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Scientific research across and beyond disciplines

Challenges and opportunities of interdisciplinarity

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Contemporary research is increasingly characterized by two contrasting trends [1]. One is a process of increasing and continuous specialization, which requires scientists to attain a congruent degree of expertise in a particular area of research. This trend is reflected in the proliferation of new scientific disciplines, and their further division into subfields. The other trend, which developed over the past decades, is increasing cooperation not only at an intradisciplinary level, but also across and beyond disciplines: that is, multi-, inter- and trans-disciplinary research. The aim is to bring together scientists with different expertise and resources, with the possibility of cross-fertilizing each other and to develop new, synthetic views.

The rationale for involving multiple disciplines

The need for involving several different disciplines arose as scientists realized that particular problems are too complex to be effectively addressed by a single field of study. An obvious example is climate change along with environmental challenges, sustainable development and the societal implications. It requires the competencies and tools from multiple disciplines—natural sciences, engineering and social sciences—to study the causes and effects and develop solutions.

It is also recognized that many systems or phenomena can and should be investigated at different levels and from different points of view, given their multidimensional nature. Take for example human beings, which can be referred to as physical, chemical, biological, cognitive, and sociocultural objects [2]. Each level of organization raises specific issues that should be studied through appropriate strategies and methods, along with the interactions between different levels. Generally, instead of being disciplinary oriented, another way of conceiving scientific investigation is phenomenon- or object of study-oriented.

Multidisciplinarity and interdisciplinarity have also become important for research policy, as exemplified by European Research Council's initiatives, and numerous areas of study, including science education and research management. Various research institutions around the world, such as the Santa Fe Institute, which has no permanent faculty or departments, were also created with the explicit purpose of overcoming the limitations of the academic organization into distinct disciplines.

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What does not help the development of interdisciplinary research are exaggerated, rhetorical claims, about its presumed liberating and innovative nature versus the constraints and conservatism of disciplinarity. Interdisciplinarity intrinsically depends on disciplinary knowledge as a prerequisite even if it is a response to the shortcomings of the disciplinary organization.

Disciplinarity and its limits

The disciplinary organization of scientific knowledge and practice became a central element during the 1960s, when philosophy of science highlighted the importance of evaluating scientific theories and ideas as embedded in their own historical context. Leading scholars in this field portrayed the advance of science in terms of "normal science"—science under the guidance of a paradigm—and "revolutionary science"—paradigm-changing science—(Thomas Kuhn's *The Structure of Scientific Revolutions* [1962]), progressive and degenerative research programmes (Imre Lakatos's *History of Science and its Rational Reconstruction* [1979]) or as successive research traditions (Larry Laudan's *Progress and its Problems. Towards a Theory of Scientific Growth* [1977]).

In a disciplinary framework, scientists tend to share a vocabulary, along with a set of basic epistemic means and commitments, depending on the training that has formed them—here, the term "epistemic" means "relating to knowledge or the conditions for acquiring it". This training is organized in such a way to enable apprentices to progressively specialize to become experts, so that they can employ their methods even in new contexts. Accordingly, there are two distinct but related ways in which a scientific discipline or specialty can be described: as an epistemic structure, a shared set of cognitive devices—theories, methods, exemplary problem solutions—like those used in molecular biology; or as a social structure, a scholarly community like that of molecular biologists, who makes use of these devices and further refines them [1].

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Disciplinary research has been and will be extraordinary effective in ensuring scientific and technological advancement. On the other hand, as argued by the Spanish philosopher José Ortega y Gasset, a possible side effect of the ever-growing specialization is the narrowing of intellectual horizons and the creation of what he called "learned ignorami": people who are experts in their own particular area, but not capable to see beyond. The French sociologist Edgar Morin similarly has criticized the ensuing fragmentation of knowledge and hyperspecialization, which are linked to a reductionist way of thinking that has had a deep influence on how we organize knowledge and educational systems.

