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Profile and challenges of interdisciplinary physics

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We discuss profile and challenges of interdisciplinary physics. We start discussing the current definition of physics. We therefore focus on the type of experimental settings observed in different branches of physics. We recall how the term predictability has changed over the last century and we comment on the effects of data deluge in science and society. Lastly we present a few examples of current profile and challenges of interdisciplinary physics.

KEYWORDS

physics, interdisciplinary physics, big data, heterogeneity, noise

1 Introduction

Interdisciplinary research is promoted by many public and private institutions. The main reason for this type of promotion is the observation that solutions of some important social and economic problems can be achieved only by considering problems whose ingredients lay at the boundary of different scientific disciplines. In spite of this widespread view, promoting, planning, funding and organizing interdisciplinary research turns out to be a quite complex task. One of the reasons of this complexity is the fact that interdisciplinary research is intrinsically of hybrid nature and it involves knowledge, methods and concepts belonging to different research communities. This hybrid nature gives researchers the potential to tackle complex problems but the same hybrid nature can be rather frustrating for researchers' identity. Sometime a researcher (especially when he or she is at the beginning of his/her career) performing interdisciplinary research might feel like the half dog and half wolf of the movie *Balto* [1]. In an iconic moment of the film, the wise goose Boris describes Balto by saying "He's no lap dog. Not a dog, not a wolf. All he knows is what he is not. If only he could see what he is." In other words, in interdisciplinary research often researchers know *what they are not* but they miss the positive aspects and values of their identity.

The aim of this paper is to provide a few thoughts to define profile and challenges of *interdisciplinary physics*. In spite of the risk associated with its hybrid nature, interdisciplinary physics is a research area widespread all over the world. To highlight the profile of interdisciplinary physics, we first perform a critical analysis of the most common definitions of *physics* and we discuss the types of experiments that are performed in its different branches and that are typical in interdisciplinary physics. We therefore consider the type of predictability achieved by physics and we recall how a weakening of predictability implies the enlargement of the fields of application of theories and concepts of physics. Lastly we briefly consider the main challenges encountered in current interdisciplinary physics research also by taking into account the impact that data deluge of the last 20 years has had in science and society.

2 Defining physics

Although at first sight it might seem superfluous, the analysis of the profile and challenges of interdisciplinary physics requires a preliminary careful definition of the terms. A special focus needs to be dedicated to the term physics. Apparently there is a quite large consensus on what is physics today. Wikipedia states that “*Physics is the natural science of matter, involving the study of matter, its fundamental constituents, its motion and behavior through space and time, and the related entities of energy and force.*” [2] Similarly, Britannica Encyclopedia is stating that physics is a “*science that deals with the structure of matter and the interactions between the fundamental constituents of the observable Universe*” [3]. In both cases the emphasis is on matter, energy and force and on fundamental constituents of the observable Universe.

Before we focus on the limitations of such a definition, it should be noticed that the core definition of physics has changed over the centuries. In fact, Britannica Encyclopedia correctly reminds us that “*In the broadest sense, physics (from the Greek *physikos*) is concerned with all aspects of nature on both the macroscopic and submicroscopic levels*” [3]. When we consider the etymology of the term, we conclude that in the past the term physics was used to describe the modeling of all natural things. The current restricted sense of “*science treating of properties of matter and energy*” starts to be used only from 1715 [4].

It is incontestable that major successes of physics of the last three centuries are related to the modeling of matter, radiation, and energy, but physics has also developed tools and concepts that have modelling potentials going well beyond the properties of matter, energy, and of so-called fundamental constituents. Prominent examples of these concepts and tools have been developed by the branch of physics named statistical physics. Statistical physics can model emergence, i.e., the setting up of collective properties, in large homogeneous systems with local interactions [5]. The archetypal model in statistical physics is the Ising model originally developed to describe the paramagnetic-ferromagnetic (or antiferromagnetic) phase transition. Ising model is only approximately describing the paramagnetic-ferromagnetic phase transition, but its study has clarified the ability of statistical physics in modeling many-body systems with local interactions. Statistical physics models (in a few cases exactly solvable) have huge potentials of applications to several types of many-body systems including systems where each elementary unit represents a social unit characterized by specific heuristics.

Therefore, defining physics as “*natural science of matter, involving the study of matter, its fundamental constituents, its motion and behavior through space and time, and the related entities of energy and force*” is too restrictive and does not cover main concepts and results of statistical physics especially for many body interacting elements giving rise to emergent properties. Considering statistical physics as a proper branch of physics was at the core of the huge and sometime isolated efforts made from Ludwig Boltzmann for obtaining a full recognition of his seminal and fundamental results [6].

