Computing Curricula: Teaching Theory of Science to Computer Science Students

(Science Education / Curriculum, Research and Development)

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Abstract

An ideal Science for the existing Theory of Science (Popper, Carnap, Kuhn, Chalmers) is *Physics*. Not many modern Sciences conform to that ideal, however. Philosophy of Science (Theory of Science) as it is today is not of much help when trying to understand e.g. Computer Science. There is an urgent need to broaden the Theory of Science perspective in order to match the present situation within the area, as well as to help its further development.

Computer Science has its basis in Logic and Mathematics, and in many cases its theoretical and experimental research methods follow patterns of classical scientific fields of Logic/Mathematics and Natural Sciences. On the other hand, computer modeling and simulation which is specific for the discipline and it is rapidly growing in importance, applied to computers, as well as to other scientific and artistic fields, hardly corresponds to traditional definition of scientific method.

Situation gets even more complicated in the field of Intelligent Systems (Artificial Intelligence, AI). AI is generally associated with Computer Science, but it has many important links with other fields such as Mathematics, Psychology, Cognition, Biology, Behavioral and Brain Sciences, Linguistics and Philosophy, among others.

This paper addresses the need for paradigm shift within Theory of Science. It shows that it is essential for students of Computer Science to not only acquire the concepts from Theory of Science within its conventional domain, but also widen the perspective and see the field in its context of other scientific traditions.

Introduction

It is not so obvious, as the name might suggest that the Computer Science qualifies as "Science" in a sense traditional theory of Science [1-4] defines the term. Computer Science (CS) is a young discipline and necessarily starting from the outset very different from Mathematics, Physics and similar "classic" Sciences, that all have their origins in the Philosophy of ancient Greece.

Emerging in modern time (in 1940's the first electronic digital computer was built), CS has necessarily other already existing Sciences in the background. Computer Science draws its foundations from a wide variety of disciplines [5], [6], [7]. Study of Computer Science consequently requires utilizing concepts from many different fields. Computer Science integrates theory and practice, abstraction (general) and design (specific).

The historical development has led to emergence of a big number of Sciences that in our time communicate more and more not only because the means of communication are becoming very convenient and effective, but also because a need increases for getting a holistic view of our world that is presently strongly dominated by reductionism.

1. What Is Computer Science?

According to the present view, Computer Science can be situated in a broader context of Computing in the following way (see Figure 1) [8].

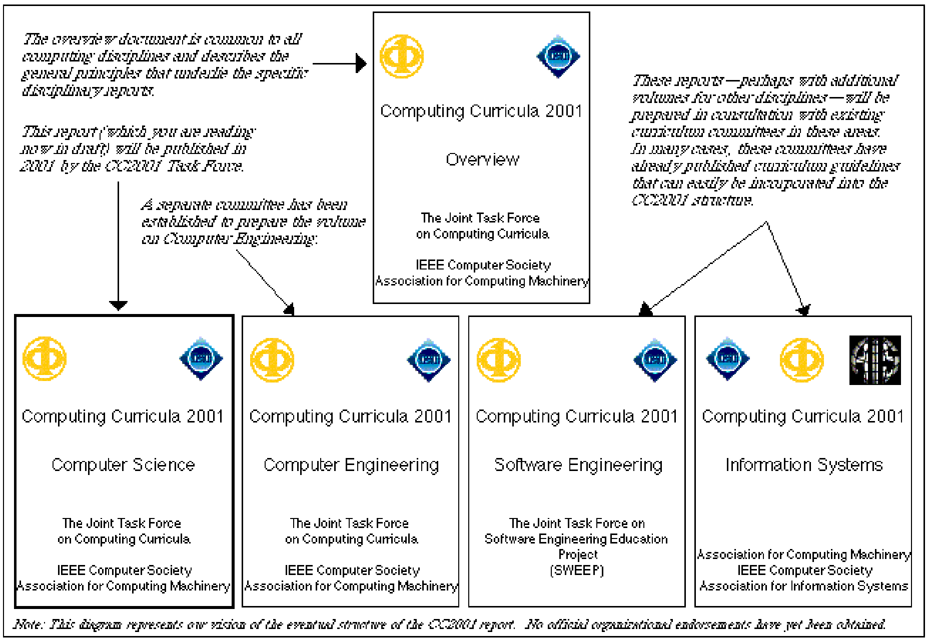

Figure 1 Computer Science within the field of Computing

The discipline of Computing thus encompasses Computer Science, Computer Engineering, Software Engineering and Information Systems.

The German and French use the respective terms "Informatik" and "Informatique" to denote Computer Science. It is interesting to observe that the British term "Computer Science" has an empirical orientation, while the corresponding German and French term “Informatics” has an abstract orientation. This difference in terminology appears to support the view that the nineteenth-century characters of British empiricism and continental abstraction have persisted.

