relations are known for most physical systems. Simple ones among them have been solved, but many complex ones remain unsolved. Some of the ill-understood systems are—quantum chromodynamics, turbulence, nonlinear relativistic equations that govern black holes and complex astrophysical objects, strongly interacting electrons, plasma confinement for fusion, etc. We know the equations or Lagrangian of these highly interacting systems (at least approximately), but not the solution. Standard tools like perturbative methods do not work for them. Hence, knowing the fundamental forces and interactions is one thing, and solving the equations is another. These issues are connected to algorithm complexity theory, quantification of complexity and interactions, etc. (issues bordering mathematics, computation and physics). Interestingly, practical and approximate computer solutions prove to be very handy in such situations.

In the next section we shall briefly discuss the debate on whether description of nature requires a single law or many laws to describe hierarchy of phenomena.

2. Single law or many laws

In the introductory section we provided a glimpse of the triumph of unification and search for a universal theory. These developments are indeed very enthralling, which led many to believe that everything (physical universe, biology, social science, economics, . . .) could be explained starting from the fundamental interactions. Though many researchers believe in this 'reductionist paradigm', many do not. Here, we quote two giants who put forth different perspectives:

To rephrase Anderson [3]: "The main fallacy in this kind of thinking is that the reductionist hypothesis does not by any means imply a constructionist one: The ability to reduce everything to simple fundamental laws does not imply ability to start from those laws and reconstruct the universe." Anderson adds further: "When I speak of scale change causing fundamental change, I do not mean that the phenomena at a new scale may obey actually different fundamental laws. I think it will be accepted that all ordinary matter obeys simple electrodynamics and quantum theory."

Hawking [6]: "I think the next [21st] century will be the century of complexity. We have already discovered the basic laws that govern matter and understand all the normal situations. We don't know how the laws fit together, and what happens under extreme conditions. But I expect we will find a complete unified theory sometime this century. There is no limit to the complexity that we can build using those basic laws."

Our proposition is slightly different from the above. Though same fundamental forces work at all levels, the systems are differently organised at different levels. And the relevant questions and phenomena at various levels are different. It is in the same spirit as the three-dimensional pictures that contain different pictures at different focus. We cannot view all these pictures by focussing only at a single distance.

We shall elaborate this viewpoint using the following real-life examples:

1. A building is constructed using bricks and mortar. However, the design, architecture and aesthetics of the building is not captured by these basic constituents. In addition, the multiscale stresses in the structures arise as a collective effect. The complexity is further enhanced when we deal with sun light and air flow for the building.

2. Though human body is made of cells, which in turn is made of electrons and protons, human metabolism is a collective and emergent phenomena. Human behaviour and consciousness are even more complex. Given this, it seems preposterous to assume that we can derive these phenomena starting from the fundamental forces.

3. Human body is an example of the hierarchical structure with DNA, cells, muscles, bones, blood, neutron systems, functional units such as digestive, circulator systems etc., . . . , senses and mind. Biologists, doctors, pharmacists and psychologists have discovered different laws for different elements of the body. Some may call these laws practical or derivative, but some (like Freud) may treat them as fundamental at that level.

These examples may appear to be qualitative and too far away from physics. In the following two sections we shall present two examples that clearly demonstrate that several laws of physics are NOT derivatives of microscopic physics.

3. Example 1: Phase transition

Here we provide a very brief introduction to phase transition. Landau [5, 7] constructed a theory of phase transition using a macroscopic model of free energy. For the second-order phase transition, he assumed that the free energy F is given by

$$F = a(T - T_c)\Psi^2 + b\Psi^4, \tag{1}$$

where Ψ is the order parameter, T is the temperature of the system, T_c is the critical temperature, and a, b are positive constants. Note that at the critical temperature, the coefficient $a(T - T_c)$ changes sign. Therefore, the stable state (minimum value) of F changes from $\Psi = 0$ to

$$\Psi_\pm = \pm\sqrt{\frac{a|T - T_c|}{b}}. \tag{2}$$

This is a generic framework for phase transition. An example of such transition is from a paramagnet to a ferromagnet, which correspond to $\Psi = 0$ and $\Psi = \Psi_\pm$ states, respectively.

Landau's theory is a mean field theory where Ψ represents an average value of the order parameter. Unfortunately, some of the predictions of Landau's theory do not agree with experiments. Later, Wilson [5, 7] refined Landau's theory by including fluctuations in the order parameter in the model. The predictions of Wilson's theory match quite well with the experimental results. At present, Wilson's theory is the accepted theory of phase transition.

Thus, Landau and Wilson showed that the aforementioned laws of the phase transition are independent of microscopic physics as long as the interactions are local. In fact, the main strength of their universal theory is that their predictions are independent of the microscopic interactions. It is important to note that several researchers have provided a bottom-up derivation of eq. (1) from microscopic models. However, such derivations can be treated as demonstration of the above idea; the theory of phase transition stands on its own.

