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Why Theory Matters More than Ever in the Age of Big Data

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ABSTRACT: It is an exhilarating and important time for conducting research on learning, with unprecedented quantities of data available. There is a danger, however, in thinking that with enough data, the numbers speak for themselves. In fact, with larger amounts of data, theory plays an ever-more critical role in analysis. In this introduction to the special section on learning analytics and learning theory, we describe some critical problems in the analysis of large-scale data that occur when theory is not involved. These questions revolve around what variables a researcher should attend to and how to interpret a multitude of micro-results and make them actionable. We conclude our comments with a discussion of how the collection of empirical papers included in the special section, and the commentaries that were invited on them, speak to these challenges, and in doing so represent important steps towards theory-informed and theory-contributing learning analytics work. Our ultimate goal is to provoke a critical dialogue in the field about the ways in which learning analytics research draws on and contributes to theory.

Keywords: Learning analytics, learning theory, learning design, research methodologies, statistics, large-scale data

1 INTRODUCTION

The quantities of learning-related data available today are truly unprecedented. Whether the size comes from the number of individuals involved, such as thousands of learners taking a MOOC, or the fine-grained nature of the capture process, such as second-by-second changes in a learner's gaze, it provides exciting new opportunities to probe the patterns and processes of how people learn. It is an exhilarating and important time for conducting research on learning. However, there is a danger in falling into the trap of thinking that with sufficient data, the numbers speak for themselves. In fact, the opposite is true: with larger amounts of data, theory plays an ever-more critical role in analysis.

2 WHERE TO CAST OUR FISHING NETS

There is an important cascade of problems in data analysis and interpretation that scale rapidly when theory is not involved. The first is somewhat obvious but bears repeating: if we collect tens or hundreds of variables from millions of individuals, in the absence of theory, how does a researcher decide which

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ones to include in an analysis? Each variable could be tested in isolation, or a backward-stepwise approach could eliminate variables that contribute little to the explanatory power of a model, but any approach that relies solely on statistical techniques raises a critical conceptual problem:

What counts as a meaningful finding when the number of data points is so large that ***something*** *will always be significant?*

The conceptual and mathematical machinery of statistical sampling was developed for datasets of a particular size and in a particular context: large enough that random effects are normally distributed in the data, but small enough to be obtained using traditional methods. Thus inferential statistics were designed to help us tell whether a big idea can be warranted from a small sample. With relatively small samples, statistically significant effects are also those with larger effect sizes, and thus a practical significance as well. Increasing sample sizes stresses these techniques. Statistically significant results are now plentiful, but appear even for very small — perhaps tiny, effects. There have been numerous studies in recent years showing that one or more variables in a large data set is associated with student success of one form or another. But a result derived from a test of 2 million data points that is significant with $p = 0.01$ has an effect size (Cohen's d) on the order of 0.004. To put that in perspective, this effect is over 100 times smaller than the impact of a student's overall motivation on their learning outcomes (Hattie, 2009). In other words the mathematics of statistical analysis means that macro-data will consistently produce micro-results.

There may, of course, be multiple variables each with that effect size. But unfortunately, effects do not typically add linearly. One hundred and fifty variables with a very small effect do not simply add up to a moderate effect overall. The impact of any two variables may reflect the common influence of some other underlying latent factor, or there may be interaction effects between variables. Without a theoretical framework, in other words, it is hard to know what variables to include in a model, how they might interact, which micro-results to pay attention to, or how to select a useful model from the immense array of combinatorial possibilities. This exacerbates the more general problem, pointed out many years ago by Hill (1965), that the "glitter" of statistics can be a hypnotizing distraction from inadequacies in the original data and the critical influence of the many decisions researchers must make in cleaning, structuring, and modelling it (Leek & Peng, 2015). To safeguard against the danger that analytic outcomes are a result of arbitrarily taken decisions (Simmons, Nelson, & Simonsohn, 2011), theory is a critical tool to limit researchers' degrees for freedom by providing a coherent and reasoned framework from which to make decisions. In sum, when working with big data, theory is actually more important, not less, in interpreting results and identifying meaningful, actionable results. For this reason we have offered Data Geology (Shaffer, 2011; Arastoopour et al., 2014) and Data Archeology (Wise, 2014) as more appropriate metaphors than Data Mining for thinking about how we sift through the new masses of data while attending to underlying conceptual relationships and the situational context.

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3 BIRDS OF FEATHER MODEL TOGETHER

The challenges of atheoretical analysis of large-scale data are not just concerned with having large numbers of features to consider. Large sample sizes in and of themselves create problems in the absence of a theoretical framework. In a sample of 2 million learners, there will almost certainly be some pertinent subgroups (and the number of these may scale with the size of the dataset). It is easy to see how unidentified subgroups can mask results or lead to faulty conclusions about the population as a whole. Consider a variable, such as external pressure to succeed, which has a moderate positive effect on male students and a large negative effect on female students. In a course setting where the genders are equally represented, the variable might show no impact overall. In undergraduate engineering, it might show an overall positive impact, even though the effect on female students was negative, because female engineering students are a small but critical minority in the field. The same problem can occur when we seek to combine data from different course offerings without a clear theoretical rationale for why we expect key variables or relationships to be similar across them. For example, a recent study by Gašević, Dawson, Rogers, and Gašević (2015) showed that predictive modelling across multiple courses consistently misidentified the predictors most relevant for specific ones. Techniques such as structural equation modelling or data partitioning can account for subgroups (and even nested subgroups) in a data set, but this requires the researcher to specify the relevant groups in advance based on some theory of relevant differences. Without such a theory, we run the risk of our analyses both drawing inappropriate conclusions for the population as a whole and failing to detect more nuanced findings for relevant subgroups within it. Both create serious concerns (and potential ethical issues) for using the resultant analytics to make diagnoses appropriate for improving learning processes and outcomes for all learners.

This relates to the critical issue of generalization in learning analytics. It is straightforward to take a training set, develop a model, and then test it on a validation set from another corpus collected under the same circumstances. But to extend this to another situation, a researcher needs to have an explanation of what features of the data are salient to make the model (or findings from it) applicable in another context. For example, our own recent work suggests that similar discourse patterns within a discipline can support the transfer of MOOC discussion forum models despite differences in topic-specific vocabulary (Cui & Wise, 2015).

4 BEYOND “WHO” AND “WHAT” TO “WHY” AND “WHAT NOW”?

The problems multiply when we want to move beyond simple descriptive and predictive findings to make claims about causality and provide a basis for action. Educational research using big data frequently relies on post-hoc analysis, and a correlation between a student’s actions and some outcome does not imply causality. As in all non-experimental designs, there is the possibility of reverse causation or an underlying third variable. In such cases, we can still present evidence to support causal claims if we can document both a logical (theoretical) explanation of the observed relationship and eliminate

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plausible rival explanations (Johnson, 2001). There are statistical techniques that can help address the issue, for example by controlling for possible confounds, but the researcher first needs to identify the important variables that should be controlled for. Given the infinite number of possibilities, theory is needed to direct the attention and efforts of researchers. A good example is provided in the Miyamoto et al. paper (this issue), which identifies and controls for the possibility of individual student differences as driving both the spacing of study sessions and the ultimate certification rates by making within-subject comparisons. They also introduce additional variables to try to account for the more complicated possibility that these variables are a function of a student–course interaction factor: the degree of struggle a student experiences.

Beyond improving explanatory potential, there is also the critical issue of how to make learning analytics intelligence actionable (Clow, 2012). At a basic level, we need to ensure that some of the variables studied can be changed to influence the learning process. In this vein, Holland (1986) argues that, while useful for prediction, attributes of a person (e.g., a student's gender, socio-economic status, or prior achievement) can never be considered true causal variables since they provide neither an explanation of a mechanism for why the associated outcome occurred nor any recourse for remedying the situation. This is an important critique given the many attribute variables used for prediction in learning analytics work. One way to avoid such problems is to invert our research logic; that is, instead of starting with an outcome and retroactively searching back for what might have caused it, we begin with identified input (or process) variables and look for what effects they may have.

It is also important to keep in mind that there is frequently a gap between knowing that a variable matters and knowing what to do about it. For example, a recent study of MOOC learner behaviour suggested an association between the increased use of certain resources and the likelihood that a student would drop out of the class in the following week (Breslow et al., 2013). What do we do with such information? Learning is not likely to be enhanced by advising students to study these resources less. Similarly, van der Maas and Wagenmakers (2005) show that chess expertise can be predicted by how rapidly a player makes their moves, but telling novices to move more quickly will not help them improve their game. There are an infinite number of other possible actions we could take in response to such information, but we cannot test them all. Thus there has to be some basis — some underlying theory — for whatever choice or choices we make. Unless we want to return to a new age of dustbowl empiricism,[1] theory plays a crucial role in developing models, interpreting them, and converting those interpretations to meaningful — and scientifically justified — actions.

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[1] A term referring to an approach to research that focuses on the haphazard accumulation of empirical observations and relationships between variables without attention to logic or meaning.

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5 NOT ONLY A "ONE-WAY BRIDGE"

The role of theory in the analysis of large-scale data thus has several important functions:

- Theory gives a researcher guidance about which variables to include in a model
- Theory gives a researcher guidance about what potential confounds, subgroups, or covariates in the data to account for
- Theory gives a researcher guidance as to which results to attend to
- Theory gives a researcher a framework for interpreting results
- Theory gives a researcher guidance about how to make results actionable
- Theory helps a researcher generalize results to other contexts and populations

In saying this, we want to be clear that exploratory data analysis is a good thing. One of the most exciting aspects of large-scale data and learning analytics is the ability to discover patterns and associations across modalities (e.g., coordinating gaze and talk), over time (e.g., in the revisiting of previously studied material), or at a micro-genetic level (e.g., how a teacher uses analytics to monitor and support student learning activity). However, if there is not some theory to which such studies later contribute, it will be hard to develop any systematic understanding of learning. A useful analogy is to the antiquarian movement of the late 18th and early 19th centuries, where amateur collectors gathered bones, shells, and other natural objects from around the world in "curio cabinets" in a relatively haphazard fashion. These were (literally) curiosities that raised interest in natural science. It was a stunning collection of data, but its primary scientific value was that it led to later, more systematic investigations of the natural world. Similarly, at the beginnings of discovering a new tool there is a phase of exploration, of seeing what the tool can do, and marvelling at what it can show us. But science only starts when we begin to synthesize findings and ask how the use of a new tool can help us to move forward as a field. In other words, exploratory investigations of big data can be done without an explicit theory to guide them, but they must lead to testable hypotheses, and eventually to explanations and appropriate generalizations of important phenomena in learning. There is only so long that one can celebrate individual findings that certain data is useful to predict some outcome measure of students' learning, such as eventual completion or grade in a course; eventually these need to become part of a systematic scientific framework — that is, a theory.

6 GOAL AND STRUCTURE OF THE SPECIAL SECTION

The role of theory in the analysis of large-scale data and the relationship between empirical learning analytics work and theory more generally are the focus of this special section of the *Journal of Learning Analytics*. In this section of the journal, we look at five studies, each of which connect their work to theory in some way. The papers provide examples of how learning theories are being used to craft analytics, but also in some cases how analytics are helping to advance learning theories. We think this collection of papers is particularly timely because, for the reasons outlined above, understanding the role of theory in the analysis of large-scale data is an urgent need for this young field. To help meet this

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need, the special section takes a distinctive format intended to spark a larger conversation around the role of learning theory in learning analytics work. Each of the five research articles included in the section presents an exploration of how to move toward a theory-based approach to learning analytics. Following each article, a commentary has been invited to discuss the ways in which the paper draws on and/or contributes back to theory, as well as the challenges that were faced and what productive next steps forward might be. We believe that, collectively, the five articles and associated commentaries that make up this special section provide a fertile beginning for a larger conversation about the importance, role, and challenges for learning analytics in working with theory.

Kelly et al. (this issue) begin with the fundamental premise that applying learning theory to drive analytics is not a straightforward process but rather an artful one. Indeed, the construction of learning analytics is a design activity and thus an act of innovation that requires both deep familiarity with the theory and the context of application. Their work proposes a strategy for bridging theory and user needs through the development of first principles to guide function, behaviour, and structure, and provides an example of this approach in action in the context of a collaborative learning activity. In his commentary, Teplovs (this issue) acknowledges the value in developing process guidance for the application of theory to analytics design, and points out the need to extend such guidance to the complementary process of feeding back what is learned from the designed analytics to inform theory development. Here learning analytics researchers might look to the tradition of design-based research for methodological guidance (e.g., Barab, 2014; McKenney & Reeves, 2014; Reimann, 2011) as well as considering how they might infuse experimentation into their studies (Hewitt, this issue).

Both Miyamoto et al. (this issue) and Svihla et al. (this issue) engage in the activity of applying learning theory to analytics design, drawing their inspiration from the theory of distributed practice — a well-established psychological finding that memory retention is increased when rehearsal is spread out over time rather than massed. In a clear example of the generative nature of the dialogue between theory and situation, the way this construct is taken up by the two research groups is dramatically different. Working in the context of diverse massive open online courses (MOOCs), Miyamoto et al., examine the notion of "spaced study" (the degree to which time spent generally interacting with course material is concentrated or dispersed into some number of log-in sessions). In contrast, in the context of a classroom-supported, web-based inquiry learning environment, Svihla et al. probe students' practices of "revisiting" (whether and when they re-engage with particular learning environment elements).

The commentaries on these papers both speak to the challenges in applying carefully formulated lab findings in "the wild." As Hewitt notes (this issue) "a good deal of the learning theory we use today has emerged out of experimental studies where control groups were used to isolate variables. This bears little resemblance to much of today's research the learning analytics field, in which data tends to be collected from naturalistic learning settings" (p. 104). Further exacerbating the challenge, as learning analytics researchers, we often don't have tight control over the design of the learning environments we

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are studying, working with post-hoc data generated from systems and data structures that we didn't create; we thus must rely on proxy indicators "that may only roughly approximate the phenomena of interest" (p. 104). Both Pardos (this issue) and Miyamoto et al. themselves (this issue) note that the mechanism behind the effects of space study they observed may be very different from the original ones involved in distributed practice, perhaps relating more to motivation than to memory retrieval.

