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TRILHA PRINCIPAL

Reflections about Research in Computer Science regarding the Classification of Sciences and the Scientific Method

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***Abstract* —This paper presents some observations about Computer Science and the Scientific Method. Initially, the paper discusses the different aspects of Computer Science regarding the classification of sciences. It is observed that different areas inside Computer Science can be classified as different Sciences. The paper presents the main philosophical schools that define what is understood as the Scientific Method, and their influence on Computer Science. Finally, the paper discusses the distinction between Science and Technology and the degrees of maturity in Computer Science research.**

***Keywords* — Research in Computer Science, Scientific Method, Classification of Sciences, Research Techniques, Science and Technology.**

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I. Introduction

Computer Science is sometimes classified as an exact science and sometimes seen as an engineering field. Nevertheless, some of its sub areas are very close to human and social sciences. Proceedings from conferences in different sub areas are so different that sometimes a scientist from a sub area does not fully understand the jargon or even the methodology from another sub area. This article analizes Computer Sicence under the light of scientific method, no matter if it is an exact or social science, hard or soft, empirical or formal science. Our goal is to enlighten the Computer Science practicioners on the richness and variety of this research field.

This article is a reflection and therefore it does not follow the usual formatting for research articles. There is no underlying pretension of it being a complete and definitive study on the subject. Its goal is to explore and raise questions and reflect on them, rather than answer them.

II. Computer Science and the Classification of Sciences

According to Wikipedia (1), Science is the effort to discover and increase human knowledge on the inner workings of reality. Therefore, the term "Science" includes several human activities, such as, for example, technological development, as we will see later in this article.

Analysis is one of the common tools used by scientists, who try to use it to divide the universe and explain its parts in a more understandable way. Hence, given the diversity of approaches, several classifications of science have been created in order to better understand its methods and goals.

A. *Formal and Empirical Sciences*

One of the most known criteria for science classification is the division between formal and empirical sciences (2). It can be said that formal sciences study ideas while empirical sciences study things.

Formal Sciences study ideas without connection to its application to nature or the human being. That does not mean that they cannot be applied (usually they are), but that their goal is to study the form, that is, the purely logical and mathematical processes.

Among formal sciences we can include Logic, Mathematics, Microeconomics, Statistics and formal aspects of Linguistics. Among the sub areas of Computer Sciences there are many formal sciences: algorithm theory (including programming techniques, data structures, complexity and decidability), formal language theory (used to build compilers), formal aspects of artificial intelligence, relational calculus and many others.

Empirical sciences are also called real or factual sciences. They study phenomena that occur in the real world and, hence, are not merely formal. They must use observations to create the foundation for their discoveries. In empirical sciences a beautiful theory that does not match observations is worthless.

Empirical sciences can also be divided into two groups: those that study nature (natural sciences) and those that study the human being and its interactions (social sciences) (3).

Natural Sciences study the universe in its aspects that are not dependent either on the existence of the human being or on its actions. Among them are Astronomy, Physics, Chemistry, Biology and Earth Sciences. The aspects of Computer Science related to natural sciences usually concern the hardware they use to compute. Electronics, logical circuits, processors and all the physical components of a computer are studied as natural phenomena. A Turing Machine (4), for instance, is an ideal processor, with infinite memory and is studied in Computer Science Theory as a formal artifact. Processors, on the other hand, have real physical limitations on space and speed and, therefore, are studied as natural phenomena.

Social Sciences study the aspects of human relations, that is, the social life of individuals. Among social sciences are Anthropology, Communications Study, Economics, History, Politics, Sociology and others.

Sub areas of Computer Science closer to social sciences are computer science in education, electronic commerce and some aspects of artificial intelligence that study social interaction of multi-agent systems based on observations of human social behavior, among others.

Hence, we can say that given this way of classifying sciences, there are sub areas of Computer Sciences in all of them. Besides, we did not mention the multidisciplinary areas that are derived from a real interaction of Computer Science with other sciences, such as Economics, Medicine, Geography and others. There are many situations where Computer Science is used to promote studies in other areas, such as geo-referential systems, where knowledge in other fields is applied to Computer Science, as in neural networks and genetic algorithms (both of which are computational mechanisms heavily inspired in Biology).