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At any rate, Kuhn makes a distinction between normal science, which is mostly analytical and involves a continuous work of articulation of the dominant paradigm, and scientific revolutions, which involve large-scale, holistic changes of how a particular scientific area is understood. Kuhn also mentions other ways in which the development of science takes place, for instance, by combining two fields as in the case of biochemistry. Nevertheless, his main focus, still reflected in today's prevailing approach of the philosophy of science, is the dynamics of individual disciplines. As a result, what occurs across disciplinary boundaries—or also within disciplines owing to internal fragmentation that may also lead to the creation of new branches—has not received enough attention yet. According to Morin, the history of science cannot be limited to the story of creation, evolution and proliferation of individual disciplines, but should take into consideration the moments when disciplinary boundaries were overcome. Scientific disciplines are not, in fact, totally enclosed and separate islands of knowledge with immutable borders as migration of notions and methods across disciplines constantly takes place.

Take the case of molecular biology. Its rise could not have happened without contacts and transfers between disciplines at the edge of physics, chemistry and biology. The quantum physicist Erwin Schrödinger with his book entitled *What Is Life?* (1944) was greatly influential in inspiring pioneers scientists, who were involved in the rise of molecular biology during the 1950s. Many of them were physicists like Max Delbrück, a distinguished student of Niels Bohr. During that period, theoretical physics played a crucial role in the development of new directions in biology, and new analytical techniques were derived from biophysics and biochemistry.

Hybridization is today seen as an increasingly important feature of knowledge production, even with the creation of second-generation hybrid disciplines, especially in the natural sciences. An example is neuroendocrinology, which is a hybrid of endocrinology and neurophysiology [2].

These facts question traditional metaphors and images of knowledge, for instance, a tree with different branches as represented by Francis Bacon in the 16th century, which emphasize the foundation and unity of knowledge and science. Owing to its growing complexity, the way knowledge is represented makes use of nonlinear images, such as the rhizome, which is typified by a dynamic connectivity (any point can be connected to any other), and is not organized around a central root or hierarchical axis but has multiple entryways [2].

Different ways of going beyond disciplinarity

As already mentioned, the limits of the disciplinary organization of knowledge are also revealed by an increasing appeal to alternative approaches, namely multidisciplinarity, interdisciplinarity and transdisciplinarity. What these have in common is that they all aim to relate people who have been trained in distinct disciplinary environments, and have diverse expertise. However, multidisciplinarity, interdisciplinarity and transdisciplinarity use different strategies and usually have diverging purposes and implications.

In multidisciplinarity, different specialists come to investigate a common issue, which is nowadays common in many research projects. An enriched view is gained by using tools and information from multiple disciplines. However, disciplinary boundaries are still maintained. Actually, multidisciplinarity juxtaposes disciplines, combining them in an additive way and with little cross-fertilization, that is, without an overall framework for integrating the different perspectives. The likely outcome of a multidisciplinary project is a collection of yet separated research strategies and products.

Interdisciplinarity requires more commitment to go beyond disciplinary boundaries. It involves the search of a common ground for different disciplinary contributions and their amalgamation or synthesis into something new. Whereas multidisciplinarity is simply additive, interdisciplinarity recognizes that solutions to particular problems can only be reached by integrating parts of the original disciplines into a broader, more comprehensive framework, even if such an amalgamation or integration might not necessarily be complete.

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Transdisciplinarity involves the formulation of cognitive schemes that cross disciplinary boundaries. It usually seeks a more holistic approach, which in some versions is linked to an attempt to regain some sort of unity of science or to particular readings of complexity theory. However, in other "contextualized" versions, the focus is on joint problem solving, something that still requires more than just juxtaposition: it is the interpenetration of disciplinary epistemologies, which should go hand in hand with the acknowledgement that scientific knowledge cannot be divorced by the social context.

Challenges to interdisciplinarity

Let us now focus more specifically on interdisciplinarity, although the following considerations may be relevant for the other types of interactions too. These interactions are,

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however, hampered by obstacles at different levels. For example, the social organization of science and most academic patterns of knowledge production and evaluation are still ingrained in the disciplinary scheme. The situation is reflected in the organization of university departments and their teaching and training programmes. Academic structures are often characterized by conservatism, something that, however, also depends on their commitment to preserve the disciplines' core and to guarantee proper standards of training and research; academics and researchers are therefore not encouraged to venture too far from the safe ground of the disciplinary borders, sometimes even believing that "real" science is possible only within these borders [3]. An "echo" of such a disciplinary orientation can be found in research funding and reward systems, in the scope of journals, in the modes of peer-reviewing and quality control [4] and in the standards for evaluating scientific research that prefer normalized citation measures.