The view that information is the central idea of Computer Science is both scientifically and sociologically indicative. Scientifically, it suggests a view of Computer Science as a generalization of information theory that is concerned not only with the transmission of information but also with its transformation and interpretation. Sociologically, it suggests an analogy between the industrial revolution, which is concerned with the utilizing of energy, and the computer revolution, which is concerned with the utilizing of information.

It is argued in [9] that Computer Science was dominated by empirical research paradigms in the 1950s, by mathematical research paradigms in the 1960s and by engineering oriented paradigms beginning with the 1970s.

The diversity of research paradigms within Computer Science may be responsible for the divergences of opinion concerning the nature of Computer Science research.

Sub-areas of Computer Science

Dijkstra said that to call the field "Computer Science" is like calling surgery "Knife Science". He noted that departments of Computer Science are exposed to a permanent pressure to overemphasize the "Computer" and to underemphasize the "Science". This tendency matches the inclination to appreciate the significance of computers solely in their capacity of tools.
According to [8], sub-areas of Computer Science curricula are:

1. Discrete Structures
2. Programming Fundamentals
3. Algorithms and Complexity
4. Programming Languages
5. Architecture and Organization
6. Operating Systems
7. Net-Centric Computing
8. Human-Computer Interaction
9. Graphics and Visual Computing
10. Intelligent Systems
11. Information Management
12. Software Engineering
13. Social and Professional Issues
14. Computational Science and Numerical Methods

As Computer Science develops, the list is expanding. Fields 7, 8 and 9 e.g. are new compared to predecessor [17](Denning report) list.

2. Scientific Methods of Computer Science – The Traditional View

What is specific for CS is that its objects of investigation are artifacts (computer-related phenomena) that change concurrently with the development of theories describing them and simultaneously with the growing practical experience in their usage.

A computer from the 1940s is not the same as a computer from the 1970s, which in its turn is different from a computer in 2002. Even the task of defining what a computer is in the year 2002 is far from trivial!

With respect to methodology, Computer Science can be divided into Theoretical, Experimental and Simulation CS.

2.1 Theoretical Computer Science

Concerning Theoretical Computer Science, which adheres to the traditions of Logic and Mathematics, we can conclude that it follows the classical methodology of building theories as logical systems with stringent definitions of objects (axioms) and operations (rules) for deriving/proving theorems.

Logic is important for computing not only because it forms the basis of every programming language, or because of its investigating into the limits of automatic calculation, but also because of its insight that strings of symbols (also encoded as numbers) can be interpreted both as data and as programs.

Theory creates methodologies, Logics and various semantic models to help design programs, to reason about programs, to prove their correctness, and to guide the design of new programming languages.

However, CS theories do not compete with each other as to which better explains the fundamental nature of information. Nor are new theories developed to reconcile theory with experimental results that reveal unexplained anomalies or new, unexpected phenomena, as in Physics. In Computer Science there is no history of critical experiments that decide between the validity of various theories, as there are in physical Sciences. The basic, underlying mathematical model of digital computing is not seriously challenged by theory or experiments.

In Computer Science, results of theory are judged by the insights they reveal about the mathematical nature of various models of computing and/or by their utility to the practice of computing and their ease of application. Do the models conceptualize and capture the aspects computer scientists are interested in, do they yield insights in design problems, and do they aid reasoning and communication about relevant problems?

The design and analysis of algorithms is a central topic in theoretical Computer Science. Methods are developed for algorithm design, measures are defined for various computational resources, tradeoffs between different resources are explored, and upper- and lower-resource bounds are proved for the solutions of various problems. In the design and analysis of algorithms measures of performance are well defined, and results can be compared quite easily in some of these measures (which may or may not fully reflect their performance on typical problems). Experiments with algorithms are used to test implementations and compare their "practical" performance on the subsets of problems considered important.

Theoretical Computer Science seeks to understand both the limits of computation and the power of computational paradigms. Theoreticians also develop general approaches to problem solving. Some of the main methodological themes in Theoretical Computer Science (inherited from Mathematics) are *iteration, induction and recursion*.

One of theoretical Computer Science's most important functions is the distillation of knowledge acquired through conceptualization, modeling and analysis. Knowledge is accumulating so rapidly that it must be collected, condensed and structured in order to get useful.

2.2 Experimental Computer Science

The subject of inquiry in the field of Computer Science is information rather than energy or matter which is characteristic of classical Sciences. However, it makes no difference in the applicability of the traditional scientific method. To understand the nature of information processes, computer scientists must observe phenomena, formulate explanations and theories, and test them.

Experiments are used both for theory testing and for exploration [10], [11], [12]. Experiments test theoretical predictions against reality. A scientific community gradually accepts a theory if the known facts within its domain can be deduced from the theory, if it has withstood experimental tests, and if it correctly predicts new phenomena. Conditio sine qua non of any experiment is repeatability/reproducibility. Repeatability ensures that results can be checked independently and thus raises confidence in the results.