B. *Pure and Applied Sciences*

Another classification of sciences is due to the way their studies are applied. According to this classification, there are pure and applied sciences (5).

Pure Sciences or fundamental sciences study the basic concepts of knowledge without any concern over its immediate application. That does not mean that they are not empirical sciences – they can be either empirical or formal. Being basic means being more interested on the fundamental laws that rule over the physical phenomena or over the ideas. Cosmology is considered a basic science *per se*, given that it studies the creation of the universe without an explicit concern with practical applications. Nevertheless, Cosmology is an empirical science, because its theories must be validated by the observation of phenomena. In some cases, there are phenomena observed before a coherent theory existed, such as the case of planets and stars movement. In other cases, a theory existed before the phenomena were observed, as in the case of black holes that were effectively observed decades after they were foreseen.

Logic can also be considered a pure science, but it is formal, given that it studies the relation among ideas and not physical entities.

The basic science part of Computer Science is hard to identify, given that most of its results have a practical application. Therefore, maybe this aspect is more connected to the researcher's intent than to a specific sub area. An example of basic research that only generated practical applications much later is Chaos Theory (6), which evolved based on the phenomena that were observed with computational tools.

Another sub area of Computer Science that resembles closely Basic Science is the field of multi-agent systems and the area known as computational mathetics (7), that is, the study of human learning simulated by computers. The goal of those sub areas usually is to understand how both social processes among human beings and human learning occur. This intent is pursued by the creation of computation models that incorporate theories that try to explain some phenomena and its subsequent test.

Applied sciences, on the other hand, intend to discover facts that can be immediately applied to an industrial process or similar project, with the underlying goal of generating a gain. Engineering in general can be included in this definition.

Computer Science is often seen as a discipline of Engineering. There is Software Engineering and Computer Engineering, each one with a different goal, but all of them with the commonality of generating knowledge for the application in the process of creating software systems or hardware.

Applied science is many times confused with technology. Nevertheless, as we will see later in this paper, they are different things.

C. Exact and Inexact Sciences

Another classification differentiates between exact and inexact sciences (8). Computer Science is usually classified among the exact sciences but some sub areas may have completely different characteristics.

Exact Sciences are those whose results are precise. Their laws are highly predictable and useful as a tool to forecast a result. Experiments may be repeated several times with the same results or at least with statistically predictable results. Among those we can include Mathematics, Physics, Chemistry and parts of some natural and social sciences.

Inexact Sciences are those who can forecast general results on the phenomena they describe, but whose results are not always what is expected. This is usually due because it is very difficult to evaluate all the data that generate those results. Among those we can include Meteorology, Economics and most social sciences.

Computer Science, as many other exact sciences, also has inexact aspects. Genetic algorithms and some neural network models may generate unexpected results even when applied repeatedly to the same data set.

D. Hard and Soft Sciences

Another classification, which is perhaps less known, divides sciences into hard and soft ones (9). This classification relates to the rigor on how the scientific method is used.

Hard Sciences are those that use scientific rigor in their observations, experiments and deductions. When hard sciences are formal, they rely strongly on Logic and Mathematics as theoretical building tools. On the other hand, natural hard sciences depend many times on statistical comprovation in order to confer credibility to their experiments. Medical research can be classified as a hard natural science, for it demands strict rigor in the confirmation of its empirical results.

Soft Sciences, on the other hand, tend to accept evidences based on anedoctal data, that is, case studies. This is the case when it is difficult or even impossible to perform totally controlled experiments.

Usually, Computer Science can be classified as a hard science, but in many cases researchers have a hard time providing data in an amount large enough to provide empirical support for their conclusions. Hence, there are many articles in Computer Science that use only one or a few case studies to try to “validate” a technique, model or theory. As we will see, a case study is an excellent data source for exploratory research, but except for the case of a contradiction to a widely accepted theory, it does not validate the hypothesis that the authors intend to prove.

E. Nomothetic and Idiographic Sciences

Most sciences are *nomothetic* because they study phenomena that repeat themselves and that can lead to the discovery of general laws that allow us to forecast future phenomena.

On the other hand, some sciences are *idiographic* because they analyze unique unrepeatable events, but they are, nevertheless, valid as a field of study (10).