3 Fully controlled experiments versus observational investigations

In its long history, physics has developed a methodological experimental approach aiming to isolate and control as much as possible the setup of each specific experiment. This approach has its best achievements when the system of interest is at a molecular, atomic or subatomic scale but it is less effective when such isolation is difficult or impossible to achieve as, for example, in turbulence, geophysics or astrophysics. Note that in my last sentence in the last two examples I had to use compound words that are specifying the type of system of interest being the Earth or the entire Universe respectively. In other words, any physics experiment aims to achieve fully control of performed experiment, but the full control is only an idealized state. Experimentalists try to converge towards a state as close as possible to the idealized one.

Matter, radiation, and energy are present in systems ranging often more than 40 orders of magnitude. Consider, for example, the matter range existing between a single proton and massive black holes or the Hercules-Corona-Borealis Great Wall. This enormous range implies that fully controlled experiments can usually be performed only for some of the phenomena investigated. In fact, it is impossible to perform experiments on the scale of a star or on the scale of an ocean or of a tectonic plate. In these cases, the methodological approach followed by physicists is the approach of observing physical phenomena and interpreting them with models of physics. In astronomy, astrophysics, and geophysics scientists are therefore using observatories. In several cases the observatories are recording the temporal evolution of a non equilibrium system. Some branches of physics are therefore dealing with observational practices monitoring non equilibrium systems. The mainstream epistemological paradigm of physics often seems to forget this specific aspect and it is often based on the tacit assumption that all experiments of physics are fully controlled.

The observational attitude is typical in several areas of interdisciplinary physics. As in the case of astrophysics or geophysics new interdisciplinary areas as, for example, econophysics or sociophysics monitor and model systems that cannot be isolated or modeled by considering only some of their parts. Moreover, in a large number of settings, these systems are also manifestly out of equilibrium with respect to some of the key variables describing the system. In summary, observational studies are not unusual in core physics and are almost ubiquitous in interdisciplinary physics.

4 Predictability in physics and the evolution of its meaning during the last century

Nineteenth century physics was considered an “exact” science. This statement originates from the observation that models of physics of that period provided quantitative forecasts of the future state of investigated systems. The prediction was fully deterministic, i.e., it can be invalidated only by the failure of the theory in describing the system or by limits in numerical computation of forecasts. As pointed out by Giorgio Parisi in

1999 [7], new theories of late nineteenth and twentieth centuries, specifically statistical mechanics, quantum mechanics, and chaos theory strongly changed the meaning of the word prediction in physics. In fact, it is nowadays recognized that prediction in physics is rarely fully deterministic, and it rather has an unavoidable statistical aspect originating from multiple reasons. Examples of these reasons are the large number of elements composing the system, the quantum nature of particles and interactions, and nonlinear interactions present in physical systems. Giorgio Parisi has superbly expressed the impact of the change of the meaning of the word prediction in physics by stating that *“As an effect of these revolutions, the word prediction acquired a weaker meaning. Predictions in the context of the new paradigm are not acceptable with the old one (and sometimes the supporters of the old point of view try to deny to them scientific validity). The positive consequence of the process is that the scope of physics becomes much larger and the constructions of physics find many more applications”* [7].

Stochastic description is therefore unavoidable in several areas of physics. Moreover, even when a determinist modeling is present the experimental investigation of the model cannot eliminate all uncontrolled perturbances. In physics these perturbances take the name of “noise”. It is worth noting that noise is all one cannot control in the experiment or in the stochastic modeling of a process. Of course, noise (i.e., uncontrolled, or unforeseen events) is also present outside core physics. Noise can be completely avoided only in idealized settings. In real system noise is usually seen as a nuisance and huge efforts are done to minimize it in all experiments. In studies of complex systems, noise (often addressed as idiosyncratic signals) is controlled by assessing the statistical validity of empirical observations. Noise therefore requires a lot of care from experimenters and from researchers focusing on statistical regularities but can sometime play a counterintuitive positive role both in physical and in social systems [8, 9].

5 Data deluge in science and in the society

During the last 20 years, we have seen huge changes in the society and in the scientific practice. These changes are related to the data deluge observed both in science and in the society. Technological and IT revolution, the crucial role assumed by Internet and by the World Wide Web, the development of e-commerce and social networks have produced and are producing a deluge of data. Here we wish to discuss the impact of data deluge in science. New technologies have made experiments in physics more and more IT controlled and with large memory capacity. For example, the CERN data centre documents that *“As of the end of May 2021, we had 380 PB (petabyte) of data on tapes . . .”,* and *“271 PB were stored on disks for a total capacity of 487 PB on disks”* [10]. One petabyte is equal to 1,000 Terabytes and it is equivalent to about 500 billion pages of standard printed text. Physics is not the only discipline experiencing a huge increase in the rate of production of experimental data. Indeed, several other disciplines have changed their status from low to high rate of production of experimental data. Examples are biology (consider, for example, genomic-wide investigations), medical sciences, economic sciences, and social sciences. In the case of medical

sciences and humanities, data are produced by both scientific research projects and medical, business, economic, and social practices.