Schneider and Pea (this issue), beginning with a different set of theories from the field of collaborative learning, investigate the potential for a variety of measures of collaborating pairs' language use to serve as a proxy for their degree of "common ground." Different from the Svihla et al. paper, they search not for actions contributing to learning processes, but for automatically trackable "markers" of productive (and unproductive) collaborative learning processes. In his commentary on the piece, Hoppe (this issue) explores the theoretical basis for this work, diving deeply into the literature on "common ground," and noting the great variety and contention in the exact meaning and use of this concept. This raises an important question for learning analytics researchers: How do we move forward to operationalize a concept when the theory itself is not fully agreed upon?

Finally, van Leeuwen (this issue) diverges from the other papers in the special section by proposing and presenting initial evidence supporting a theory of how analytics can support teacher regulation of collaborative learning via support for "noticing" that increases the specificity and confidence of a teacher's diagnosis of the situation. This contribution is notable for being one of first efforts in the field to develop a distinct theory of learning analytics. In his commentary, Chen (this issue) notes the importance of such work in helping learning analytics be "not merely the accepting side of a 'one-way bridge'" when it comes to theory, also helping to "shed light on learning theory and lead to theory building of its own" (p. 164). Specifically he highlights that, as a new field, we should take a generative stance, appreciating theoretical contributions for their ability to explain findings and stimulate new directions for research rather than focusing exclusively on verification and validation.

7 CONCLUSION

All of the papers in this special section begin with accepted educational or psychological constructs.[2] As noted by Schneider and Pea (this issue), this constrains the ways in which the data can be analyzed, and is thus powerful in reducing the risks of finding an effect due to chance. Equally powerfully, taking theory as a starting point helped these researchers to move past the simple time-on-task and activity

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[2] Both Pardos (this issue) and Teplovs (this issue) highlight the importance of this — that is, working with well-established learning theories, rather than peripheral ones or theoretical premises chosen in a piecemeal fashion; however, Chen (this issue) also warns of the danger of adhering so tightly to one theoretical doctrine that other relevant ones are ignored. He goes on to comment that to address this concern we may need to go beyond taking a theoretical stance to "articulate why competing theories are less fruitful for a given scenario" (p. 164).

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count metrics commonly used in the field (and which imply a de facto "theory" of more-is-better) to explore more nuanced metrics of learning processes. Nonetheless, a critical question raised in many of the commentaries is this: To what extent do the papers simply evoke theory as a point of departure versus carefully using theoretical constructs to inform the specific analytics created? Theory-inspired learning analytics research is certainly an improvement over dustbowl empiricism, but it is not enough to build a body of knowledge nor to sustain a field. Thus the question of *how* theory is operationalized in a given analytics effort and the justifications for this become important in assessing the work. One notable example of this appears in the paper by Svihla et al. (this issue) who include a chart that lays out a theoretical justification for each of their revisiting metrics (p. 86). This precision in how theory informed their different analytics (and the specification of more than one potential operationalization that could then be tested) made it possible for them to then speak back to their nascent idea of revisiting in a meaningful way — in other words, Svihla et al. do conceptual work in proposing and empirically testing how the theory of distributed practice might be *productively adapted* to the context of student-driven activity in a web-based inquiry learning environment.

With the goal of doing such conceptual work, collectively the papers in this special section both provide powerful examples of how to move towards theory-informed and theory-contributing learning analytics work and raise a number of important challenges for researchers to consider. We hope that together, the set of papers and associated commentaries provoke a productive dialogue in the field about the ways in which learning analytics research can draw on and contribute to theory.

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The Internet commons: towards an eclectic theoretical framework

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Abstract: Recent developments in communications technologies, in particular, the advent of the Internet and its widespread applications in all spheres of human activity, have posed a serious challenge to the mainstream neo-institutional theory of the commons (common goods) and, especially, common pool resources theory (CPR). Although the term 'new commons' has been coined to describe a new area of study, previous attempts to analyze Internet goods within the framework of CPR theory have not been successful, as they have not been able to capture the important new characteristics of the Internet commons. Based upon an empirical analysis of over 20 Internet goods, the author argues that Internet goods do not fall within the common pool category of goods. In addition to the key characteristics used so far within mainstream theory – excludability and substractability – other attributes of a "commons" such as sharing potential, joint use in production rather than only in consumption and non-hierarchical governance of production definitely are relevant, and should be included in any analysis of Internet commons. The neo-institutional approach retains its explanatory power with respect to the Internet commons if one emphasizes the path-dependent evolution of the Internet and the role of informal and formal rules shaping its operating environment. Yet the approach does not capture the direct impact of major breakthroughs in information and telecommunication technologies (ICT) on the Internet commons.

A more eclectic theoretical framework is proposed as a step aimed at grasping the complexity of the Internet commons. It attempts to integrate new concepts developed in various disciplines of social sciences (economics, sociology, history, anthropology) with the mainstream theory of the commons, which developed from the neo-institutional perspective. Among those new concepts and theories, the most important are general purpose technologies (GPT), network externalities, positive free riding, the concept of shareable goods, the architecture of participation, peer production, and the gift economy.

Keywords: Common pool resources, information technology, Internet, neo-institutionalism, new commons

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1. Introduction

'Is There Anything New Under the Sun ...?' was the title of a paper by Charlotte Hess, presented at the Eighth Biennial Conference of the International Association for the Study of Common Property, held in 2000 in Bloomington, Indiana (Hess 2000). She raised this provocative question with respect to the new phenomenon – technology-driven, human made commons, including the Internet. Based upon a review of the rapidly growing body of literature on this subject, she pointed out apparent weaknesses in current research. Many contributions were lacking methodological rigor, particularly reflected in ambiguity as to the meaning of 'commons', which made it very difficult to position the growing literature on the 'new commons' relative to mainstream commons theory, which predominantly focuses on common-pool resources (CPRs). In conclusion, Hess emphasized the need to promote high-quality research, particularly on the Internet commons, which can overcome some of the weaknesses recognized at the initial stage.

This paper attempts to contribute to the current theoretical debate on the Internet commons by addressing the following questions:

1. To what extent do the Internet commons demonstrate the two principal characteristics (bio-physical attributes) that have been utilized widely in the analysis of traditional commons: excludability and joint consumption?
2. Which new intrinsic characteristics of the Internet commons make them a distinct category, thus calling for expansion of the theoretical framework to include these characteristics?

The neo-institutional framework is the principal platform used in the construction of the mainstream theory of commons.[1] The neoinstitutional approach has been attractive for the analysis of commons for two reasons. First, the core argument that 'institutions matter' is particularly relevant to CPR goods, where the classic market mechanism cannot function in an efficient way. Second, neoinstitutionalism offers a powerful base for promoting proactive analysis and research, leading to the design of specific institutional arrangements, thereby enabling the more efficient production and consumption of particular CPRs. I refer, for example, to the Institutional Analysis and Development (IAD) framework (Ostrom et al. 1994). Consequently, a third research question is:

3. Does the neoinstitutional approach retain its explanatory strength and usefulness in the investigation of the Internet commons?

In this article, I will adopt the definition of commons that has prevailed in the CPR literature, which emphasizes the crucial role of the key biophysical attributes of goods: non-excludability and non-rivalrous consumption, differentiating common goods from private goods. It is because of these characteristics that the classic market mechanism for the production and exchange of common goods largely becomes inefficient. The tension between individual and group rationality has been exemplified in the formulation of social dilemmas – the tragedy of commons, the prisoner's dilemma, and the logic of collective action (Olson 1965) being the key conceptual pillars of the mainstream theory of commons.

Although the categorization of various goods using the two characteristics mentioned above was initiated by economists in the context of the public goods debate (Samuelson 1954), its refined formulation by E. Ostrom and V. Ostrom has laid down the foundation for what I refer to as the mainstream theory of commons (Ostrom and Ostrom 1991) in social sciences.[2] It has largely concentrated on one category of goods – common-pool resources (CPRs) – in which case, the difficulty in excluding unauthorized beneficiaries coincides with rivalrous consumption after reaching a certain degree of exploitation of a given resource. Other non-private goods with alternative combinations of key biophysical attributes – like pure public goods and so-called 'club goods' (toll goods) – have received much less attention from scholars. A broader framework, including all combinations of

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[1] While referring to the mainstream theory of commons, I have in mind research conducted by the scholars associated with the Bloomington Workshop in Political Theory and Policy Analysis. The formulation of the key concepts in this field can be found in the works (publications) of E. Ostrom, V. Ostrom, C. Hess, R. J. Oakerson, E. Gardner, and J. Walker.

[2] I do not here address the broader meaning of commons as a 'public space' – originally a town square, village green, etc. This does not mean that I consider it less important. Just the opposite, I believe that the Internet adds a fundamentally new dimension to the concept of commons as a public space. However, its detailed analysis would call for addressing a different set of research questions and using different tools and methodologies, which is beyond the scope of this paper.

excludability and substractability or types of goods, is called for in examining the case of the Internet, which is characterized by a conglomerate of goods and internal diversification. This, in turn, calls for a broader definition of commons to include pure public goods and club goods as well as CPRs. Such a broad concept has been reflected in E. Ostrom's recent definition of the commons: "A general term that refers to a resource shared by a group of people and often vulnerable to social dilemmas" (Ostrom 2007, 349).

The rest of the paper is organized as follows. First, I look at the rise and evolution of the Internet from the neoinstitutional perspective – testing general explanatory strengths and the applicability of its specific concepts and methodologies. Next, I conduct an empirical analysis of the characteristics of the Internet, focusing on its key biophysical attributes (non-excludability and non-rival consumption). In order to draw some general conclusions, I will investigate, in greater detail, the principal characteristics of individual Internet goods. The adoption of an analytical perspective where the Internet is being "decomposed" into specific goods identified within its holistic framework can be justified by its diversified structure and the existence of its three basic layers: hardware, software, and information content.[3]

Identifying new and important characteristics of the Internet commons that are not adequately captured within the mainstream theory of commons, in the context of Internet goods, leads to the proposal for an eclectic framework, wherein new concepts from other disciplines are incorporated, thereby broadening the research perspective. Key findings are summarized in the final section.

2. Internet and the neoinstitutional approach

Although the origins of the neoinstitutional approach in economics are reflected in the early work of Ronald Coase (Coase 1937), the methodological framework and analytical apparatus, as well as the extension of its scope to other social sciences – like sociology, law, and political science – is of recent origin, all having taken place since 1960. This happens to coincide with the rise of the Internet – a new phenomenon which, despite a very short history of less than 50 years, has brought about fundamental changes in practically all aspects of human life – economic, social, cultural, educational, political, etc. (Abbate 1999). Neoinstitutional analysis can be helpful in understanding this development.

2.1. Path dependency

Path dependency is one of the key concepts of neoinstitutional analysis. It reflects the situation wherein outcomes are "shaped by a previous sequence of decisions" (Ostrom and Hess 2007, 351). These decision sequences can be incidental; on the

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[3] The "decomposed" way of analysis may be conducted in the case of other common goods like lakes or forests. Due to the internal complexity of the Internet, its adoption seems to be particularly relevant here.

other hand, they may result in enduring patterns, procedures and standards. The persistence of the QWERTY keyboard despite the availability of ergonomically superior alternatives is a classic example of the path dependent phenomenon. During the short history of the Internet and particularly, its formation period in the 1960s, there were numerous examples of path-dependent sequences of events.

The initial impulse and funding for the Internet came from the government military sector. However, from the very beginning, members of the academic community enjoyed great freedom while helping create the Internet, and that freedom has remained as a major source of path dependency, as seen in the following shaping principles and operating rules of the Internet:

- The lack of a central command (co-ordination) unit. Instead, a democratic procedure based on consensus has been introduced to define detailed operational procedures;
- The principle of network neutrality, which implied that the Internet network, as such, shall be as simple as possible, whereas all specialized elements (network intelligence) shall reside at the level of user-end stations;
- The open access principle reflected in the determined effort by the Internet founders to establish a technical infrastructure allowing local networks, both in the United States and abroad, to join the emerging global Internet structure.

In the short history of the Internet, one can point out other instances of path-dependency resembling the classic QWERTY case (Liebowitz and Margolis 1990). One is the system of allocating domain names to the end-users based on a ‘first come, first served principle’. Although there are obvious deficiencies with such an allocation mechanism combined with the oversimplified categorization of domain names, this has remained basically unchanged, as accumulated experience and tradition made changes difficult to implement.

Moreover one cannot neglect the path-dependent outcomes of the initiatives taken by Bill Gates in the mid-1970s. At that time, open access to software programs and operating systems was standard; making the source code freely available was quite logical as it facilitated the elimination of certain flaws and the configuration of computers to satisfy individual needs. In 1976, Gates, at that time a renowned if very young IT specialist and nascent entrepreneur, challenged the open access principle. In his ‘Open Letter to Hobbyists’, he laid down key arguments in favour of proprietary software, pointing to the detrimental effects of the free access principle for software providers, and spurred the development of the software industry in general (Gates 1976).

The initiative taken by Gates was a turning point in the development of the software retail market, which began to operate independently from the computer hardware market. The success of Bill Gates and his company Microsoft as a founder and key player in the emerging software industry was aided by Gates’ affinity for institutions – contracts, laws and regulations, introduced in order to protect software providers against the unauthorized use of their products. At the same time, Gates' initiative paved the way for consolidation of the open source community, which initially relied exclusively on unwritten rules and practices established during the formation period of the Internet. The visible outcome has been a variety of formal institutions related to the open source initiatives.

2.2. Informal rules

Neoinstitutional analysis also emphasizes informal as well as formal rules. The experiences of the 1960s – during the early 'formation period' of the Internet – were crucial for shaping informal rules which became the pillars of 'Internet culture'. Networking was the key coordinating mechanism in the implementation of initial projects (Himanen 2001; Castells 2003). According to Frances et al. (1991) efficient functioning of networks largely depends upon the spirit of cooperation, loyalty and trust among network members. This, in turn, generates social capital, defined as a set of informal values and norms shared by group members (Fukuyama 1999). In the community of early Internet enthusiasts, there was a very favourable climate for building such capital and facilitating efficient network coordination. First, the people involved in the early stage projects (such as Network Working Group, ARPANET, USENET) had similar occupational backgrounds, coming mostly from academic circles. Secondly, they represented an emerging IT profession that was considered highly complex and, therefore, hermetic to outsiders. This helped to forge internal ties between project team members.