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As a result, interdisciplinary research remains underestimated. Young scholars usually regard it as something that risks their career advancement, and genuine interdisciplinary projects or grant proposals are not common. Many grant proposals include interdisciplinarity only superficially, mostly to increase the chance of being funded. One way to improve its appeal is to make substantial structural changes at the institutional and science policy levels, for example, by reforming university's department organization and training programmes to find a balance between maintaining disciplinary core expertise and enabling the creation of synergistic research environments, or by improving peer-review systems [3].

Further challenges concern the intellectual and conceptual level. For instance, there are the well-known difficulties in communicating between specialized fields, such as when the same term is used with different meanings in distinct contexts. Interdisciplinarity is also made difficult by cognitive barriers between disciplines. It is true that all scientists share fundamental principles—such as observation and inferential forms like deduction and induction—together with the basic tenets of modern science, notably relying on experiments. However, it is also true that researchers from different disciplinary backgrounds are likely to embrace dissimilar assumptions, generalizations and models, including those concerning the object of study itself. They may also diverge in their research strategies, methodologies, even reasoning styles. This contrast is, of course, even more evident between researchers from the natural sciences, who implement quantitative and experimentally based method, and value technical precision and predictive power, and researchers from the humanities and social sciences, who make mostly use of qualitative and sociohistorical analyses.

A case study to exemplify these difficulties regards the encounter between experimental social psychologists and ethnographic anthropologists. It concerns recent research supplying experimental evidence to the thesis that there are deep dissimilarities in the thought patterns of people from distinct cultural settings, for example Western and Asian people (as reported in Richard Nisbett's book *The Geography of Thought: How Asians and Westerners Think Differently...and Why* [2003]). Cultural differences are the *raison d'être* of anthropology and have been thoroughly investigated in this field, albeit not on an experimental ground, but mostly on ethnographic data. The bone of contention is the suitability of the type of method involved: ethnographic versus experimental. Anthropologists consider experiment at best as unnecessary, but even potentially harmful, since cultural issues cannot be studied under artificial conditions, that is, outside their living environment. Psychologists claim the importance of experimental method even in studying cultural matters, believing that anthropologists are opposed to something without fully understanding it [5].

A related obstacle to interdisciplinary research depends on preconceptions about the degree of "scientificity" of disciplines. As reported in many cases of projects involving natural scientist and social scientists, there is a clear asymmetry between them. Usually, the role and skills of social scientists are underestimated, together with their possible contribution to the project [6]. More generally speaking, many interdisciplinary projects end up privileging a single disciplinary perspective, relegating others to secondary roles.

Potential advantages of interdisciplinarity

The development of science still depends on specialization, and in fields such as physics and chemistry, the organization in disciplines and specialties will likely continue to work very well. However, there are also situations in which disciplinary boundaries hinder or slow down scientific advance. Further progress precisely needs working at the interface of multiple fields of study.

> *"The ability to work at the edge of multiple knowledge domains is what actually typifies many innovative thinkers, who are capable of intuitively establishing connections between apparently unrelated pieces of information."*

Divergent thinking can be productive, but on the other hand it requires ways to manage it. A complex process of mutual learning and continuous negotiation helps to bridge and accommodate different disciplinary perspectives and to meaningfully relate their respective methods, concepts and protocols. The degree to which this is possible strongly affects how interdisciplinary research is undertaken and its accomplishment [1]. Scholars engaged in interdisciplinary research therefore should have a genuine appreciation of pluralism in its different forms and at different levels. Recognizing its value involves, for example, admitting the fact that different disciplinary viewpoints may counterbalance or complement each other to get a broader picture of the question at issue.

On the other hand, individual interdisciplinary researchers, who are pressed out their disciplinary boundaries, have to navigate through unexplored territory. The ability to work at the edge of multiple knowledge domains is what actually typifies

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many innovative thinkers, who are capable of intuitively establishing connections between apparently unrelated pieces of information. It is precisely here where ground-breaking, unexpected insights could arise: new explanations and solutions to old problems, together with new questions; innovation at the methodological level; new ideas, usually developed by nonlinear mechanisms like analogy or contamination; or new conceptual links.

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In order to better substantiate these observations, it is important to look at specific case histories. Such an analysis helps to go beyond conceptual distinctions, considering the ambiguity of terminologies that refer to interactions across disciplines. The same research project may be labelled differently depending on the meanings attributed to multidisciplinarity, interdisciplinarity and transdisciplinarity.