An amusing corollary of the aforementioned idea in social science is that the mob behaviour cannot necessarily be derived from individual behaviour. Not all sorts of mob behaviour and mob violence can be traced to individual behaviour.

4. Example 2: Energy flux in turbulence

A combination of Navier–Stokes equations, and equations for density and internal energy describe all kinds of fluid flows. Note that Navier–Stokes equations are essentially Newton's law of motion in the continuum. We do not need to resort to microscopic physics to derive the Navier–Stokes equations, though it can be done using kinetic theory. When the flow speeds are large, the flow becomes turbulent, which is a complex mix of order and chaos [8]. Turbulence is one of the unsolved problems of classical physics. There is however an interesting theory of turbulence by Kolmogorov [8, 9] for an isotropic and homogeneous turbulence, which is described below.

Imagine that a fluid in a container is stirred at large scales. The energy fed by the stirring cascades to the intermediate scales and then to small scales where it is dissipated by viscous force. In the intermediate scale, called inertial range, the multiscale energy flux is constant, and it is denoted by Π. Note that the energy flux arises due to coherent and multiscale interactions among the velocity Fourier modes. In fact, Π is proportional to the average of triple correlations of the velocity Fourier modes [10].

Using these assumptions and dimensional analysis, we can derive the energy spectrum $E_u(k)$ as [8]:

$$E_u(k) = K_{\mathrm{Ko}} \Pi^{2/3} k^{-5/3}. \tag{3}$$

The above prediction matches with many experimental and numerical results. In addition, similar multiscale energy transfers have been observed in other kinds of flows, such as magnetohydrodynamic turbulence [10], scalar turbulence [8] , buoyancy-driven turbulence [11], etc.

Note that Kolmogorov's theory of turbulence does not invoke fundamental forces or microscopic constituents of the fluid. As described above, the energy flux arises due to coherent and multiscale interactions among the velocity Fourier modes, not by microscopic interactions.

The above phenomena give new perspectives on nonequilibrium nature of the flow, time irreversibility, breakage of the detailed balance, multiscale interactions, etc. The aforementioned formulation of multiscale transfer is quite general, and it could be employed to money flux in an economy [12], or cascade of information flow.

5. Discussions and conclusions

The aforementioned ideas and examples illustrate that many natural phenomena cannot be explained using fundamental forces and basic constituents of matter (laptons and quarks). In fact, nature has complexity at all levels—quarks, nuclei, atoms and molecules, virus and bacteria, larger animals, planets and stars, galaxies, and universe. Though the same fundamental forces act at all scales, system dynamics at every level brings in new complexities. For example, the climate change remains an elusive problem though we know all its equations (fluid flow equations, thermodynamics, and radiation physics). For this phenomena, the difficulty lies in the nonlinear interactions among land, oceans, atmosphere, solar radiation, etc. The Earth itself is so complex that some consider it to be a living organism (Gaia hypothesis). Similar complexities exist in stars. For example, a full understanding of the solar magnetic field and corona heating is still lacking, though the basic laws for these phenomena are known.

Thus, the structure of the universe is hierarchical (quarks, nuclei, . . . , to universe), and we possibly need different laws at different levels. Some of these laws may be hierarchically interlinked, but many of them (like theory of phase transition and turbulence) may stand on their own. There may however be certain common principles among these phenomena, such as multiscale interactions, energy conservation, etc. We believe that giving sufficient importance to the perspectives of 'many laws' will lead to scientific growth at all levels, and help solve some of the outstanding problems such as climate change, aesthetics, human behaviour, etc.

Acknowledgements

The author would like to thank Michael Berry and Anurag Gupta for valuable discussions.

References

[1] M K Verma, *Introduction to Mechanics*, 2nd edn (Universities Press, Hyderabad, 2016)

[2] G Kane, *Modern Elementary Particle Physics*, 2nd edn (Cambridge University Press, Cambridge, 2017)

[3] P W Anderson, *Science*, **177(4)**, 393 (1972)

[4] P W Anderson, *More and Different: Notes from a Thoughtful Curmudgeon* (World Scientific, 2011)

[5] K G Wilson, *Phys. Rep.*, **12(2)**, 75 (1974)

[6] S Hawking, https://en.wikiquote.org/wiki/Complexity (2018)

[7] J M Yeomans, *Statistical Mechanics of Phase Transitions* (Clarendon Press, Oxford, 1992)

[8] M Lesieur, *Turbulence in Fluids* (Springer-Verlag, Dordrecht, 2008)

[9] A N Kolmogorov, *Dokl Acad Nauk SSSR* **32(1)**, 16 (1941)

[10] M K Verma, *Phys. Rep.* **401(5)**, 229 (2004)

[11] M K Verma, *Physics of Buoyant Flows: From Instabilities to Turbulence* (World Scientific, Singapore, 2018)

[12] M K Verma, Hierarchical Financial Structures with Money Cascade, In *New Perspectives and Challenges in Econophysics and Sociophysics*, eds. F Abergel, B K Chakrabarti, A Chakraborti, N Deo and K Sharma (Springer, 2019) p. 61