The informal norms and values guiding the implementation of early-stage Internet projects included a decentralized philosophy, encouragement for bottom-up initiatives, respect for minority views, and strong efforts to reach consensus (accepting, however, non-unanimous voting). This may sound like an essentially egalitarian, socialist orientation typically demanding some sacrifices with respect to efficiency and quality. However, this definitely was not the case during the Internet's formation period, which was strongly influenced by the cult of professionalism, based on merit and not on formal criteria. As a result, the best professionals were invited to join project teams, irrespective of their formal education, status, age, nationality sex or race.[4]

The mutual trust based on the accumulated social capital within the network was crucial in shaping, from the very beginning, a broader, global vision of the Internet. It was so powerful that it overshadowed the orientation that initially had been pursued by the government agencies focused on building specific military applications.

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[4] P. Himanen compares the above set of values characterizing founders of Internet and later embodied in the so-called hackers ethic to the protestant ethic, which has been argued as the basis for modern capitalism (Himanen 2001).

2.3. The convergence of informal and formal rules

The issue of convergence (or lack thereof) between formal and informal rules represents one of the interesting subjects tackled within neoinstitutional analysis in sociology (Nee 2005). Convergence is reflected in the close-coupling of formal and informal rules. However, when the formal rules are at odds with the informal norms and values of the network community, this gives rise to a decoupling through opposition norms.

Processes of close-coupling and de-coupling can be seen in the evolution of the Internet. Although the rise and early development of the Internet has been governed mostly by informal rules, formal rules (laws and regulations) have emerged as the Internet space has been increasingly used for commercial activities, in order to protect the economic interests of parties involved in market transactions. The extension of existing intellectual property protection regimes, to include software and, later, information content stored electronically, can be mentioned as the primary examples of this trend. In addition, commercialization of important segments of the Internet space has resulted in formalized restrictions relating to source codes and information content, thus reflecting close-coupling between said laws and regulations and the core set of capitalist values emphasizing profit motives.

Simultaneously, however, these processes have clashed with the norms and values of open access which emerged during the formation stage of the Internet. The advocates of 'free access' not only resisted the emerging formal infrastructure facilitating commercialization, but actively embarked on setting up some formal regulations that instead were 'close-coupled' with open access norms and values. What has emerged, as a result, has been a dual structure within the Internet, of commercial and free access segments.

3. Characteristics of Internet goods

The Internet is a complex, heterogeneous good that can be alternatively defined accordingly to its different functions. In this paper, I shall adopt the wide definition of the Internet, viewed as a system of communication between users (Benkler 2000; Solum and Chung 2003). Similar to other systems of communication, such as language, the Internet consists of three distinct layers: physical, logical, and content (Benkler 2000). The physical layer enables communication by providing physical equipment; the logical layer is responsible for maintaining the code; and the content layer is the final message that is transmitted from sender to recipient. This categorization constitutes the basic axis of the following analysis.

In order to determine whether the term commons is applicable to Internet goods, I shall conduct first an analysis of the key biophysical attributes of excludability and substractability, in line with the methodology adopted in the mainstream theory of commons. Additionally, I shall identify features which differentiate Internet commons from traditional common goods. Analyzing the technical aspects of the Internet is beyond the scope of the present paper, so I will restrict references to technical aspects to a minimum (See Lemley and Lessig 2000; Clark and Blumenthal 2001).

3.1. The physical layer

The physical layer consists of all the physical tools and equipment that enable the process of communication. These include computers (the equipment to produce and send information), and tools that enable communication between computers – routers, wires, cables and wireless networks. Recently, a wide range of mobile devices – such as mobile phones, handhelds and mp3 players – have been added, which also facilitate communication. Following the terminology used in the mainstream theory of commons, the key hardware components are pure private goods (excludability combined with rivalrous consumption). However, a closer look points to a somewhat diversified picture.

3.1.1. Telephone cables

In order to connect to the Internet, the user needs a computer connected to a telephone network, cable line or some other device that can receive a wireless signal (like a router). Cables that transmit the signal to the end user belong to telecoms or cable operators. These are private goods, which are extremely expensive due to the high costs of building and maintaining the cable infrastructure. Therefore, ownership of the cables usually belongs to big telecommunication companies, who generate profits by leasing the cables to smaller operators. The dominant and often monopolistic position of the telecoms results in very strict policies related to sharing access to cables. These relations also are monitored and controlled by specified governmental agencies. Therefore, the cable infrastructure falls into the category of regulated private goods.

3.1.2. Wireless networks

Wireless networks are an alternative source of Internet connection. These networks have distinctive features, making them an interesting object of analysis. Until recently, due to the high level of radio wave interference, consumption of the radio spectrum was steeped in rivalry, thereby falling within the CPR category. This spectrum was considered to be a scarce resource that needed to be regulated by the authorities. Moreover, alternative governance structures were based either on restricted access to specialized government agencies (collective goods) or the privatization of specific frequencies through concession systems (private goods).

Recent technological developments have enabled smart receivers to distinguish signals from different sources, thereby allowing the sharing of certain frequencies (Benkler 2006). Consequently, multiple users can use the same frequency with very little or no decline in the quality of service. For that reason, modern wireless networks are becoming an open alternative to closed broadband networks. Therefore, in this case alone we find different forms of "goods":

- Commercial networks owned by telecommunication companies or private corporations, to which access is granted to subscribers or designated members fall into the club goods category;
- Municipal networks built by local governments, to be freely used by citizens or visitors can be classified as public goods – the costs of providing the good are covered by the local government, and access usually is free to all citizens or users in range of the network;
- The most interesting category of wireless networks is comprised of open, bottom-up networks, usually set up by individuals who allow anyone to connect to their transmitters. These so-called social WiFi networks or mesh networks generally fall within the public goods category.

Technological developments in wireless communications also have given rise to the widely spreading concept of an 'open spectrum'. Open spectrum proponents call for decision makers to deregulate and free up the radio spectrum (Benkler 1998). They claim that, as a result of recent technological developments, radio waves have become public goods. Consequently, they appeal to regulators to create a friendly, institutional environment, facilitating and encouraging bottom-up civic initiatives.

To summarize, wireless networks are in the midst of major changes. New institutional arrangements that allow for the transformation of classic private goods into club or public goods are particularly interesting. The informal networks serve as a primary example of the impact major technological developments in the ICT field have had on the common character of specific goods that comprise the physical layer of the Internet structure.

3.1.3. Computer hardware

Computer hardware should be easy to classify as private goods, owned by individuals or organizations. What is interesting, however, is that they can change their purely private character once the equipment is connected to the Internet. This is because personal computers hooked to the network can share excessive processing power or disk storage. Since this involves practically no additional costs to the owner, this paves the way to the provision of extensive processing power free of charge to perform certain socially valuable initiatives, as in distributed computing projects like SEITI@home and peer-to-peer networks.

It should be noted that individuals share their resources with a community of strangers, having often little or no knowledge about the way the resources will be used. Therefore, a certain duality with respect to private versus common becomes an essential characteristic of some Internet goods.

Moreover, private goods that are jointly used within a network – becoming common goods – can in turn become valuable resources for commercial activities. One of the most profound examples is Skype, the company that offers free VoIP calls. Skype uses the power of computers connected to the network to establish VoIP connections. When the user installs and runs Skype on his computer, he joins the community of users that form a peer-to-peer network. The network enables free Internet calls (benefitting users) but also affords opportunities for revenue to the private company. Here, the private goods (computers) shared for free are being commercialized by a private company while benefitting a community of users, who are often unaware that their computers are taking part in such an exchange, due to the complexity of the system.

3.2. The logical layer

The goods that constitute the middle, or logical, layer are Internet protocols, technical standards and software that enable the process of communication.

3.2.1. Technical standards

Technical specifications and protocols define the rules of communication between computers. The choice of a technical standard not only influences the basic operations of the computer system, it also has vital implications for the hardware industry, Internet providers and end-users. Standards are a form of control not only over technology, but also over the user (Abbate 1999).

Technical standards can be either open or closed as far as ownership and availability are concerned. The Internet has been built on non-proprietary protocols, such as the TCP/IP suite of protocols, which were defined as common property of the whole Internet user community (Solum and Chung 2003) and which have the property of public goods. Tim Berners-Lee, the inventor of the World Wide Web, has deliberately kept the HTTP protocol and HTML programming language open, i.e. available to the general public and developed via collaborative process, in order to maintain the innovative character of the network for as long as possible (Berners-Lee 1999). Such standards are non-rivalous resources, free for everyone to use without access restrictions.

Proprietary standards owned by private entities fall into the category of private goods or club goods. While the network technical standards responsible for the seamless cooperation of different networks and devices are, to the great extent, open, many technical specifications and file formats are proprietary and closed, protected by copyright or patent law. These formats are designed by companies which want to have exclusive rights to produce specific software. Among the examples of proprietary formats are the following types of files: .doc (text files), .pdf (text files), .gif (images), flash (animation), and .mp3 (music). One is not allowed to tinker with the formats without the copyright holder's consent, and access to specific tools is granted only to licensees.

3.2.2. Domain name system

Among the most important resources within the logical layer are IP addresses and domain names. These are private goods governed by the dedicated organization called the Internet Corporation for Assigned Names and Numbers (ICANN). The right to use a certain Internet domain name is granted to a person or organization who rents the domain for a limited period of time (with priority to extend that time, if wanted). Although the process of domain names allocation is complex and includes systems for dispute resolution, the first-come, first-served rule is applicable to new and previously-unknown domain names. Otherwise, a person or organization must prove that it should be granted exclusive rights to use a certain domain.

3.2.3. Applications and software

Applications and software comprise the largest group of resources within the logical layer. Software enables computers to perform productive tasks for users – it translates content and commands from machine language into human language and vice-versa. Among software, we can list operating systems, programming tools, and applications (word processors, email applications, video software, games, etc.). Although computers can work perfectly well without an Internet connection, more and more software is designed to work within the network. Therefore, I do not make a distinction between Internet and non-Internet software.

Bill Gates' 1976 initiative resulted in the division of the software market into two segments: proprietary and open source. In the case of proprietary software, the source code is closed as well. Such software can be distributed either for free (Internet Explorer, Adobe Acrobat Reader) or licensed to the individual or multiple users (Microsoft Office). Open source software is characterized by free access to source codes and a wide range of freedom for the user. The majority of open source software distributions are given away for free; but there also are versions of the software that are distributed on a commercial basis.

Computer software is an intangible good in digital form. Software code can be copied almost for free (the cost of a recordable CD is negligible) and without any loss of quality, and therefore without limiting the consumption potential of other users. Therefore, computer software, both non-proprietary and proprietary, belongs to the category of non-rivalrous resources. In the case of proprietary software, the owners restrict the access by specific licensing arrangements. Once obtaining the licence and subject to some limitations within its scope the user can freely decide about the intensity of software "consumption". Thus, proprietary software falls into the category of club goods. On the other hand, open source software is both non-rivalrous and difficult to exclude. Therefore open source software can be classified as a public good.

3.3. The content layer

The resources in the content layer of the Internet are intangible. These are human intellect products in digital form – information, ideas, knowledge, music, text, videos and images. Information is a key resource that is a basis for all the other goods in the content layer.

CPR scholars have recognized that informational resources are of a different nature than tangible, material goods. Hess and Ostrom stressed that analyzing information is much more tenuous than natural resources, because "*Information … often has complex tangible and intangible attributes: fuzzy boundaries, a diverse community of users on local, regional, national, and international levels, and multiple layers of rule-making institutions*" (Hess and Ostrom 2004, 132). They distinguish three forms of informational resources: artefacts, facilities and ideas. *"An artefact is a discreet, observable, nameable representation of an idea or set of ideas (for ex. articles, research notes, books, databases, maps, computer files, and web pages. […] A facility stores artefacts and makes them available. […] The ideas contained in an artefact can be understood to mean the creative vision, the intangible content, innovative information, and knowledge. Ideas are the non-physical flow units contained in an artefact"* (Ibid, 129–130).

Technological developments, especially digitization, have redefined the environment of informational goods. In the 'analogue' era, artefacts were physical and mostly private goods, and the infrastructure – like libraries and archives – that made these resources available to the public either were club goods or public goods. Ideas always were a common good and remained as such within the digitalized environment.

Although traditional artefacts in physical form belong to the category of classic private goods, digital artefacts, promoted by the Internet, represent a wider range of goods. One of the most distinguished features of digital artefacts is the possibility of copying without the loss of quality and at almost no cost. This makes digital artefacts non-rivalrous goods, as one person's use of a digital file does not subtract from another person's capacity to use it. Free copying – and technical difficulties preventing it – changes the whole process of distribution, enabling the immediate delivery of digital artefacts.

Additionally, new technologies entering the market have facilitated the collective production of informational goods, so that they have become common property. Thanks to collaborative website creators, such as *wiki*, the users can edit and share information easily with others, best exemplified by Wikipedia. In addition, authors have new tools for managing their copyrights, licenses that enable copyright holders to grant some of their rights to users while retaining other rights. Examples of new licensing models include Creative Commons licenses or GNU Free Documentation Licenses. The digitization of artefacts and the whole electronic environment for producing information has fundamentally altered their basic attributes. On one hand, their consumption has become non-rivalrous. As for access, the existing arrangements range from full exclusion of unauthorized users to free and open access with some intermediary solutions. Consequently, digital artefacts fall within various categories of common good, depending upon the degree of exclusion as the licenses allow the authors to choose different freedoms granted to users.

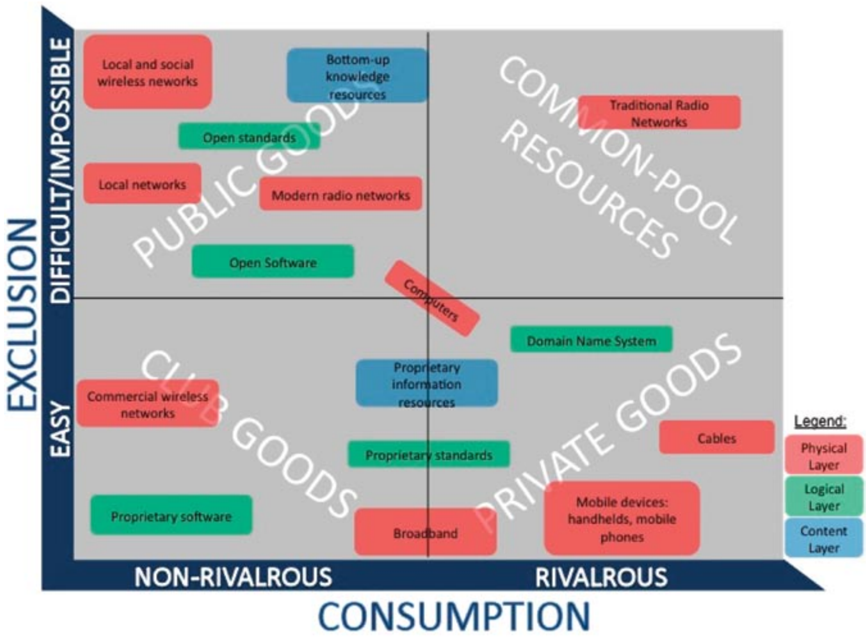
As far as the information infrastructure is concerned, one also may note a visible shift to digital forms. Digital repositories and databases typically fall within the category of club goods (they are open only to authorized users), but there is a growing number of digital open access archives that gather informational resources which are free for anyone to use. Therefore, one may conclude that, within the realm of informational goods, one can observe very interesting changes corresponding to the radical innovations being developed in information technologies, which are shaping entirely new conditions for the production and exchange of such goods.