Integration processes in interdisciplinarity

Usually interdisciplinarity is understood as strictly linked to the degree of conceptual, theoretical and methodological integration between the disciplines involved. Such an integration is both a basic expectation for its success and a required condition for distinguishing interdisciplinarity from multidisciplinarity. However, in alternative, that is "instrumental" versions of interdisciplinarity, integration is understood on a pragmatic basis, relating to specific purposes and working on a local and temporary basis [7]. Actually, integration risks to be a tricky notion or to function as an abstract ideal. In fact, as a prerequisite, it may be matched in different ways and to different degrees.

Sometimes the integration process may lead to the birth of new interdisciplinary areas, which in time turn into new disciplines. Consider again the origin of molecular biology, which implied intense interdisciplinary exchange. Molecular biology is now an established discipline—a paradigmatic science—and its practitioners are no longer labelled as interdisciplinary. Interdisciplinary research only corresponded to the early days of the field's development: in the beginning, it was carried out by interdisciplinary teams ("collaborative" interdisciplinarity) and then driven by the first molecular biologists ("individual" interdisciplinarity). These individual pioneers were able to fully amalgamate the knowledge spanning from different domains, catalysing the foundation of a completely new discipline and, indeed, of a new view of biology [8].

This has frequently occurred in the history of science. What initially appears as radical and revolutionary ideas or methods, developed through interactions between researchers from separate disciplines, becomes over time an ordinary part of the disciplinary training of subsequent generations of scientists. If this is the case, interdisciplinary research should not then be valued for its own sake, but for creating the suitable conditions for novel disciplines to emerge: "Perhaps the whole idea of interdisciplinary science is the wrong way to look at what we want to encourage. What we really mean is 'antedisciplinary' science—the science that precedes the organization of new disciplines" [8].

Such a scheme works well in many situations, but not in all. The degree of integration does not establish *per se* a scale of values, and does not correspond to a necessary evolution. In some cases, the new interdisciplinary fields resulting from a partial merging stabilize over time, and they do not coagulate into a new single discipline, as happened for molecular biology.

Consider, for instance, the case of cognitive sciences, the development of which has also involved multiple disciplines from neuroscience, psychology, artificial intelligence, philosophy, linguistics, anthropology and so on. Still, after a few decades, no amalgamation of these disciplines into a unified cognitive science has been reached. Cognitive sciences still maintain an interdisciplinary character, something that is reflected in the looser institutional organization if compared with traditional disciplines [5].

The case history of systems biology

One of the fields that benefits in particular from interactions across disciplines is biology, which is in an ongoing process of transformation, both theoretically and technology-driven. A number of interdisciplinary areas are involved, such as computational biology (which combines knowledge from molecular biology, computer science, statistics and mathematics), synthetic biology (which draws from molecular biology, evolutionary biology, biotechnology, chemical and biological engineering, electrical and computer engineering) and systems biology.

The rise of systems biology has been made possible by molecular biology, but it also corresponds to a broadening of molecular biology's original scope. It involves a shift in the object of study and type of approach. The focus is no longer on studying isolated phenomena one at a time, for example single genes or proteins. A systems approach, instead, investigates the interrelations between multiple pieces of biological information, considering, for example, the pathways and networks underlying cellular function, with the purpose of understanding how the component parts come together to form the living whole.

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An important contribution to the field's development has come from the omics approach, initiated by the human genome project and other sequencing efforts. Systems biology is, in fact, attempting to integrate comprehensive sets of biological data from various hierarchical levels and explain them by combining formal numerical modelling and computational analysis with large-scale experimental techniques. In order to achieve such goals, multiple fields of expertise must be coordinated, together with the respective methods and modes of investigation. At present, systems biology is then primarily grounded on collaborative interdisciplinarity, requiring the skills of biologists, physicists, mathematicians, statisticians, computer scientists and engineers.

Many of the questions discussed so far are well exemplified by systems biology, beginning with the difficulties to institutionalize the field with its interdisciplinary features to

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facing the constraints of academic organization. There is also a need for new conductive research environments to facilitate collaboration between different types of expertise (e.g. theoretical, experimental and computational). Such a collaboration usually requires cohabitation of researchers and appropriate infrastructure and facilities [3]. New dedicated research centres were built with specifically designed spaces to favour cross-disciplinary and interlaboratory interactions. A few examples of such structures are the Manchester Interdisciplinary Biocentre (http://www.mib.ac.uk/), the Institute for Systems Biology in Seattle (USA; https://systemsbiology.org/) and The Systems Biology Institute in Japan (www.sbi.jp/).