History is the biggest example of idiographic science, given that the facts never repeat themselves and that it is extremely hard, if not impossible, to find patterns that are sufficiently deterministic in History to allow us to forecast future events based on observations.

In Computer Science, few areas are idiographic. We can point to the study of Computer Science history and the development of certain technologies, such as languages, paradigms and computational architectures as examples of topics that be treated as such.

III. The Scientific Method

Several philosophical schools have influenced what is now known as *Science*. These schools are analyzed in the following subsections.

Scientific method is particularly important in Computer Science because as a Science it cannot be concerned only about data collection. Data explanation is much more important.

It is not enough, for example, in order to prove the efficacy of a system, to apply it to two different groups: a test group *A* and a control group *B* and come to the conclusion that group A average was superior to that of group *B*. First of all, it would be necessary to demonstrate that the difference between the averages is not due to random events. Once a student applied a questionnaire to five different persons, three of each answered “yes” and two answered “no”. The student came to the conclusion that there was a tendency towards “yes” (for 60% of the answers were affirmative). But what is the value of this conclusion? For instance, could he sell to a newspaper the result of a poll based on five interviews?

Even if the difference between the averages is meaningful, this fact lacks value if there is no underlying *theory* to explain that difference.

If one group used an educational software and the other did not and the first group performed better in the evaluation, what does that prove? Is it possible that the software improved learning? Yes. But it is also possible that the students that used the software studied harder because they would be embarrassed if they achieve lower scores than the group that did not use the software. Maybe the group that did not use the software felt that they were underprivileged and did not feel an interest on the subject. Hence, there can be many explanations for the fact. The serious researcher needs to find the most probable according to the scientific method.

A. Empiricism, Positivism and Pragmatism

Maybe the most important influence to the scientific method came from the *empiricism*[1], which establishes that every scientific theory must be objective, based on observations that can be tested and creating laws that can forecast reality. This way, every scientific theory can be verified under the light of empirical evidence and when it does not explain adequately the observable facts, it can be denied.

[1] John Locke (1632-1704) is considered the first empirical philosopher.

Positivism[2] proposed that science must be based on human values, leaving Theology, Mysticism and Metaphysics in a realm that does not influence observations and scientific theories. Hence, in the case of both classes mentioned above that used the educational software, a sound scientific theory cannot consider that good ghosts have helped the students that used the software, for that is not Science.

Pragmatism[3] is a philosophical school that is opposed to scientific *realism*. Realists defend that Science effectively describes reality. The pragmatics, on the other hand, assume that it is not possible to know exactly what *is* reality and, hence, Science explains only the observed phenomena and its forecasts are consistent and useful.

One thing that most empirical scientist do not admit is absolute knowledge. Every theory and every explanation related to observed phenomena is always accepted because it is coherent with them. But every theory may be denied or refuted by new observations that do not confirm it. Even the most fundamental observations may be refuted in case they do not abide by the empirical observations.

This is due to the fact that Science, according to pragmatism, does not explain Nature as it is, but as a set of axioms on our observations of it.

Scientists must always pay attention to the result of their observations. In Computer Science, as in other areas, finding phenomena that do not fit the explanations usually accepted may be the key to new discoveries.

B. Objectivity

Another important characteristic of the scientific method is *objectivity*, that is, the possibility that two different persons with an acceptable competency level may come to the same conclusions when looking at data.

Objectivity means putting aside personal opinion in Science, because they are subjective and are dependent on experience, character and motivation of those who hold them. For instance, a programmer may affirm that functional programming is superior to imperative programming. Nevertheless, without an objective metric to define quantitatively what is "superior", that opinion can be refuted by other programmers. This feud may even be healthy but it is very difficult to build a solid Science based on this kind of subjective issues, judgments or preferences.

Computer Science does not use the principle of authority as a foundation for its research. This may be the reason why many papers published in the field do not rely on citation of classical work. Usually, most papers in Computer Science present concepts based on literature, which is also the source of related work (among the most recent ones), and an objective work, which is evaluated empirically. Hence, most opinions have little value when faced to data analysis.

Besides, a healthy principle of research is critical reading, even of the most recognized works. A reading with the single minded goal of learning may be positive, but a critical reading, in which one doubts the author's conclusions, may generate many more research ideas.