4. Internet commons – towards an eclectic framework

4.1. The need for an eclectic approach

Based upon the analysis presented in the preceding sections, I will now summarize key findings in the context of the research questions formulated in the Introduction. Definitely, there is a merit in applying the notion of commons to individual Internet goods, but also to the network as a whole. At the same time, however, the Internet adds new dimensions to the overall concept of commons, so that the question raised by Charlotte Hess back in 2000 – "Is there anything new under the sun?" definitely can be answered in the affirmative.

With respect to the two classic biophysical attributes, excludability and subtractibility or consumptive rivalry, I have noted great diversity in Internet goods (see Figure 1).



Source: Author's presentation

Figure 1: Internet goods classified according to key biophysical attributes.

Many Internet goods fall within the pure public goods category. This is especially visible in the case of the logical layer (open standards and open source software) and the content layer (open informational resources). A large group of Internet goods can be categorized as club goods (non-rivalrous consumption and excludability). Examples are broadband Internet access, proprietary software, and closed databases.

The most striking evidence of 'novelty' in the context of the mainstream CPR theory is the virtually empty 'CPR quadrant'? With the exception of traditional radio waves, it is difficult to identify any other Internet good which would fall within the CPR category. A "common pool resource," the focus of the mainstream theory of the commons, is defined in terms of a particular set of biophysical attributes: non-excludability combined with rivalrous consumption. This combination of the key biophysical attributes is almost non-existent in the case of Internet goods.

Hence, there is an obvious need for extension of the existing theoretical analysis of commons to encompass particular features of Internet goods. This will not be an easy task, particularly due to their diversified but, at the same time, interrelated structure. We need to develop new methodological tools to investigate how the key biophysical attributes used in mainstream theory of commons interact at the level of individual Internet goods and affect the functioning of the Internet as a composite structure.

An additional important feature of Internet goods is their duality. The same goods can, with different institutional arrangements, fall into either the public, private or club goods category. Duality can be observed in cases of open or closed computer software or open and proprietary information resources, or privately owned hardware that changes attributes when working within a network. A stand-alone piece of hardware like a portable computer represents a classic private good; but once it is connected to a network, it can take on features of a club or semi-public good.

The rise of the Internet gives a new impulse for incorporation of other than CPR common goods, categorized with the use of non-excludability and joint consumption criteria; namely, the (pure) public goods and club goods. Pure or semi-pure public goods features of the Internet include open standards and open access software, electronic repositories of freely available information and knowledge, etc. Free access to information in the electronic format by millions of Internet users, combined with the active involvement in the generation of said information and knowledge, already has affected human civilization in all important spheres: economic, technological, socio-cultural, and political. We need to study these new Internet goods, which calls for revisiting the concept of public goods in various disciplines within the social sciences.

The Internet commons also open new perspectives with respect to club goods. Club goods (easy exclusion combined with non-rivalrous consumption) have been treated as quite rare and predominantly local (country clubs, subscribed theatre services). This has changed radically with the Internet. Contemporary 'clubs', which gather users of proprietary software and subscription-based proprietary databases, can have millions of members all over the world. Classic club goods used to be treated in academic analysis as impure private goods, whereas the key characteristics of Internet club goods render them closer to pure public goods, as in the example of electronic repositories of scientific journal articles, which are accessible to scholars on the basis of subscriptions paid by their university. From the individual scholar perspective, such service can be viewed as a pure public good, as she/he is not confronted directly with restrictions in their use (except that the access code needs to be provided).

This expansion of common goods to encompass public and club goods as well as CPRs can be incorporated within the existing neoinstitutional framework for studying the commons. However, other features of the Internet commons call for a more fundamental change in the overall framework by incorporating new, interesting concepts outside the mainstream theory of commons. Some elements of a more eclectic theory of the Internet commons are discussed below (Figure 2).

4.2. General purpose technologies (GPT) theory

Although the history of civilization can be seen as a stream of continuous innovations in all spheres of human activity, according to general purpose technologies (GPT) theory, technical progress and growth over centuries has been driven by certain 'great leaps' in innovation affecting entire economies at the national and global level. The list of such general purpose technologies is subject to vivid debate, but the most often quoted examples include the steam engine, electricity, and information and communication technologies (ICT). ICT and

OPEN/ UNRESOLVED ISSUES/ RESEARCH DIRECTIONS	RESEARCH DIRECTIONS/ RELEVANT CONCEPTS
Mainstream Theory of Commons - Internet not a CPR good, but more often a pure public or club good - Internet as a 'composite good' - Duality of Internet goods	These novel issues need to be researched within the extended theory of commons, encompassing Internet-specific issues.
Technological breakthroughs not adequately covered within neoinstitutional theory commons	General purpose technologies theory
Sharing potential of Internet goods	- Network effects - Positive free riding - Shareable goods
Non-hierarchical involvement in the production of Internet goods	- Architecture of participation - Peer production - Gift economy

Source: Author's presentation

Figure 2: Internet commons: proposed eclectic theoretical framework.

related Internet technologies share key features of the great technological leaps, as identified in the GPT literature:

- The use of general purpose technologies spreads wide across key sectors of the economy and social life;
- GPT represent a great scope of potential improvement over time;
- GPT facilitate innovations generating new products and processes,
- GPT show strong complementarities with existing and emerging new technologies (Bresnahan and Trajtenberg 1995; Helpman 1998).

What is crucial in the context of the Internet commons debate is that GPT theory emphasizes the broader complementarily effects of the Internet as the enabling technology changing the characteristics, as well as the modes of production and consumption of many other goods. If we take the book as an example, in the standalone paper form available in the bookstore, it is a classic private good. Once it becomes freely available over the Internet in an electronic form, it becomes a pure public good. When an access charge is imposed for its electronic version, it becomes a club good. But, at the same time, we may observe a radical transformation in the entire publishing industry resulting from the wide application of ICT in the production and distribution of books in the traditional format (digital printing, and distribution via the Internet, e.g. Amazon.com). Less revolutionary, but very important for many users, is the availability of digitalized versions of books distributed through the traditional bookstores alongside their paper versions. There are other examples of the Internet as an enabling technology, some of which have been noted in previous sections. Thus, the concepts and key findings of GPT theory seem to be very useful for extending the scope of the mainstream theory of commons not only to include the specific characteristics of Internet goods, but also to illustrate the wider implications of Internet technologies for the common character of other goods.

4.3. Theoretical concepts reflecting the 'sharing potential' of Internet goods

An important attribute of the Internet commons is its 'sharing potential', which reflects the broadly-defined efficiency of joint consumption (use) of a given good, often by a very large and expanding number of users. Such joint use does not substantially diminish a good's value. Quite often, such value increases with the number of consumers. This contrasts with the characteristics of classic CPR goods, where exceeding a certain number of users causes consumption to become rivalrous. The useful concepts which might be helpful for explaining the sharing potential of Internet goods are network effects, sharable goods, and positive free riding.

4.3.1. Network effects

The network effects concept was introduced to the economic literature in 1985 by M. L. Katz and C. Shapiro, who used the term 'network externalities'. They noted that, in the case of many products, “the utility that a user derives from consumption of the good increases with the number of other agents consuming the good” (Katz and Shapiro 1985). This concept was later refined by S. Liebowitz and S. Margolis, who argued that network effects, in their pure form, do not need to coincide with externalities; i.e. positive or negative effects on parties not involved in a given transaction (Liebowitz and Margolis 1994). The added value of existing and new customers results from direct interactions between the users of a given good, as well as from the increased availability of complementary products and services.

Back in the 1980s and 1990s, when the network effects concept was introduced and refined, traditional telephone systems were viewed as the primary exemplification of these effects. Nowadays, with the rapid development of information technologies, the ICT sector is believed to demonstrate the most significant network effects, i.e. the World Wide Web, where new essential functionalities were added once the number of Internet users increased. The same goes for websites facilitating exchanges via the Internet (eBay) or dedicated portals used for social networking. The developments taking place within the Internet spectrum clearly contrast with the classic CPR scenario. Specifically, the network effects increase radically once the number of users of a given Internet good reaches a certain threshold. For CPR goods, the increased number of users results in the excessive exploitation of a given resource.

There are negative implications as well, shown in the so-called ‘locked-in situations’, exemplified in the market for professional software applications that is presently dominated by Microsoft. The providers of alternative applications, often of superior quality, have faced major obstacles convincing potential clients to shift from Microsoft Office. The clients were reluctant to lose obvious benefits derived from network effects: compatibility with the applications used by their business partners, standard installations on purchased hardware, access to auxiliary services, additional combatable applications, etc.

4.3.2. Positive free riding

The so-called ‘free-riding problem’ is a social dilemma, a conflict between individual self-interest and the community. In a classic CPR scenario (costly exclusion and rivalrous consumption) the provision of common goods normally would call for voluntary contributions from community members. However, this is in conflict with the maximization of individual benefits among community members who, following homo oeconomicus logic, are not willing to pay for goods which are otherwise freely accessible. But there are diverse non-pecuniary motives among people involved in the consumption and production of Internet goods (Stiglitz 2000). Even so, one might see the open source, free operating system Linux to be an ‘impossible public good’; i.e. having characteristics making it impossible to materialize if the classic free riding social dilemma is all there is (Kollock 1999). Positive or passive free riding, situations in which free riders do not diminish value and may actually add value to the final product, may be characteristic of the Internet: *"Internet reduces the cost of free riding… each free rider actually adds value to the final product. If the free rider is completely passive, she adds value by adding market share (and thus increasing the space for reputational returns to contributors). If she is just a little bit active, the free rider becomes a de facto tester and might just report a bug or request a new feature. The Internet reduces the communication costs of doing all that to just about zero"* (Weber 2000, 36). There are obvious inter-linkages between positive free riding and the network effects discussed earlier. This is because network effects materialize with the increased number of users, including passive free riders (Weber 2004).

4.3.3. Shareable goods

The shareable goods concept refers to intrinsic characteristics of some private goods (computers, wireless transceivers, Internet connections) which facilitate sharing with other users (Benkler 2004). The key argument behind this concept is that some goods available on the market are 'lumpy'; i.e. they are produced in discrete sizes and represent varying capacities. Typically, available capacity is fully utilized only in specific time intervals; otherwise, it remains partially underused. Such idle capacity of some Internet goods can be shared with other users at practically no additional cost to the owner. Notable examples of capacity sharing are distributed computing projects and peer-to-peer networks.

It should be noted that the issue of available excess capacity is not restricted to Internet goods. However, with the Internet sharing is much easier and more efficient. To share excess storage capacity in a warehouse located on the company premises would call for a set of additional logistic arrangements (controlled access to the warehouse, separate storage space, sharing additional costs of monitoring and insurance, etc.). Such problems are practically non-existent when sharing excess computer processing capacity via the Internet network, although one has to consider other Internet-specific limitations: trust among the network participants, privacy and the general security of systems participating in the distributed processing.

The shareable goods theory can be extended to include the increased shareability of certain other private goods, once sharing is accomplished via the Internet, just to mention carpool (especially for long distance travel) and apartment-sharing systems. On the other hand, the simplified, practically cost-free sharing opportunities that exist on the Internet may provide additional powerful stimuli to accelerate the production of specific goods, as profoundly demonstrated by the success of the YouTube exchange of short amateur movies.

4.4. Non-hierarchical involvement in the production of Internet goods

The concepts presented above help to explain the sharing potential of Internet commons, basically confined to the consumption process. But, even more important are those attributes of the Internet commons which facilitate sharing resources in various joint production undertakings. The issue of joint production should not be separated from the particular organizational forms of such production and the motives of those involved in large collaborative undertakings, particularly IT professionals. The recently-formulated concepts of architecture of participation, peer production and the gift economy seem to be particularly relevant here.

4.4.1. Architecture of participation

The key argument behind the ‘architecture of participation’ concept is that the rules and principles laid down by the founders of the Internet during its early formation period established a very favourable and encouraging environment for joining the network, even by non-experienced users, and subsequent engagement by those most active in various collaborative undertakings. The silent feature of Internet architecture is that web activities that are intended to satisfy individual, egoistic interests, irrespective of their intentions, contribute finally to the increased collective value (O’Reilly 2004).

Among the basic rules that shape the participatory structure of the Internet is the end-to-end principle (Saltzer et al. 1984). This states that the network, as such, should remain as simple as possible, whereas all specialized elements (network intelligence) should reside with the computers of end-users and their software programs and applications. Second, efficient data transfer has been achieved with the help of an open TCP/IP network protocol, under which neither diverse operating systems nor computer brands were discriminated by the network. Everyone was allowed to use and exchange data with others, because the protocols were made to share, not to exclude. One also shall point out the simplicity of the HTML language and the open HTTP protocol, allowing for the flexible and unrestricted creation of new websites, and for the expansion and updating of their contents, even by the users with very limited experience.

The participatory architecture of the Internet has been further reinforced by its new technological platform, called Web 2.0. New tools and technologies are meant to enhance the exchange of information and flexible engagement in various collaborative efforts and events. These new developments within the Internet spectrum can be seen as the exemplification of an emerging complex social phenomenon, coined by H. Jenkins (2006) as participatory culture. It reflects an ongoing process whereby fans and consumers are effectively encouraged to participate in the creation and exchange of new media content (Jenkins 2006). The participatory culture largely contradicts the traditional notion of ‘audience’, which implied the generally passive, static role of the recipient of information and cultural goods. Needless to say, the Internet network plays crucial role as an ‘enabler’, making such cultural participation and exchange possible on a massive scale, with maximum flexibility and efficiency.