It is worth noting that this data revolution is impacting research both in terms of quantity of data and in terms of quality of the data. The present ability of recording large amount of data allows to track experiments with multivariate spatial and/or temporal series. Some of the data originates from experiments carefully designed to investigate very specific phenomena. This type of approach is in line with the tradition of designing fully controlled experiments. Other data originates from continuous (or frequent) monitoring of large systems as, for example, seismological data, satellite weather data, or astronomical data. Observational experiments are therefore widespread in some branches of core physics.

Big data revolution has also multiplied the availability of multivariate datasets. Univariate and multivariate datasets present intrinsic differences. The investigation of a univariate data connotes the implicit special relevance of the variable selected. In the presence of multivariate datasets, redundancies are typically present. In the general case, correlations are present between pairs of variables of the dataset. For modeling reasons, dimensionality reduction is needed to highlight those variables that primarily are driving the systems and are therefore essential in parsimonious models of the investigated phenomenon. Dimensionality reduction is performed with a variety of statistical approaches rooted to principal component analysis. In systems where a stochastic dynamic is present, noise (or an idiosyncratic signal) is unavoidably present in the dataset. In these systems, information and noise need to be distinguished by appropriate statistical methods. For these type of problems, statistical inference plays a crucial role. The development and use of statistical inference concept and methods has a long tradition in economics and humanities, but it is not so typical and diffused in core physics. This aspect will certainly change in the coming years due to the need of a successful modeling of multivariate datasets in interdisciplinary and core physics.

6 Profile and challenges of interdisciplinary physics

In a typical setting of interdisciplinary research, a problem present in a specific discipline is approached and/or solved with the use or adaptation of a methodology and/or of a concept originated in another discipline. Starting from this basic setting, interdisciplinary research usually evolves in generating new problems originating from the research practice and from the needs of the different disciplines involved in the projects. This practice induces the contributing disciplines to reflect on strengths and weaknesses of their tools and concepts.

In another setting, the interaction of researchers of two disciplines produces a new interpretation of problems and results obtained in each discipline. An example of reinterpretation of results obtained in a discipline under concepts of relevance in another is, for example, the investigation of states and properties of an agent-based model such as the minority game in physics and in economics. In physics the model presents a phase transition between an ergodic and a non-ergodic phase [11], whereas in economics it is seen as a paradigmatic example of the failure of rational agent modeling in a

setting where information is disseminated in the presence of negative externalities [12]. Another example of reinterpretation of the same formal problem in different disciplinary setting concerns the detection of ground state of spin glasses. In fact, it can be proven that the problem of its detection is equivalent in computer science to the computational problem of finding the partition of vertices associated with the problem known as the maximum cut [13].

Another key aspect of interdisciplinary physics concerns heterogeneity. Many-body systems investigated in core physics are typically homogeneous with respect to their constituencies. One prominent exception is the study of spin glasses whose definition requires the presence of heterogeneity. Most systems outside core physics are heterogeneous and therefore their investigations require methods and tools maintaining their validity also in the presence of heterogeneity. Interdisciplinary physics has among its goals the development of methods and tools being robust with respect to the presence of heterogeneity.

The conceptual revolutions that have impacted the meaning of prediction in physics, the availability of large set of data produced by science or by business and social activities, concepts and tools of statistical physics specialized for heterogeneous and disordered systems have promoted the study of many research problems of interdisciplinary physics. As illustrative examples, hereafter I am citing a few cases I am familiar with due to my research interests. They have no ambition to be exhaustive. Concepts and methodological tools belonging to physics or originating from physics have been quite successful used in traffic analysis and modelling [14], spreading of diseases [15] or innovation [16], systemic risk [17, 18], opinion dynamics [19], complex networks [20, 21], and agent-based models [22].

Interdisciplinary physics has been so far successful in describing emerging properties, scale free phenomena and hierarchical organization in several biological, medical, economic and social heterogeneous systems. A potential major area of development of interdisciplinary physics is the modeling of information production and information processing in complex systems. In other words, interdisciplinary physics has not yet developed its full potential in its ability to tackle information production and information processing of complex systems in many-body, open, heterogeneous, non-equilibrium systems. Acquiring this ability is a challenge for the

academic community and in particular it is a challenge for all those researchers that consider physics not only the science of matter, energy, radiation and fundamental components of the Universe but rather the discipline modeling any microscopic or macroscopic material object in our Universe.

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