However, setting up new institutes is not enough. The barriers that have to broken down depend also on researchers' attitude towards collaboration. A common risk in these types of interactions is that the role of other specialists is read in the light of some cliché (e.g. computer specialists may be seen as computer jockeys by experimental scientists, and biologists may be seen as laboratory technologists by computer scientists) [9]. What is needed is a disposition towards learning from other specialists and an engagement in processes of mutual discovery, rather than a mere focus on what others should learn from us.

In addition, not all disciplines have equal status in systems biology. Clearly, biology plays a predominant role. Only biological knowledge can provide, for example, the content for abstract mathematical models, as those used for regulatory networks. However, one should avoid to consider skills in mathematical modelling and computer science, as "ancillary" to biology. All the expertise, in their own ways, is actually necessary for more thoroughly addressing the shared question [9].

In the interdisciplinary framework of systems biology, communication problems due to the lack of a common vocabulary and set of concepts are also well documented. What happens in such situations is that scientists, in order to facilitate communication, have to learn the meanings of other disciplines' terms and to develop a shared language. Here, a parallel could be made with intercultural interactions (Peter Galison's *Image and Logic: A Material Culture of Microphysics* [1997]).

In anthropology, two steps in linguistic interactions between different sociocultural groups have been distinguished: in the first step, a "pidgin" language emerges: a basic tool for communication that is usually limited to certain domains and coexists with the mother tongue of each group. In the second step, the pidgin progressively extends to other domains, until a new "creole" emerges from the mix of the languages involved. Such a creole is a full-fledged language and functions as the often unique mother tongue of the sociocultural groups who have created it and now identify with it.

Comparable situations take place when different scientific groups, which may be analogous to members of different cultures, interact in interdisciplinary ventures like systems biology [9]. It is then possible to follow the development of a field focusing on the corresponding development of its language.

In the case of molecular biology, a new (creole) vocabulary finally emerged, following the transition from collaborative to individual interdisciplinarity and then on to the new discipline. Is, however, the systems biology's case easily readable through this scheme? Will systems biology turn from being a distributed activity, as it is now, into a novel disciplinary field with its own specialized language? Perhaps, but yet there are different opinions about its possible evolution.

Such a discordance is also reflected in the dispute about how to train future system biologists. The most controversial question is whether the training in systems biology should start at the undergraduate level, even if many agree that mathematics and computation should play a more relevant role in undergraduate courses. Perhaps, there will be more researchers in the future, who have expertise in biology, mathematics and computation science. Perhaps, junior scientists, who have been trained in the new systems biology institutes, will become fully grown specialists, equipped with a new vocabulary. However, other scholars think that "this should not even be an aspiration. Instead of establishing a new discipline, maybe those who describe themselves as "systems biologists" in the future will be integrators rather than specialists" [9]. That is to say, as part of their expertise, they will have the ability to facilitate interchange across different fields. If so, disciplinary distinctions and languages will likely continue to exist, and systems biology will then maintain its interdisciplinary feature.

A role for philosophy

In conclusion, a few words could be said about the role that philosophy of science could play in the further progress of interdisciplinarity. As discussed before, interactions across disciplinary boundaries play an important role in the dynamics of research and scientific creativity. Accordingly, the mechanisms behind interdisciplinary practices are usually understood in the "context of discovery". What is less developed is a normative assessment of interdisciplinary research—for instance, what procedures should govern its testing and validation [10]. There are, indeed, many complex issues that need to be analysed, specifically to what happens in potential cases of epistemic divergence, as are often common in interdisciplinary research. There could be contrasting explanations of the same issue—for instance, molecular versus higher-level (e.g. phenotypic) explanations of biological phenomena. In addition, when information and knowledge from different disciplines come together, the generation of data and evidence and their analysis could create challenges. Evidence from one discipline might support theories and results from another discipline, but could also contradict them, and trigger scientific controversies [10]. Philosophy of science, through studying and analysing the dynamics of interdisciplinary research, could provide guidance to avoid the pitfalls and improve its methodological basis.

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