4.4.2. Peer production

The concept of ‘peer production’ (Benkler 2002) challenges the neoclassical ‘team production’ theory formulated by Alchian and Demsetz (1972). They argued that, under conditions where it is very costly to ascertain the contribution of each team member to the value of the product, there is the risk of shirking or free riding. To avoid this, the system of hierarchical control within the firm must be put in place. However, within the space of Internet many complex, collaborative undertakings – like the development of the open source software – are being successfully implemented without the degree of hierarchical control that is required for projects of similar size performed within large, offline corporations.

Benkler (2002) claims that neither the market nor the hierarchical structure of a firm can provide an efficient coordination mechanism for the provision of goods in an information commons. Such efficiency can be achieved under the alternative, third production model called ‘peer production’, which occurs when the coordination of large, complex projects is accomplished largely without formal hierarchical control, but team members are motivated, not by financial incentives, but by a range of non-pecuniary motives, including the professional satisfaction derived from creating something new and bringing value to the community (Benkler 2002). The implementation of large-scale, open-source projects, involving thousands of programmers, and the Wikipedia phenomenon are primary examples of a peer production coordination mechanism.

Benkler points to four key characteristics which render team production particularly efficient with respect to information goods in a pervasively network environment:

- Information is a purely non-rivalrous good, both as an output and as an input to the production of other information goods;
- Major technological breakthroughs in the ICT field have contributed to a radical decline in the costs of information production.
- Creative talent, being the primary input in the production of information, is much more variable than traditional labour and material inputs;
- The radical decline in the cost of exchanging information combined with the increased efficiency of such exchanges within a network economy facilitates the effective coordination of widely-dispersed resources (Benkler 2002).

The above list of the key attributes of the information commons demonstrate that the basic foundations of the peer production concept are embedded in general purpose technologies theory. It is clear that the recent major breakthroughs in the ICT field were instrumental, as the key enablers for the effective implementation of a peer production coordination mechanism.

What is particularly interesting and, in fact, unique in the peer production concept is the analysis of alternative non-hierarchical methods by which to coordinate complex undertakings. This includes, *inter alia*, the following procedures: the self-allocation of tasks, the widespread use of peer-review for evaluation, and bottom-up initiatives, aimed at identifying best candidates (both among existing and new team members) to perform specific tasks. The educational background and the professional culture of software programmers seem to play important roles here. However, the evident success of the NASA Clickworkers project suggests that professionalism may not be that important. The Clickworkers project has attracted over 85 thousand volunteers involved in identifying (marking) craters on Mars. Its key source of success can be attributed to the project's organization, which allowed for great flexibility as to the scope and timing of individual engagements (Benkler 2006).

4.4.3. The gift economy

The gift economy is distinguished from the 'exchange economy' in being a social system wherein goods are given to (shared) to the community by its members without explicit assurance of personal return. This typically occurs within small communities which attach high value to the stable, robust relationships between community members, based upon sharing, collaboration, honour, trust, scalability and loyalty (Bollier 2001). The socio-economic system of gift exchange has been studied by anthropologists in the context of traditional societies (Levi-Strauss 1969; Mauss 1974). Although many examples point to the apparent vitality of a gift economy within the contemporary capitalist system, the rise of the Internet has renewed interest in this concept as a way to explain primary motives for sharing of information and undertaking various collaborative efforts within a networked economy.

The rapid expansion of a networked information economy paves the way for broadening the spectrum of gift giving behaviours, eventually challenging the currently predominant 'exchange economy'. The Internet spectrum offers particularly favourable conditions, enabling and, in fact, encouraging the proliferation of gift-sharing attitudes. First, the cost of sharing information is practically negligible. Second, there is great flexibility in the gift-giving process, in terms of the size and timing of the donation. Third, the effects of gift giving, in terms of added social value, can be recognized easily without additional effort. Even if the sharing of information, as such, is not driven by the expectation of reciprocal rewards, the visible effects can serve as a strong incentive for continuing said behaviours in the future.

At the same time, Internet commons represent a totally different framework for gift sharing than that of small communities with established direct relationships and shared values between members. Information shared via the Internet typically is offered to a much larger and unknown set of recipients. Kollock points out that such a 'general exchange system' is more generous; but, at the same time, it is riskier than a traditional gift exchange. The absence of direct social links may elevate the temptation to free ride (Kollock 1999). On the otherhand, 'cyber-anonymity' may enhance the gift sharing behaviours that exist among Internet users, provided that an effective organizational framework ensuring anonymity is in place. The functioning of Internet-based discussion groups may offer interesting insights to this issue. Most of the participants probably hesitate to share their experiences in person or through telephone conversations. At the same time, they are most willing to provide comprehensive valuable advice via the Internet where they retain anonymity.

5. Conclusion

The rise of the Internet creates a fascinating ground for a revitalization of the theory of the commons. This is because the object of the study – the Internet commons – is expanding at an unprecedented pace. Simultaneously, its role in the global economy is increasing exponentially, affecting all key spheres of human interaction. As exemplified in the preceding analysis, the structure of the Internet commons is complex and highly diversified, thus calling for scientific exploration of its modalities and dimensions.

Considering the state-of-the-art of the theory of commons and the challenges connected with the rise and expansion of the Internet, the development of a single theoretical framework encompassing the whole diversity of the Internet commons may not be feasible. At this stage an eclectic route seems to be more promising, particularly as interesting new concepts with direct relevance to the Internet have emerged in various branches of the social sciences. The proposed format (Figure 2), which identifies both open questions and the sources of theoretical inspiration, is by no means exhaustive and serves merely as an initial platform to facilitate discussion and thereby help refine ways of understanding and explaining the Internet commons.

Finally, a word of caution shall be offered. Researchers of the Internet commons are confronted, on one hand, with the limited timeframe of the analysis which results from the very brief history of the Internet. On the other hand, expansion of the Internet brings fundamental changes that affect practically all spheres of human interaction. This expansion calls for immediate reaction from the academic community. However, the former points to the significant risks of concentrating research endeavours on issues of a transient, nature while neglecting other, significant, long-term tendencies. Obviously, such limitations do apply to the analysis contained in the present article, as well.

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Theory

A **theory** is a rational type of abstract thinking about a phenomenon, or the results of such thinking. The process of contemplative and rational thinking is often associated with such processes as observational study or research. Theories may be scientific, belong to a non-scientific discipline, or no discipline at all. Depending on the context, a theory's assertions might, for example, include generalized explanations of how nature works. The word has its roots in ancient Greek, but in modern use it has taken on several related meanings.

In modern science, the term "theory" refers to scientific theories, a well-confirmed type of explanation of nature, made in a way consistent with the scientific method, and fulfilling the criteria required by modern science. Such theories are described in such a way that scientific tests should be able to provide empirical support for it, or empirical contradiction ("falsify") of it. Scientific theories are the most reliable, rigorous, and comprehensive form of scientific knowledge,[1] in contrast to more common uses of the word "theory" that imply that something is unproven or speculative (which in formal terms is better characterized by the word *hypothesis*).[2] Scientific theories are distinguished from hypotheses, which are individual empirically testable conjectures, and from scientific laws, which are descriptive accounts of the way nature behaves under certain conditions.

Theories guide the enterprise of finding facts rather than of reaching goals, and are neutral concerning alternatives among values.[3]:131 A theory can be a body of knowledge, which may or may not be associated with particular explanatory models. To theorize is to develop this body of knowledge.[4]:46

The word theory or "in theory" is sometimes used erroneously by people to explain something which they individually did not experience or test before.[5] In those instances, semantically, it is being substituted for another concept, a hypothesis. Instead of using the word "hypothetically", it is replaced by a phrase: "in theory". In some instances the theory's credibility could be contested by calling it "just a theory" (implying that the idea has not even been tested).[6] Hence, that word "theory" is very often contrasted to "practice" (from Greek *praxis*, πρᾶξις) a Greek term for *doing*, which is opposed to theory.[6] A "classical example" of the distinction between "theoretical" and "practical" uses the discipline of medicine: medical theory involves trying to understand the causes and nature of health and sickness, while the practical side of medicine is trying to make people healthy. These two things are related but can be independent, because it is possible to research health and sickness without curing specific patients, and it is possible to cure a patient without knowing how the cure worked.[a]

Contents

Ancient usage

The English word *theory* derives from a technical term in philosophy in Ancient Greek. As an everyday word, *theoria*, θεωρία, meant "looking at, viewing, beholding", but in more technical contexts it came to refer to contemplative or speculative understandings of natural things, such as those of natural philosophers, as opposed to more practical ways of knowing things, like that of skilled orators or artisans.[b] English-speakers have used the word *theory* since at least the late 16th century.[7] Modern uses of the word *theory* derive from the original definition, but have taken on new shades of meaning, still based on the idea of a theory as a thoughtful and rational explanation of the general nature of things.

Although it has more mundane meanings in Greek, the word θεωρία apparently developed special uses early in the recorded history of the Greek language. In the book *From Religion to Philosophy*, Francis Cornford suggests that the Orphics used the word *theoria* to mean "passionate sympathetic contemplation".[8] Pythagoras changed the word to mean "the passionless contemplation of rational, unchanging truth" of mathematical knowledge, because he considered this intellectual pursuit the way to reach the highest plane of existence.[9] Pythagoras emphasized subduing emotions and bodily desires to help the intellect function at the higher plane of theory. Thus, it was Pythagoras who gave the word *theory* the specific meaning that led to the classical and modern concept of a distinction between theory (as uninvolved, neutral thinking) and practice.[10]

Aristotle's terminology, as already mentioned, contrasts theory with *praxis* or practice, and this contrast exists till today. For Aristotle, both practice and theory involve thinking, but the aims are different. Theoretical contemplation considers things humans do not move or change, such as nature, so it has no human aim apart from itself and the knowledge it helps create. On the other hand, *praxis* involves thinking, but always with an aim to desired actions, whereby humans cause change or movement themselves for their own ends. Any human movement that involves no conscious choice and thinking could not be an example of *praxis* or doing.[c]

Formality

Theories are analytical tools for understanding, explaining, and making predictions about a given subject matter. There are theories in many and varied fields of study, including the arts and sciences. A formal theory is syntactic in nature and is only meaningful when given a semantic component by applying it to some content (e.g., facts and relationships of the actual historical world as it is unfolding). Theories in various fields of study are expressed in natural language, but are always constructed in such a way that their general form is identical to a theory as it is expressed in the formal language of mathematical logic. Theories may be expressed mathematically, symbolically, or in common language, but are generally expected to follow principles of rational thought or logic.

Theory is constructed of a set of sentences that are entirely true statements about the subject under consideration. However, the truth of any one of these statements is always relative to the whole theory. Therefore, the same statement may be true with respect to one theory, and not true with respect to another. This is, in ordinary language, where statements such as "He is a terrible person" cannot be judged as true or false without reference to some interpretation of who "He" is and for that matter what a "terrible person" is under the theory.[11]

Sometimes two theories have exactly the same explanatory power because they make the same predictions. A pair of such theories is called indistinguishable or observationally equivalent, and the choice between them reduces to convenience or philosophical preference.

The form of theories is studied formally in mathematical logic, especially in model theory. When theories are studied in mathematics, they are usually expressed in some formal language and their statements are closed under application of certain procedures called rules of inference. A special case of this, an axiomatic theory, consists of axioms (or axiom schemata) and rules of inference. A theorem is a statement that can be derived from those axioms by application of these rules of inference. Theories used in applications are abstractions of observed phenomena and the resulting theorems provide solutions to real-world problems. Obvious examples include arithmetic (abstracting concepts of number), geometry (concepts of space), and probability (concepts of randomness and likelihood).

Gödel's incompleteness theorem shows that no consistent, recursively enumerable theory (that is, one whose theorems form a recursively enumerable set) in which the concept of natural numbers can be expressed, can include all true statements about them. As a result, some domains of knowledge cannot be formalized, accurately and completely, as mathematical theories. (Here, formalizing accurately and completely means that all true propositions—and only true propositions—are derivable within the mathematical system.) This limitation, however, in no way precludes the construction of mathematical theories that formalize large bodies of scientific knowledge.

Underdetermination

A theory is *underdetermined* (also called *indeterminacy of data to theory*) if a rival, inconsistent theory is at least as consistent with the evidence. Underdetermination is an epistemological issue about the relation of evidence to conclusions.

A theory that lacks supporting evidence is generally, more properly, referred to as a hypothesis.

Intertheoretic reduction and elimination

If a new theory better explains and predicts a phenomenon than an old theory (i.e., it has more explanatory power), we are justified in believing that the newer theory describes reality more correctly. This is called an *intertheoretic reduction* because the terms of the old theory can be reduced to the terms of the new one. For instance, our historical understanding about *sound*, "light" and *heat* have been reduced to *wave* *compressions and rarefactions*, *electromagnetic waves*, and *molecular kinetic energy*, respectively. These terms, which are identified with each other, are called *intertheoretic identities.* When an old and new theory are parallel in this way, we can conclude that the new one describes the same reality, only more completely.

When a new theory uses new terms that do not reduce to terms of an older theory, but rather replace them because they misrepresent reality, it is called an *intertheoretic elimination.* For instance, the obsolete scientific theory that put forward an understanding of heat transfer in terms of the movement of caloric fluid was eliminated when a theory of heat as energy replaced it. Also, the theory that phlogiston is a substance released from burning and rusting material was eliminated with the new understanding of the reactivity of oxygen.

Versus theorems

Theories are distinct from theorems. A *theorem* is derived deductively from axioms (basic assumptions) according to a formal system of rules, sometimes as an end in itself and sometimes as a first step toward being tested or applied in a concrete situation; theorems are said to be true in the sense that the conclusions of a theorem are logical consequences of the axioms. *Theories* are abstract and conceptual, and are supported or challenged by observations in the world. They are 'rigorously tentative', meaning that they are proposed as true and expected to satisfy careful examination to account for the possibility of faulty inference or incorrect observation. Sometimes theories are incorrect, meaning that an explicit set of observations contradicts some fundamental objection or application of the theory, but more often theories are corrected to conform to new observations, by restricting the class of phenomena the theory applies to or changing the assertions made. An example of the former is the restriction of classical mechanics to phenomena involving macroscopic length scales and particle speeds much lower than the speed of light.