C. Induction

The scientific method also holds as one of its tenets that a situation that holds in every observed case also holds in all cases, until proved wrong. This is known as the *induction* principle (11).

There are no reasons *a priori* to believe that laws inferred from induction on many observations have exceptions, unless this exception is observed or that some other knowledge may suggest its existence. For instance, since no flying horses have been observed (at least by reliable sources) and since there is no knowledge that could imply their existence, there are no reasons to believe that they effectively exist.

This does not mean that if one person has only seen white swans then there are no black swans. This person may accept initially the fact that all swans are white but whether he/she sees a black swan then he/she should have to abandon that theory.

Therefore, natural induction can only be applied as a scientific principle when it is effectively coherent with other knowledge and previous observations.

In Computer Science, as in formal science, *mathematical induction* (12) is widely used. In this case, proof is formal. When one wishes to demonstrate that a virtually infinite set of objects hold a certain property, one can do that through mathematical induction if one can define a rule that allows to generate all members of the set. In this case, it must be proved that the property holds for an initial object (which is not generated based on others) and that the generation rule preserves the desired property, that is, if element n holds it, then element $n+1$ generated by this rule also necessarily holds it. If these proofs can be performed, then one can come to the formal conclusion that all elements hold that property.

Since some properties are fuzzy, one must take care when evaluating them (13). For example, it can be admitted that a newborn is young. If a person is young, it is correct to assume that adding one day to its age will not make it "not young". Hence, we can come to the conclusion that persons of any age are young. The flaw in this line of thought is the fact that "young" is a fuzzy definition.

Structural Induction (14) is a more general case, of which mathematical induction is a specialization. Structural induction is needed when there is more than one rule to create the elements.

This principle can be applied, among other things, to software testing. If an object is created in a way that is consistent to its specification and if the operations that change this object preserve its specification, then the object is always consistent.

D. Refutation

The principle of *refutation* (15) or *contradiction* of a theory establishes that any scientific theory that intends to explain observable facts is open for invalidation, in the case it cannot explain new observations.

A case study, since it is exploratory research, cannot prove a general theory, for instance. Nevertheless, it can prove that a

[2] Auguste Compte (1798-1857) is considered the founder of Sociology and Positivism.

[3] John Dewey (1859-1952) was a philosopher that influenced greatly the pragmatic thought.

general and widely accepted rule is not totally valid. That will happen if the case study shows a situation where the rule does not present the expected result. Usually, the case study must have some hypothesis to be tested beforehand, for the researcher to execute it with a goal in mind.

The fact that we may find new observations that are not explained by the general rule does not mean that this law may be completely discarded. For instance, in spite of Relativity Theory, Newtonian physics still explains very well phenomena on Earth's surface. Hence, when new observations contradict a theory, we can discard the original theory replacing it with a radically new one, but we can also split the original theory into two different theories with applications in different situations.

E. Coherentism

The principle of *coherentism* (16) is highly integrated to the philosophy of pragmatism. Therefore, no scientist may ever say that his/her theory explains reality. He/she will only affirm that his/her theory is coherent with observations and that by the principle of induction, in the absence of any refutation, this theory may be accepted as an explanation.

Coherentism avoids Descartes' *criterium problem* (17) in which any affirmation must be justified by a previous affirmation, leading to an infinite regression. With coherentism, it is not expected for each affirmation to have an explanation, but that it is coherent with a previously accepted body of knowledge.

F. Occam's Razor

One question that would go unanswered with the principle of *Occam's Razor* (18) is the fact that any finite set of observations may be explained in infinite ways, specially if the differences among theories cannot be immediately tested empirically. For example, the theory that says that gravity's acceleration is 9,8 m/s^2 may have infinite variations if we include exceptions such as "except on 2070, January 10th, when it will be 9,6 m/s^2". Since it is not possible to test this theory before 2070, it is as equally plausible as the most widely accepted theory.

The principle of Occam's Razor says that in the case when several theories explain the same observations, the simpler one must be preferred[4]. The simplest will then be accepted as the most correct. In the example above, the alternative theory cannot be tested before 2070, but the addition to the general theory is gratuitous and has no foundation in any explanation or plausible cause. Besides, it is not coherent with the observations and general knowledge on the workings of gravity.