Nevertheless, there is always an element of uncertainty in experiments and tests as well: To paraphrase Edsger Dijkstra, an *experiment can only show the presence of bugs (flaws) in a theory, not their absence*. Scientists are keenly aware of this uncertainty and are therefore ready to disqualify a theory if contradicting evidence shows up.

A good example of theory falsification in Computer Science is the famous Knight and Leveson experiment, [13] which analyzed the failure probabilities of multiversion programs. Conventional theory predicted that the failure probability of a multiversion program was the product of the failure probabilities of the individual versions. However, John Knight and Nancy Leveson observed that real multiversion programs had significantly higher failure probabilities. In fact, the experiment falsified the basic assumption of the conventional theory, *namely that faults in different program versions are statistically independent*.

Experiments are also used in areas to which theory and deductive analysis do not reach. Experiments probe the influence of assumptions, eliminate alternative explanations of phenomena, and unearth new phenomena in need of explanation. In this mode, experiments help with induction: deriving theories from observation.

Artificial neural networks (ANN) are a good example of the explorative mode of experimentation. After ANN having been discarded on theoretical grounds, experiments have demonstrated properties better than those theoretically predicted. Researchers are now developing better theories of ANN in order to account for these observed properties [12].

Experiments are made in many different fields of CS such as search, automatic theorem proving, planning, NP-complete problems, natural language, vision, games, neural nets/connectionism, and machine learning. Furthermore, analyzing performance behavior on networked environments in the presence of resource contention from many users is a new and complex field of experimental Computer Science. In this context it is important to mention Internet.

Yet, there are plenty of Computer Science theories that haven't been tested. For instance, functional programming, object-oriented programming, and formal methods are all thought to improve programmer productivity, program quality, or both. Yet, none of these obviously important claims have ever been tested systematically, even though they are all 30 years old and a lot of effort has gone into developing programming languages and formal techniques [12]. One important reason is the difficulty in devising quantitative methods to measure programmer productivity, program quality and alike. *Here the human aspects are obviously an inseparable part of the problem.*

Even some other fields of Computing such as Human-Computer Interaction and parts of Software Engineering have to take into consideration humans (users, programmers) in their models of the investigated phenomena.

The consequence of widening the problem domain to include humans is introduction of a "soft" empirical approach more characteristic for Humanities and Social Sciences, with methodological tools such as interviews and case studies.

2.3 Computer Simulation

In recent years computation which comprises computer-based modeling and simulation, see Figure 2, has become the third research methodology within CS, complementing theory and experiment.

Computational Science has emerged, at the intersection of Computer Science, applied Mathematics, and Science disciplines in both theoretical investigation and experimentation.

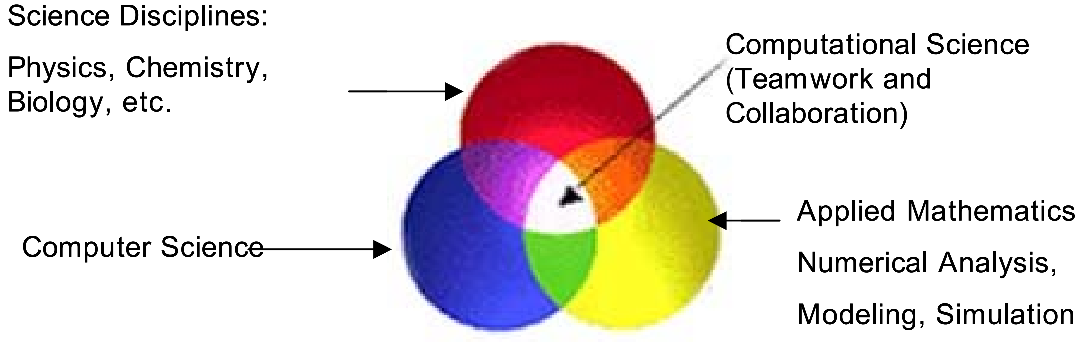

Figure 2 Computational Science

Mastery of Computational Science tools, such as modeling with 3D visualization and computer simulation, efficient handling of large data sets, ability to access a variety of distributed resources and collaborate with other experts over the Internet, etc. are now expected of university graduates, not necessarily Computer Science majors. Those skills are becoming a part of scientific culture.

Today, computing environments and methods for using them have become powerful enough to tackle problems of great complexity. With the dramatic changes in computing, the need for dynamic and flexible Computational Science becomes ever more obvious.

Computer simulation makes it possible to investigate regimes that are beyond current experimental capabilities and to study phenomena that cannot be replicated in laboratories, such as the evolution of the universe. In the realm of Science, computer simulations are guided by theory as well as experimental results, while the computational results often suggest new experiments and theoretical models. In engineering, many more design options can be explored through computer models than by building physical ones, usually at a small fraction of the cost and elapsed time.