The theory-practice gap

Theory is often distinguished from practice. The question of whether theoretical models of work are relevant to work itself is of interest to scholars of professions such as medicine, engineering, and law, and management.[12]: 802

This gap between theory and practice has been framed as a knowledge transfer where there is a task of translating research knowledge to be application in practice, and ensuring that practictioners are made aware of it academics have been criticized for not attempting to transfer the knowledge they produce to practitioners.[12]: 804[13] Another framing supposes that theory and knowledge seek to understand different problems and model the world in different words (using different ontologies and epistemologies) . Another framing says that research does not produce theory that is relevant to practice.[12]: 803

In the context of management, Van de Van and Johnson propose a form of engaged scholarship where scholars examine problems that occur in practice, in an interdisciplinary fashion, producing results that create both new practical results as well as new theoretical models, but targeting theoretical results shared in an academic fashion.[12]: 815 They use a metaphor of "arbitrage" of ideas between disciplines, distinguishing it from collaboration.[12]: 803

Scientific

In science, the term "theory" refers to "a well-substantiated explanation of some aspect of the natural world, based on a body of facts that have been repeatedly confirmed through observation and experiment."[14][15] Theories must also meet further requirements, such as the ability to make falsifiable predictions with consistent accuracy across a broad area of scientific inquiry, and production of strong evidence in favor of the theory from multiple independent sources (consilience).

The strength of a scientific theory is related to the diversity of phenomena it can explain, which is measured by its ability to make falsifiable predictions with respect to those phenomena. Theories are improved (or replaced by better theories) as more evidence is gathered, so that accuracy in prediction improves over time; this increased accuracy corresponds to an increase in scientific knowledge. Scientists use theories as a foundation to gain further scientific knowledge, as well as to accomplish goals such as inventing technology or curing diseases.

Definitions from scientific organizations

The United States National Academy of Sciences defines scientific theories as follows:

> The formal scientific definition of "theory" is quite different from the everyday meaning of the word. It refers to a comprehensive explanation of some aspect of nature that is supported by a vast body of evidence. Many scientific theories are so well established that no new evidence is likely to alter them substantially. For example, no new evidence will demonstrate that the Earth does not orbit around the sun (heliocentric theory), or that living things are not made of cells (cell theory), that matter is not composed of atoms, or that the surface of the Earth is not divided into solid plates that have moved over geological timescales (the theory of plate tectonics) ... One of the most useful properties of scientific theories is that they can be used to make predictions about natural events or phenomena that have not yet been observed.[16]

From the American Association for the Advancement of Science:

> A scientific theory is a well-substantiated explanation of some aspect of the natural world, based on a body of facts that have been repeatedly confirmed through observation and experiment. Such fact-supported theories are not "guesses" but reliable accounts of the real world. The theory of biological evolution is more than "just a theory." It is as factual an explanation of the universe as the atomic theory of matter or the germ theory of disease. Our understanding of gravity is still a work in progress. But the phenomenon of gravity, like evolution, is an accepted fact.[15]

The term *theory* is not appropriate for describing scientific models or untested, but intricate hypotheses.

Philosophical views

The logical positivists thought of scientific theories as *deductive theories*—that a theory's content is based on some formal system of logic and on basic axioms. In a deductive theory, any sentence which is a logical consequence of one or more of the axioms is also a sentence of that theory.[11] This is called the received view of theories.

In the semantic view of theories, which has largely replaced the received view,[17][18] theories are viewed as scientific models. A model is a logical framework intended to represent reality (a "model of reality"), similar to the way that a map is a graphical model that represents the territory of a city or country. In this approach, theories are a specific category of models that fulfill the necessary criteria. (See Theories as models for further discussion.)

In physics

In physics the term *theory* is generally used for a mathematical framework—derived from a small set of basic postulates (usually symmetries, like equality of locations in space or in time, or identity of electrons, etc.)—which is capable of producing experimental predictions for a given category of physical systems. One good example is classical electromagnetism, which encompasses results derived from gauge symmetry (sometimes called gauge invariance) in a form of a few equations called Maxwell's equations. The specific mathematical aspects of classical electromagnetic theory are termed "laws of electromagnetism", reflecting the level of consistent and reproducible evidence that supports them. Within electromagnetic theory generally, there are numerous hypotheses about how electromagnetism applies to specific situations. Many of these hypotheses are already considered adequately tested, with new ones always in the making and perhaps untested.

Regarding the term "theoretical"

Certain tests may be infeasible or technically difficult. As a result, theories may make predictions that have not been confirmed or proven incorrect. These predictions may be described informally as "theoretical". They can be tested later, and if they are incorrect, this may lead to revision, invalidation, or rejection of the theory. [19]

Mathematical

In mathematics the use of the term *theory* is different, necessarily so, since mathematics contains no explanations of natural phenomena, *per se*, even though it may help provide insight into natural systems or be inspired by them. In the general sense, a mathematical *theory* is a branch of or topic in mathematics, such as Set theory, Number theory, Group theory, Probability theory, Game theory, Control theory, Perturbation theory, etc., such as might be appropriate for a single textbook.

In the same sense, but more specifically, the word *theory* is an extensive, structured collection of theorems, organized so that the proof of each theorem only requires the theorems and axioms that preceded it (no circular proofs), occurs as early as feasible in sequence (no postponed proofs), and the whole is as succinct as possible (no redundant proofs).[d] Ideally, the sequence in which the theorems are presented is as easy to understand as possible, although illuminating a branch of mathematics is the purpose of textbooks, rather than the mathematical theory they might be written to cover.

Philosophical

A theory can be either *descriptive* as in science, or *prescriptive* (normative) as in philosophy.[20] The latter are those whose subject matter consists not of empirical data, but rather of ideas. At least some of the elementary theorems of a philosophical theory are statements whose truth cannot necessarily be scientifically tested through empirical observation.

A field of study is sometimes named a "theory" because its basis is some initial set of assumptions describing the field's approach to the subject. These assumptions are the elementary theorems of the particular theory, and can be thought of as the axioms of that field. Some commonly known examples include set theory and number theory; however literary theory, critical theory, and music theory are also of the same form.

Metatheory

One form of philosophical theory is a *metatheory* or *meta-theory*. A metatheory is a theory whose subject matter is some other theory or set of theories. In other words, it is a theory about theories. Statements made in the metatheory about the theory are called metatheorems.

Political

A political theory is an ethical theory about the law and government. Often the term "political theory" refers to a general view, or specific ethic, political belief or attitude, thought about politics.

Jurisprudential

In social science, jurisprudence is the philosophical theory of law. Contemporary philosophy of law addresses problems internal to law and legal systems, and problems of law as a particular social institution.

Examples

Most of the following are scientific theories. Some are not, but rather encompass a body of knowledge or art, such as Music theory and Visual Arts Theories.

- Anthropology: Carneiro's circumscription theory
- Astronomy: Alpher–Bethe–Gamow theory — B^2FH Theory — Copernican theory — Giant impact hypothesis — Newton's theory of gravitation — Hubble's law — Kepler's laws of planetary motion — Nebular hypothesis — Ptolemaic theory
- Cosmology: Big Bang Theory — Cosmic inflation — Loop quantum gravity — Superstring theory — Supergravity — Supersymmetric theory — Multiverse theory — Holographic principle — Quantum gravity — M-theory
- Biology: Cell theory — Evolution — Germ theory
- Chemistry: Molecular theory — Kinetic theory of gases — Molecular orbital theory — Valence bond theory — Transition state theory — RRKM theory — Chemical graph theory — Flory–Huggins solution theory — Marcus theory — Lewis theory (successor to Brønsted–Lowry acid–base theory) — HSAB theory — Debye–Hückel theory — Thermodynamic theory of polymer elasticity — Reptation theory — Polymer field theory — Møller–Plesset perturbation theory — density functional theory — Frontier molecular orbital theory — Polyhedral skeletal electron pair theory — Baeyer strain theory — Quantum theory of atoms in molecules — Collision theory — Ligand field theory (successor to Crystal field theory) — Variational transition-state theory — Benson group increment theory — Specific ion interaction theory
- Climatology: Climate change theory (general study of climate changes) and anthropogenic climate change (ACC)/ global warming (AGW) theories (due to human activity)
- Economics: Macroeconomic theory — Microeconomic theory — Law of Supply and demand
- Education: Constructivist theory — Critical pedagogy theory — Education theory — Multiple intelligence theory — Progressive education theory
- Engineering: Circuit theory — Control theory — Signal theory — Systems theory — Information theory
- Film: Film Theory
- Geology: Plate tectonics
- Humanities: Critical theory
- Jurisprudence or 'Legal theory': Natural law — Legal positivism — Legal realism — Critical legal studies

- Law: see Jurisprudence; also Case theory
- Linguistics: X-bar theory — Government and Binding — Principles and parameters — Universal grammar
- Literature: Literary theory
- Mathematics: Approximation theory — Arakelov theory — Asymptotic theory — Bifurcation theory — Catastrophe theory — Category theory — Chaos theory — Choquet theory — Coding theory — Combinatorial game theory — Computability theory — Computational complexity theory — Deformation theory — Dimension theory — Ergodic theory — Field theory — Galois theory — Game theory — Graph theory — Group theory — Hodge theory — Homology theory — Homotopy theory — Ideal theory — Intersection theory — Invariant theory — Iwasawa theory — K-theory — KK-theory — Knot theory — L-theory — Lie theory — Littlewood–Paley theory — Matrix theory — Measure theory — Model theory — Morse theory — Nevanlinna theory — Number theory — Obstruction theory — Operator theory — PCF theory — Perturbation theory — Potential theory — Probability theory — Ramsey theory — Rational choice theory — Representation theory — Ring theory — Set theory — Shape theory — Small cancellation theory — Spectral theory — Stability theory — Stable theory — Sturm–Liouville theory — Twistor theory
- Music: Music theory
- Philosophy: Proof theory — Speculative reason — Theory of truth — Type theory — Value theory — Virtue theory
- Physics: Acoustic theory — Antenna theory — Atomic theory — BCS theory — Dirac hole theory — Dynamo theory — Landau theory — M-theory — Perturbation theory — Theory of relativity (successor to classical mechanics) — Quantum field theory — Scattering theory — String theory — Quantum information theory
- Psychology: Theory of mind — Cognitive dissonance theory — Attachment theory — Object permanence — Poverty of stimulus — Attribution theory — Self-fulfilling prophecy — Stockholm syndrome
- Public Budgeting: Incrementalism — Zero-based budgeting
- Public Administration: Organizational theory
- Semiotics: Intertheoricity (https://www.degruyter.com/view/j/hssr.2015.4.issue-1/hssr-2015-0002/hssr-2015-0002.xml) - Transferogenesis (https://www.degruyter.com/view/j/hssr.2015.4.issue-2/hssr-2015-0014/hssr-2015-0014.xml)
- Sociology: Critical theory — Engaged theory — Social theory — Sociological theory - Social capital theory
- Statistics: Extreme value theory
- Theatre: Performance theory
- Visual Art: Aesthetics — Art educational theory — Architecture — Composition — Anatomy — Color theory — Perspective — Visual perception — Geometry — Manifolds
- Other: Obsolete scientific theories

See also

- Falsifiability
- Hypothesis testing
- Physical law
- Predictive power
- Testability
- Theoretical definition

Notes

a. See for example Hippocrates Praeceptiones, Part 1 (https://www.perseus.tufts.edu/hopper/text?doc=Perseus:text:1999.01.0251:text=Praec.:section=1&highlight=medical%2Ctheory). Archived (https://web.archive.org/web/20140912175614/http://www.perseus.tufts.edu/hopper/text?doc=Perseus:text:1999.01.0251:text=Praec.:section=1&highlight=medical%2Ctheory) September 12, 2014, at the Wayback Machine

b. The word *theoria* occurs in Greek philosophy, for example, that of Plato. It is a statement of how and why particular facts are related. It is related to words for θεωρός "spectator", θέα *thea* "a view" + ὁρᾶν *horan* "to see", literally "looking at a show". See for example dictionary entries at Perseus website (https://www.perseus.tufts.edu/hopper/resolveform?type=start&lookup=qewr&lang=greek).

c. The LSJ cites two passages of Aristotle as examples, both from the *Metaphysics* and involving the definition of natural science: 11.1064a17 (https://www.perseus.tufts.edu/hopper/text?doc=Perseus%3Atext%3A1999.01.0052%3Abook%3D11%3Asection%3D1064a), "it is clear that natural science (φυσικὴν ἐπιστήμην) must be neither practical (πρακτικὴν) nor productive (ποιητικὴν), but speculative (θεωρητικὴν)" and 6.1025b25 (https://www.perseus.tufts.edu/hopper/text?doc=Perseus%3Atext%3A1999.01.0052%3Abook%3D6%3Asection%3D1025b), "Thus if every intellectual activity [διάνοια] is either practical or productive or speculative (θεωρητική), physics (φυσικὴ) will be a speculative [θεωρητική] science." So Aristotle actually made a three way distinction between practical, theoretical and productive or technical—or between doing, contemplating or making. All three types involve thinking, but are distinguished by what causes the objects of thought to move or change.

d. *Succinct* in this sense refers to the whole collection of proofs, and means that any one proof contains no embedded stages that are equivalent to parts of proofs of later theorems.

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External links

- "How science works: Even theories change" (http://undsci.berkeley.edu/article/0_0_0/howscienceworks_20), *Understanding Science* by the University of California Museum of Paleontology.
- What is a Theory? (https://zcomm.org/wp-content/uploads/zinstructionals/htdocs/RTInstruc/id6.htm)

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Scientific theory

A '*scientific theory* is not a law natural world and universe that has been repeatedly tested and verified in accordance with the scientific method, using accepted protocols of observation, measurement, and evaluation of results. Where possible, theories are tested under controlled conditions in an experiment.[1][2] In circumstances not amenable to experimental testing, theories are evaluated through principles of abductive reasoning. Established scientific theories have withstood rigorous scrutiny and embody scientific knowledge.[3]

A scientific theory differs from a scientific fact or scientific law in that a theory explains "why" or "how": a fact is a simple, basic observation, whereas a law is a statement (often a mathematical equation) about a relationship between facts. For example, Newton's Law of Gravity is a mathematical equation that can be used to predict the attraction between bodies, but it is not a theory to explain *how* gravity works.[4] Stephen Jay Gould wrote that "...facts and theories are different things, not rungs in a hierarchy of increasing certainty. Facts are the world's data. Theories are structures of ideas that explain and interpret facts."[5]

The meaning of the term *scientific theory* (often contracted to *theory* for brevity) as used in the disciplines of science is significantly different from the common vernacular usage of *theory*.[6][note 1] In everyday speech, *theory* can imply an explanation that represents an unsubstantiated and speculative guess,[6] whereas in science it describes an explanation that has been tested and is widely accepted as valid.[1][2][3]

The strength of a scientific theory is related to the diversity of phenomena it can explain and its simplicity. As additional scientific evidence is gathered, a scientific theory may be modified and ultimately rejected if it cannot be made to fit the new findings; in such circumstances, a more accurate theory is then required. Some theories are so well-established that they are unlikely ever to be fundamentally changed (for example, scientific theories such as evolution, heliocentric theory, cell theory, theory of plate tectonics, germ theory of disease, etc.). In certain cases, a scientific theory or scientific law that fails to fit all data can still be useful (due to its simplicity) as an approximation under specific conditions. An example is Newton's laws of motion, which are a highly accurate approximation to special relativity at velocities that are small relative to the speed of light.