Without a rule such as Occam's Razor, it would not be possible to create Science.

Nevertheless, there are times when this rule is badly used. It does not say that the simplest explanation is always preferable. Actually, the simplest explanation *among those that effectively explain the observations* must be chosen above all others.

[4] W. Ockham original phrasing was "*Numquam ponenda est pluralitas sine necessitate*", that is, never use more than strictly necessary.

IV. Research Methods Classification

The term "research" can refer to several human activities that go from poll data gathering to the scientific research that intends to increase human knowledge on the inner workings of reality.

Research, in the scientific context, also may be classified according to different criteria. Among them, it is possible to differentiate among types of research according to its natures, goals or technical procedures. A research work is not always limited to a single type. Besides, some types of research may serve as the foundation for others.

A. According to nature

According to the nature of the research, it can be differentiated between original work and survey.

Original work intends to present new knowledge based on observations and theories build to explain them. It is assumed that the new information is relevant when it has some implication on the way processes and systems are understood or when they have a practical implication on their achievement.

Surveys, on the other hand, intend to systematize a field of knowledge, usually pointing out its historical evolution and state of the art.

Although it is said that a survey is a non original work and, therefore, adequate to undergraduate studies, it must be considered that good surveys can only be written by experts on the research field. For a survey to actually be relevant it is necessary that the author has a solid knowledge on the area and its development, as well as its open problems. Besides, the author is expected to be able to point to causes and effects besides what can be explicitly read in the published articles, given that sometimes the motivations for an area may evolve in implicit directions. It is also expected from a survey author to be able to present a coherent structure for this evolution and not only a chronological line of isolated facts.

B. According to goals

According to its goals, the research can be exploratory, descriptive or explanatory.

Exploratory research is the one where the author does not necessarily have an hypothesis or goal well defined in his mind. Often it can be considered as the first stage on a longer research process. In exploratory research the author examines a set of phenomena searching for anomalies that are still unknown and that can be, then, the foundation for a more elaborate research.

Descriptive research is more systematic than the explanatory kind. In this type of research, the goal is to obtain a more consistent set of data on a certain reality. There is not, yet, interference from the researcher part or the attempt to find theories that can explain the phenomena. The single goal is to describe the facts just as they are. Descriptive research is characterized by data gathering and by interviews and questionnaires. Just as exploratory research, it can be considered as an initial step to find phenomena unexplained by the current theories.

Explanatory research is the most complex and complete. It is the scientific research per excellence because, besides analyzing the observed data, it also searches for causes and explanations, that is, the underlying factors for these data.

C. According to Technical Procedures

According to its technical procedures, research can be classified as bibliographic, documental, experimental, gathering or research-action.

Bibliographic research implies on the study of papers, thesis, books and other publications usually available through publish houses and indexed.

Bibliographic research is a fundamental and previous step for any scientific work, but it does not, in itself, create any new knowledge. It merely supplies public information previously unknown to the researcher.

Documental research, on the other hand, consists on the analysis of documents and data that have not been systematized and published yet. One can examine company reports, public files, data bases, mail, etc. That is, documental research intends to find information and pattern in document not yet systematically treated. Looking for patterns, for example, in definition documents created by software development companies would be an example of documental research in Computer Science.

Experimental research is characterized by the manipulation by the researcher of an aspect of reality. The researcher introduces, for example, a new technique in a software house and verifies if there is a productivity increase. Experimental research implies in having one or more experimental variables that can be controlled by the researcher (the fact of using or not a specific technique, for example) and one or more observed variables, whose measurement may lead to the conclusion that there is some kind of connection with the experimental variable (for example, evaluating programmer productivity in function points per work day, and verifying if the techniques increases that value in a meaningful way).

Experimental research must use rigorous sampling techniques and hypothesis tests in order for its results to be statistically acceptable and generalizable (19).

In some areas of Computer Science it is hard to make experimental research, either because it is difficult to manipulate or measure variables, or because of the time those interventions might take. In those cases, one can make a *gathering research*, in which existing data will be searched directly in the environment, through observations, measurement, questionnaires and interviews. After tabulation of this information, the researcher can come to conclusions on causes and effects.