Scientific theories are testable and make falsifiable predictions.[7] They describe the causes of a particular natural phenomenon and are used to explain and predict aspects of the physical universe or specific areas of inquiry (for example, electricity, chemistry, and astronomy). As with other forms of scientific knowledge, scientific theories are both deductive and inductive,[8] aiming for predictive and explanatory power. Scientists use theories to further scientific knowledge, as well as to facilitate advances in technology or medicine.

Contents

Types

Albert Einstein described two types of scientific theories: "Constructive theories" and "principle theories". Constructive theories are constructive models for phenomena: for example, kinetic theory. Principle theories are empirical generalisations such as Newton's laws of motion.[9]

Characteristics

Essential criteria

Typically for any theory to be accepted within most academia there is one simple criterion. The essential criterion is that the theory must be observable and repeatable. The aforementioned criterion is essential to prevent fraud and perpetuate science itself.

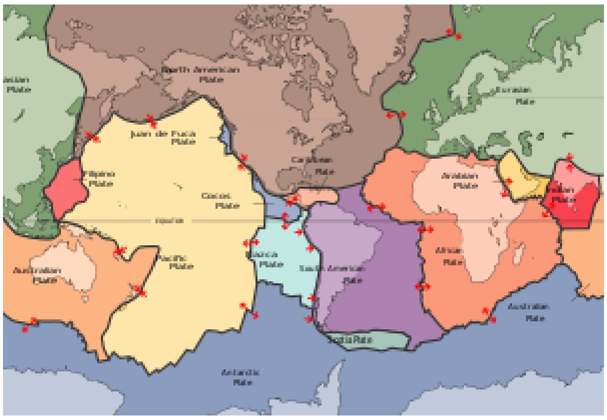
The defining characteristic of all scientific knowledge, including theories, is the ability to make falsifiable or testable predictions. The relevance and specificity of those predictions determine how potentially useful the theory is. A would-be theory that makes no observable predictions is not a scientific theory at all. Predictions not sufficiently specific to be tested are similarly not useful. In both cases, the term "theory" is not applicable.

A body of descriptions of knowledge can be called a theory if it fulfills the following criteria:

- It makes falsifiable predictions with consistent accuracy across a broad area of scientific inquiry (such as mechanics).
- It is well-supported by many independent strands of evidence, rather than a single foundation.

- It is consistent with preexisting experimental results and at least as accurate in its predictions as are any preexisting theories.

These qualities are certainly true of such established theories as special and general relativity, quantum mechanics, plate tectonics, the modern evolutionary synthesis, etc.



The tectonic plates of the world were mapped in the second half of the 20th century. Plate tectonic theory successfully explains numerous observations about the Earth, including the distribution of earthquakes, mountains, continents, and oceans.

Other criteria

In addition, scientists prefer to work with a theory that meets the following qualities:

- It can be subjected to minor adaptations to account for new data that do not fit it perfectly, as they are discovered, thus increasing its predictive capability over time.[10]
- It is among the most parsimonious explanations, economical in the use of proposed entities or explanatory steps as per Occam's razor. This is because for each accepted explanation of a phenomenon, there may be an extremely large, perhaps even incomprehensible, number of possible and more complex alternatives, because one can always burden failing explanations with *ad hoc* hypotheses to prevent them from being falsified; therefore, simpler theories are preferable to more complex ones because they are more testable.[11][12][13]

Definitions from scientific organizations

The United States National Academy of Sciences defines scientific theories as follows:

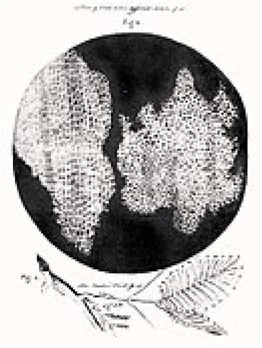
> The formal scientific definition of theory is quite different from the everyday meaning of the word. It refers to a comprehensive explanation of some aspect of nature that is supported by a vast body of evidence. Many scientific theories are so well established that no new evidence is likely to alter them substantially. For example, no new evidence will demonstrate that the Earth does not orbit around the Sun (heliocentric theory), or that living things are not made of cells (cell theory), that matter is not composed of atoms, or that the surface of the Earth is not divided into solid plates that have moved over geological timescales (the theory of plate tectonics)...One of the most useful properties of scientific theories is that they can be used to make predictions about natural events or phenomena that have not yet been observed.[14]

From the American Association for the Advancement of Science:

> A scientific theory is a well-substantiated explanation of some aspect of the natural world, based on a body of facts that have been repeatedly confirmed through observation and experiment. Such fact-supported theories are not "guesses" but reliable accounts of the real world. The theory of biological evolution is more than "just a theory". It is as factual an explanation of the universe as the atomic theory of matter or the germ theory of disease. Our understanding of gravity is still a work in progress. But the phenomenon of gravity, like evolution, is an accepted fact.

Note that the term *theory* would not be appropriate for describing untested but intricate hypotheses or even scientific models.

Formation



The first observation of cells, by Robert Hooke, using an early microscope.[15] This led to the development of cell theory.

The scientific method involves the proposal and testing of hypotheses, by deriving predictions from the hypotheses about the results of future experiments, then performing those experiments to see whether the predictions are valid. This provides evidence either for or against the hypothesis. When enough experimental results have been gathered in a particular area of inquiry, scientists may propose an explanatory framework that accounts for as many of these as possible. This explanation is also tested, and if it fulfills the necessary criteria (see above), then the explanation becomes a theory. This can take many years, as it can be difficult or complicated to gather sufficient evidence.

Once all of the criteria have been met, it will be widely accepted by scientists (see scientific consensus) as the best available explanation of at least some phenomena. It will have made predictions of phenomena that previous theories could not explain or could not predict accurately, and it will have resisted attempts at falsification. The strength of the evidence is evaluated by the scientific community, and the most important experiments will have been replicated by multiple independent groups.

Theories do not have to be perfectly accurate to be scientifically useful. For example, the predictions made by classical mechanics are known to be inaccurate in the relatistivic realm, but they are almost exactly correct at the comparatively low velocities of common human experience.[16] In chemistry, there are many acid-base theories providing highly divergent explanations of the underlying nature of acidic and basic compounds, but they are very useful for predicting their chemical behavior.[17] Like all knowledge in science, no theory can ever be completely certain, since it is possible that future experiments might conflict with the theory's predictions.[18] However, theories supported by the scientific consensus have the highest level of certainty of any scientific knowledge; for example, that all objects are subject to gravity or that life on Earth evolved from a common ancestor.[19]

Acceptance of a theory does not require that all of its major predictions be tested, if it is already supported by sufficiently strong evidence. For example, certain tests may be unfeasible or technically difficult. As a result, theories may make predictions that have not yet been confirmed or proven incorrect; in this case, the predicted results may be described informally with the term "theoretical". These predictions can be tested at a later time, and if they are incorrect, this may lead to the revision or rejection of the theory.

Modification and improvement

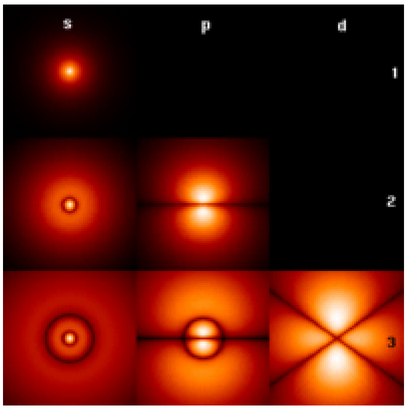
If experimental results contrary to a theory's predictions are observed, scientists first evaluate whether the experimental design was sound, and if so they confirm the results by independent replication. A search for potential improvements to the theory then begins. Solutions may require minor or major changes to the theory, or none at all if a satisfactory explanation is found within the theory's existing framework.[20] Over time, as successive modifications build on top of each other, theories consistently improve and greater predictive accuracy is achieved. Since each new version of a theory (or a completely new theory) must have more predictive and explanatory power than the last, scientific knowledge consistently becomes more accurate over time.

If modifications to the theory or other explanations seem to be insufficient to account for the new results, then a new theory may be required. Since scientific knowledge is usually durable, this occurs much less commonly than modification.[18] Furthermore, until such a theory is proposed and accepted, the previous theory will be retained. This is because it is still the best available explanation for many other phenomena, as verified by its predictive power in other contexts. For example, it has been known since 1859 that the observed perihelion precession of Mercury violates Newtonian mechanics,[21] but the theory remained the best explanation available until relativity was supported by sufficient evidence. Also, while new theories may be proposed by a single person or by many, the cycle of modifications eventually incorporates contributions from many different scientists.[22]

After the changes, the accepted theory will explain more phenomena and have greater predictive power (if it did not, the changes would not be adopted); this new explanation will then be open to further replacement or modification. If a theory does not require modification despite repeated tests, this implies that the theory is very accurate. This also means that accepted theories continue to accumulate evidence over time, and the length of time that a theory (or any of its principles) remains accepted often indicates the strength of its supporting evidence.

Unification

In some cases, two or more theories may be replaced by a single theory that explains the previous theories as approximations or special cases, analogous to the way a theory is a unifying explanation for many confirmed hypotheses; this is referred to as *unification* of theories.[23] For example, electricity and magnetism are now known to be two aspects of the same phenomenon, referred to as electromagnetism.[24]



In quantum mechanics, the electrons of an atom occupy orbitals around the nucleus. This image shows the orbitals of a hydrogen atom (*s*, *p*, *d*) at three different energy levels (1, 2, 3). Brighter areas correspond to higher probability density.

When the predictions of different theories appear to contradict each other, this is also resolved by either further evidence or unification. For example, physical theories in the 19th century implied that the Sun could not have been burning long enough to allow certain geological changes as well as the evolution of life. This was resolved by the discovery of nuclear fusion, the main energy source of the Sun.[25] Contradictions can also be explained as the result of theories approximating more fundamental (non-contradictory) phenomena. For example, atomic theory is an approximation of quantum mechanics. Current theories describe three separate fundamental phenomena of which all other theories are approximations;[26] the potential unification of these is sometimes called the Theory of Everything.[23]

Example: Relativity

In 1905, Albert Einstein published the principle of special relativity, which soon became a theory.[27] Special relativity predicted the alignment of the Newtonian principle of Galilean invariance, also termed *Galilean relativity*, with the electromagnetic field.[28] By omitting from special relativity the luminiferous aether, Einstein stated that time dilation and length contraction measured in an object in relative motion is inertial—that is, the object exhibits constant velocity, which is speed with direction, when measured by its observer. He thereby duplicated the Lorentz transformation and the Lorentz contraction that had been hypothesized to resolve experimental riddles and inserted into electrodynamic theory as dynamical consequences of the aether's properties. An elegant theory, special relativity yielded its own consequences,[29] such as the equivalence of mass and energy transforming into one another and the resolution of the paradox that an excitation of the electromagnetic field could be viewed in one reference frame as electricity, but in another as magnetism.

Einstein sought to generalize the invariance principle to all reference frames, whether inertial or accelerating.[30] Rejecting Newtonian gravitation—a central force acting instantly at a distance—Einstein presumed a gravitational field. In 1907, Einstein's equivalence principle implied that a free fall within a uniform gravitational field is equivalent to inertial motion.[30] By extending special relativity's effects into three dimensions, general relativity extended length contraction into space contraction, conceiving of 4D space-time as the gravitational field that alters geometrically and sets all local objects' pathways. Even massless energy exerts gravitational motion on local objects by "curving" the geometrical "surface" of 4D space-time. Yet unless the energy is vast, its relativistic effects of contracting space and slowing time are negligible when merely predicting motion. Although general relativity is embraced as the more explanatory theory via *scientific realism*, Newton's theory remains successful as merely a predictive theory via *instrumentalism*. To calculate trajectories, engineers and NASA still uses Newton's equations, which are simpler to operate.[18]

Theories and laws

Both scientific laws and scientific theories are produced from the scientific method through the formation and testing of hypotheses, and can predict the behavior of the natural world. Both are typically well-supported by observations and/or experimental evidence.[31] However, scientific laws are descriptive accounts of how nature will behave under certain conditions.[32] Scientific theories are broader in scope, and give overarching explanations of how nature works and why it exhibits certain characteristics. Theories are supported by evidence from many different sources, and may contain one or several laws.[33]

A common misconception is that scientific theories are rudimentary ideas that will eventually graduate into scientific laws when enough data and evidence have been accumulated. A theory does not change into a scientific law with the accumulation of new or better evidence. A theory will always remain a theory; a law will always remain a law.[31][34][35] Both theories and laws could potentially be falsified by countervailing evidence.[36]

Theories and laws are also distinct from hypotheses. Unlike hypotheses, theories and laws may be simply referred to as scientific fact.[37][38] However, in science, theories are different from facts even when they are well supported.[39] For example, evolution is both a theory and a fact.[6]

About theories

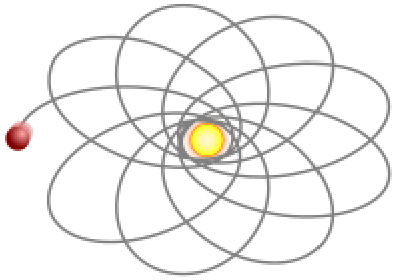
Theories as axioms

The logical positivists thought of scientific theories as statements in a formal language. First-order logic is an example of a formal language. The logical positivists envisaged a similar scientific language. In addition to scientific theories, the language also included observation sentences ("the sun rises in the east"), definitions, and mathematical statements. The phenomena explained by the theories, if they could not be directly observed by the senses (for example, atoms and radio waves), were treated as theoretical concepts. In this view, theories function as axioms: predicted observations are derived from the theories much like theorems are derived in Euclidean geometry. However, the predictions are then tested against reality to verify the theories, and the "axioms" can be revised as a direct result.

The phrase "the received view of theories" is used to describe this approach. Terms commonly associated with it are "linguistic" (because theories are components of a language) and "syntactic" (because a language has rules about how symbols can be strung together). Problems in defining this kind of language precisely, e.g., are objects seen in microscopes observed or are they theoretical objects, led to the effective demise of logical positivism in the 1970s.

Theories as models

The semantic view of theories, which identifies scientific theories with models rather than propositions, has replaced the received view as the dominant position in theory formulation in the philosophy of science.[40][41][42] A model is a logical framework intended to represent reality (a "model of reality"), similar to the way that a map is a graphical model that represents the territory of a city or country.[43][44]



Precession of the perihelion of Mercury (exaggerated). The deviation in Mercury's position from the Newtonian prediction is about 43 arc-seconds (about two-thirds of 1/60 of a degree) per century.[45][46]

In this approach, theories are a specific category of models that fulfill the necessary criteria (see above). One can use language to describe a model; however, the theory is the model (or a collection of similar models), and not the description of the model. A model of the solar system, for example, might consist of abstract objects that represent the sun and the planets. These objects have associated properties, e.g., positions, velocities, and masses. The model parameters, e.g., Newton's Law of Gravitation, determine how the positions and velocities change with time. This model can then be tested to see whether it accurately predicts future observations; astronomers can verify that the positions of the model's objects over time match the actual positions of the planets. For most planets, the Newtonian model's predictions are accurate; for Mercury, it is slightly inaccurate and the model of general relativity must be used instead.

The word "semantic" refers to the way that a model represents the real world. The representation (literally, "re-presentation") describes particular aspects of a phenomenon or the manner of interaction among a set of phenomena. For instance, a scale model of a house or of a solar system is clearly not an actual house or an actual solar system; the aspects of an actual house or an actual solar system represented in a scale model are, only in certain limited ways, representative of the actual entity. A scale model of a house is not a house; but to someone who wants to *learn about* houses, analogous to a scientist who wants to understand reality, a sufficiently detailed scale model may suffice.

Differences between theory and model

Several commentators[47] have stated that the distinguishing characteristic of theories is that they are explanatory as well as descriptive, while models are only descriptive (although still predictive in a more limited sense). Philosopher Stephen Pepper also distinguished between theories and models, and said in 1948 that general models and theories are predicated on a "root" metaphor that constrains how scientists theorize and model a phenomenon and thus arrive at testable hypotheses.

Engineering practice makes a distinction between "mathematical models" and "physical models"; the cost of fabricating a physical model can be minimized by first creating a mathematical model using a computer software package, such as a computer aided design tool. The component parts are each themselves modelled, and the fabrication tolerances are specified. An exploded view drawing is used to lay out the fabrication sequence. Simulation packages for displaying each of the subassemblies allow the parts to be rotated, magnified, in realistic detail. Software packages for creating the bill of materials for construction allows subcontractors to specialize in assembly processes, which spreads the cost of manufacturing machinery among multiple customers. See: Computer-aided engineering, Computer-aided manufacturing, and 3D printing

Assumptions in formulating theories

An assumption (or axiom) is a statement that is accepted without evidence. For example, assumptions can be used as premises in a logical argument. Isaac Asimov described assumptions as follows:

> ...it is incorrect to speak of an assumption as either true or false, since there is no way of proving it to be either (If there were, it would no longer be an assumption). It is better to consider assumptions as either useful or useless, depending on whether deductions made from them corresponded to reality...Since we must start somewhere, we must have assumptions, but at least let us have as few assumptions as possible.[48]

Certain assumptions are necessary for all empirical claims (e.g. the assumption that reality exists). However, theories do not generally make assumptions in the conventional sense (statements accepted without evidence). While assumptions are often incorporated during the formation of new theories, these are either supported by evidence (such as from previously existing theories) or the evidence is produced in the course of validating the theory. This may be as simple as observing that the theory makes accurate predictions, which is evidence that any assumptions made at the outset are correct or approximately correct under the conditions tested.

Conventional assumptions, without evidence, may be used if the theory is only intended to apply when the assumption is valid (or approximately valid). For example, the special theory of relativity assumes an inertial frame of reference. The theory makes accurate predictions when the assumption is valid, and does not make accurate predictions when the assumption is not valid. Such assumptions are often the point with which older theories are succeeded by new ones (the general theory of relativity works in non-inertial reference frames as well).

The term "assumption" is actually broader than its standard use, etymologically speaking. The Oxford English Dictionary (OED) and online Wiktionary indicate its Latin source as *assumere* ("accept, to take to oneself, adopt, usurp"), which is a conjunction of *ad-* ("to, towards, at") and *sumere* (to take). The root survives, with shifted meanings, in the Italian *assumere* and Spanish *sumir*. The first sense of "assume" in the OED is "to take unto (oneself), receive, accept, adopt". The term was originally employed in religious contexts as in "to receive up into heaven", especially "the reception of the Virgin Mary into heaven, with body preserved from corruption", (1297 CE) but it was also simply used to refer to "receive into association" or "adopt into partnership". Moreover, other senses of assumere included (i) "investing oneself with (an attribute)", (ii) "to undertake" (especially in Law), (iii) "to take to oneself in appearance only, to pretend to possess", and (iv) "to suppose a thing to be" (all senses from OED entry on "assume"; the OED entry for "assumption" is almost perfectly symmetrical in senses). Thus, "assumption" connotes other associations than the contemporary standard sense of "that which is assumed or taken for granted; a supposition, postulate" (only the 11th of 12 senses of "assumption", and the 10th of 11 senses of "assume").

Descriptions

From philosophers of science

Karl Popper described the characteristics of a scientific theory as follows:[7]

1. It is easy to obtain confirmations, or verifications, for nearly every theory—if we look for confirmations.
2. Confirmations should count only if they are the result of risky predictions; that is to say, if, unenlightened by the theory in question, we should have expected an event which was incompatible with the theory—an event which would have refuted the theory.
3. Every "good" scientific theory is a prohibition: it forbids certain things to happen. The more a theory forbids, the better it is.
4. A theory which is not refutable by any conceivable event is non-scientific. Irrefutability is not a virtue of a theory (as people often think) but a vice.
5. Every genuine test of a theory is an attempt to falsify it, or to refute it. Testability is falsifiability; but there are degrees of testability: some theories are more testable, more exposed to refutation, than others; they take, as it were, greater risks.
6. Confirming evidence should not count except when it is the result of a genuine test of the theory; and this means that it can be presented as a serious but unsuccessful attempt to falsify the theory. (I now speak in such cases of "corroborating evidence".)
7. Some genuinely testable theories, when found to be false, might still be upheld by their admirers—for example by introducing post hoc (after the fact) some auxiliary hypothesis (http://www.hu.mtu.edu/~tlockha/h3700hemp2.htm) or assumption, or by reinterpreting the theory post hoc in such a way that it escapes refutation. Such a procedure is always possible, but it rescues the theory from refutation only at the price of destroying, or at least lowering, its scientific status, by tampering with evidence. The temptation to tamper can be minimized by first taking the time to write down the testing protocol before embarking on the scientific work.

Popper summarized these statements by saying that the central criterion of the scientific status of a theory is its "falsifiability, or refutability, or testability".[7] Echoing this, Stephen Hawking states, "A theory is a good theory if it satisfies two requirements: It must accurately describe a large class of observations on the basis of a model that contains only a few arbitrary elements, and it must make definite predictions about the results of future observations." He also discusses the "unprovable but falsifiable" nature of theories, which is a necessary consequence of inductive logic, and that "you can disprove a theory by finding even a single observation that disagrees with the predictions of the theory".[49]

Several philosophers and historians of science have, however, argued that Popper's definition of theory as a set of falsifiable statements is wrong[50] because, as Philip Kitcher has pointed out, if one took a strictly Popperian view of "theory", observations of Uranus when first discovered in 1781 would have "falsified" Newton's celestial mechanics. Rather, people suggested that another planet influenced Uranus' orbit—and this prediction was indeed eventually confirmed.

Kitcher agrees with Popper that "There is surely something right in the idea that a science can succeed only if it can fail."[51] He also says that scientific theories include statements that cannot be falsified, and that good theories must also be creative. He insists we view scientific theories as an "elaborate collection of statements", some of which are not falsifiable, while others—those he calls "auxiliary hypotheses", are.

According to Kitcher, good scientific theories must have three features:[51]

1. Unity: "A science should be unified…. Good theories consist of just one problem-solving strategy, or a small family of problem-solving strategies, that can be applied to a wide range of problems."
2. Fecundity: "A great scientific theory, like Newton's, opens up new areas of research…. Because a theory presents a new way of looking at the world, it can lead us to ask new questions, and so to embark on new and fruitful lines of inquiry…. Typically, a flourishing science is incomplete. At any time, it raises more questions than it can currently answer. But incompleteness is not vice. On the contrary, incompleteness is the mother of fecundity…. A

good theory should be productive; it should raise new questions and presume those questions can be answered without giving up its problem-solving strategies."

3. Auxiliary hypotheses (http://www.hu.mtu.edu/~tlockha/h3700hemp2.htm) that are independently testable: "An auxiliary hypothesis ought to be testable independently of the particular problem it is introduced to solve, independently of the theory it is designed to save." (For example, the evidence for the existence of Neptune is independent of the anomalies in Uranus's orbit.)

Like other definitions of theories, including Popper's, Kitcher makes it clear that a theory must include statements that have observational consequences. But, like the observation of irregularities in the orbit of Uranus, falsification is only one possible consequence of observation. The production of new hypotheses is another possible and equally important result.

Analogies and metaphors

The concept of a scientific theory has also been described using analogies and metaphors. For instance, the logical empiricist Carl Gustav Hempel likened the structure of a scientific theory to a "complex spatial network:"

> Its terms are represented by the knots, while the threads connecting the latter correspond, in part, to the definitions and, in part, to the fundamental and derivative hypotheses included in the theory. The whole system floats, as it were, above the plane of observation and is anchored to it by the rules of interpretation. These might be viewed as strings which are not part of the network but link certain points of the latter with specific places in the plane of observation. By virtue of these interpretive connections, the network can function as a scientific theory: From certain observational data, we may ascend, via an interpretive string, to some point in the theoretical network, thence proceed, via definitions and hypotheses, to other points, from which another interpretive string permits a descent to the plane of observation.[52]

Michael Polanyi made an analogy between a theory and a map:

> A theory is something other than myself. It may be set out on paper as a system of rules, and it is the more truly a theory the more completely it can be put down in such terms. Mathematical theory reaches the highest perfection in this respect. But even a geographical map fully embodies in itself a set of strict rules for finding one's way through a region of otherwise uncharted experience. Indeed, all theory may be regarded as a kind of map extended over space and time.[53]

A scientific theory can also be thought of as a book that captures the fundamental information about the world, a book that must be researched, written, and shared. In 1623, Galileo Galilei wrote:

> Philosophy [i.e. physics] is written in this grand book—I mean the universe—which stands continually open to our gaze, but it cannot be understood unless one first learns to comprehend the language and interpret the characters in which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is humanly impossible to understand a single word of it; without these, one is wandering around in a dark labyrinth.[54]

The book metaphor could also be applied in the following passage, by the contemporary philosopher of science Ian Hacking:

> I myself prefer an Argentine fantasy. God did not write a Book of Nature of the sort that the old Europeans imagined. He wrote a Borgesian library, each book of which is as brief as possible, yet each book of which is inconsistent with every other. No book is redundant. For every book there is some humanly accessible bit of Nature such that that book, and no other, makes possible the comprehension, prediction and influencing of what is going on…Leibniz said that God chose a world which maximized the variety of phenomena while choosing the simplest laws. Exactly so: but the best way to maximize phenomena and have simplest laws is to have the laws inconsistent with each other, each applying to this or that but none applying to all.[55]

In physics

In physics, the term *theory* is generally used for a mathematical framework—derived from a small set of basic postulates (usually symmetries—like equality of locations in space or in time, or identity of electrons, etc.)—that is capable of producing experimental predictions for a given category of physical systems. A good example is classical electromagnetism, which encompasses results derived from gauge symmetry (sometimes called gauge invariance) in a form of a few equations called Maxwell's equations. The specific mathematical aspects of classical electromagnetic theory are termed "laws of electromagnetism," reflecting the level of consistent and reproducible evidence that supports them. Within electromagnetic theory generally, there are numerous hypotheses about how electromagnetism applies to specific situations. Many of these hypotheses are already considered to be adequately tested, with new ones always in the making and perhaps untested. An example of the latter might be the radiation reaction force. As of 2009, its effects on the periodic motion of charges are detectable in synchrotrons, but only as *averaged* effects over time. Some researchers are now considering experiments that could observe these effects at the instantaneous level (i.e. not averaged over time).[56][57]

Examples

Note that many fields of inquiry do not have specific named theories, e.g. developmental biology. Scientific knowledge outside a named theory can still have a high level of certainty, depending on the amount of evidence supporting it. Also note that since theories draw evidence from many fields, the categorization is not absolute.

- **Biology**: cell theory, theory of evolution (modern evolutionary synthesis), abiogenesis, germ theory, particulate inheritance theory, dual inheritance theory, Young–Helmholtz theory, opponent process
- **Chemistry**: collision theory, kinetic theory of gases, Lewis theory, molecular theory, molecular orbital theory, transition state theory, valence bond theory
- **Physics**: atomic theory, Big Bang theory, Dynamo theory, perturbation theory, theory of relativity (successor to classical mechanics), quantum field theory
- **Earth Science**: Climate change theory (from climatology),[58] plate tectonics theory (from geology), theories of the origin of the Moon, theories for the Moon illusion
- **Astronomy**: Self-gravitating system, Stellar evolution, solar nebular model, stellar nucleosynthesis

Notes

1. Quote: "The formal scientific definition of theory is quite different from the everyday meaning of the word. It refers to a comprehensive explanation of some aspect of nature that is supported by a vast body of evidence."

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