Research-action (20) is less common in Computer Science, but it is possible. In this kind, the researcher interacts with his subjects involving himself in the research field in a participative way, searching for a specific result.

V. SCIENCE AND TECHNOLOGY

In Computer Science, the terms science and technology are almost always so connected that many individuals tend not to be able to separate them.

Nevertheless, *Science* is the search for knowledge and explanations. Science builds theories to explain observed facts. *Technology*, on the other hand, is the application of knowledge in practical activities, such as, for example, industrial and economical activities.

Unlike science, the technique does not intend to explain the world. It is practical and exists to change the world, not to create theories about it.

Several dissertations and thesis in Computer Science, as well as several articles, still are strongly characterized as technical presentations. Systems, prototypes, frameworks, architectures, models, processes: all those constructions are techniques and not necessarily Science.

For a work to be effectively scientific, it is necessary that the information in it explain a little more on the reasons why things work as they do. If so, Science can be present in ideas presented in a work. Usually there is a problem identified for which there is no satisfactory solution. There is also an hypothesis, that is, an idea that might be tested to solve the problem fully or partially. The work must show that the idea in question really is valid, employing the constructions of the scientific method that apply.

The work must be full of evidences that new knowledge is actually being presented. Among those evidences, we can mention case studies, comparative bibliographic research, experimental research, etc. Besides, it is usual to show that the new ideas can be applied practically as a tool, algorithm, prototype, process, etc. This way, these artifacts can and should be presented as elements to which an idea in incorporated, gaining life and practical application, that is, fulfilling its technical vocation. Nevertheless, the dissertation, thesis or article should not be about the artifact, but about the ideas it incorporates.

In Computer Science there are still works in different levels of scientific maturity. In the more naive level stand the works that only present a new technique or tool and a discussion on its advantages and improving points. Usually, there is neither research hypothesis nor comparison to related works.

Works a little more mature present some kind of comparison with other artifacts and show that the new artifact has some characteristics that the previous ones lack.

Works even more advanced present systematic and quantitative comparisons, with well defined metrics and repeatable and verifiable experiments. In the best scenario, those experiments are made with data and tests obtained through internationally accepted benchmarks.

Finally, scientific work with the highest degree in Computer Science, besides the empirical evidence, will present a theory consistent with the observations that can explain the phenomena and is coherent to the widely accepted body of knowledge.

VI. FINAL REMARKS

Research in Computer Science, no matter its sub area, must take the researcher in search of a contribution to the knowledge and not only to the presentation of new technologies (even though these are relevant and important, they are not necessarily science).

Research must be performed accordingly to the principles of scientific method. Observations and experiments must be obtained in the most rigorous and repeatable form, whenever possible. Scientific initiation, masters and doctorate tasks must, therefore, produce Science in order to be considered as scientific research.

A research work whose goal cannot be summarized in a few sentences that explain which new knowledge was produced usually has conception problems.

Usually, a scientific work is structured over a research problem that needs to be solved (a question not yet answered satisfactorily) and a hypothesis (a possible answer to be evaluated). If the hypothesis is confirmed by empirical or formal evidence, then the scientist must present a theory that explains it, usually as an extension or alternative to a previous theory.

A successful research probably will start with an adequate bibliographic review for the main concepts on the field of study to be apprehended (when the researcher is a beginner, that is, a student) and for the latest advancements on the field to be known. After this review, when the researcher is capable of recognizing the important unanswered questions, he may begin the work, for example, with a case study for an exploratory research to shed new light over questions and problems. After formulating an hypothesis to solve the problem and a theory that explains why that hypothesis works, the researcher may apply adequate empirical methods to convince the others that his/her hypothesis is correct given the tenets of the scientific method, that is, that it is coherent with the current body of knowledge and that it is sufficiently simple to be adequate by the principle of Occam's Razor.

It is evident that scientific research cannot be defined as a recipe to be followed blindly in order to achieve the expected results. Nevertheless, it is expected that it will always follow certain criteria such as those presented in this article to be objective, that is, for others to accept its results as valid independently of their opinions and preferences.

More information on how to develop scientific research on Computer Science can be found on the author's book (21).

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