Even though the term "simulation" is old, it reflects the way in which a good deal of Science will be done in the next century. Scientists will perform computer experiments in addition to testing scientific hypotheses by performing experiments on actual physical objects of investigation. One can say that simulation represents a fundamental discipline in its own right regardless of the specific application.

Computational Science involves the use of computers ("supercomputers") for visualization and simulation of complex and large-scale phenomena. Studies involving N body simulations, molecular dynamics, weather prediction and finite element analysis are within the thrust of Computational Science. If Computer Science has its basis in computability theory, then Computational Science has its basis in computer simulation.

Some of the key focus areas for simulation are: Chaos and Complex Systems, Virtual Reality, Artificial Life, Physically Based Modeling and Computer Animation.

The computing power of present day machines enables us to simulate an increasing number of phenomena and processes; especially the non-linear ones. Modern graphic capabilities makes this method a very attractive and user friendly.

3. Bird's Eye View of Science

The whole is more than the sum of its parts.
Aristotle, Metaphysica

In order to be able to talk about Computer Science, let us take a closer look at the very definition of Science…

Saying "Science" we actually mean plurality of different Sciences. Different Sciences differ very much from each other. The definition of Science is therefore neither simple nor unambiguous. See [14] and [15] for several possible classifications. For example, History and Linguistics are often but not always catalogued as Sciences.

3.1 Classical Sciences

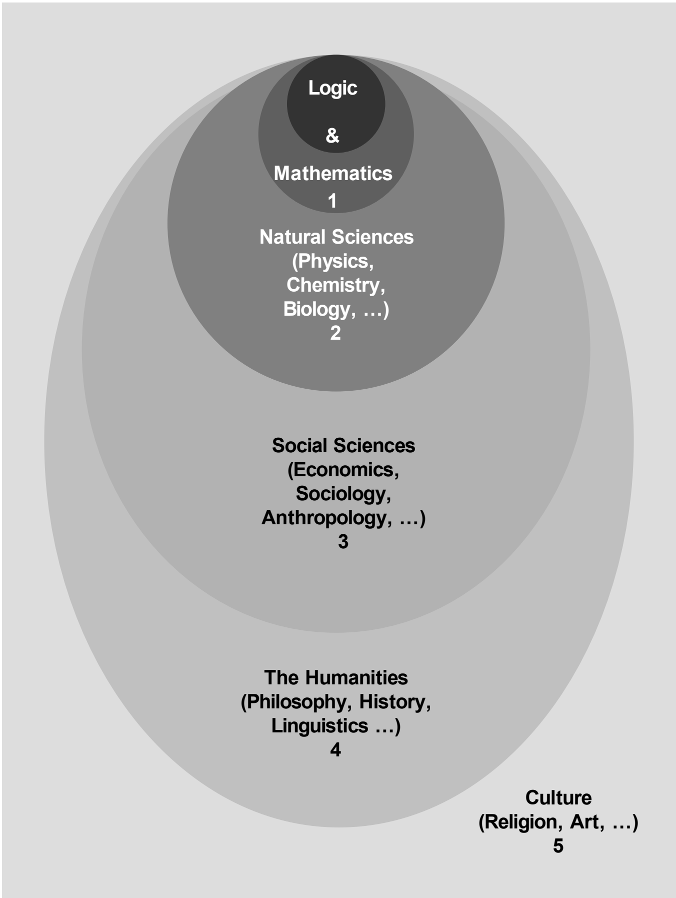

Figure 3 What is Science?

The figure above suggests that traditional Sciences have *specific areas of validity*. The Logic and Mathematics (the most abstract and at the same time the most exact Sciences) are more or less important part of every other Science. They are very essential for Physics, less important for Chemistry and Biology[1], and their significance continues to decrease towards the outer regions of our scheme.

The logical reasoning as a basis of all human knowledge is of course present in every kind of Science as well as in Philosophy.

The figure above may be seen in analogy with a microscope view. With the highest resolution we can reach the innermost region. Inside the central region Logic is not only the tool used to make conclusions. It is at the same time the object of investigation. Even though big parts of Mathematics can be reduced to Logic (Frege, Rusell and Whitehead) the complete reduction is impossible.

On every step of zooming out, the inner regions are given as prerequisites for the outer ones. Physics is using Mathematics and Logic as tools, without questioning their internal structure. In that way information about the deeper structure of Mathematics and Logic is hidden looking from the outside. In much the same way, Physics is a prerequisite for Chemistry that is a hidden level inside Biology etc.

The basic idea of Figure 3 is to show in a schematic way the relation between the three main groups of Sciences (Logic & Mathematics, Natural Sciences and Social Sciences) as well as the connections to thought systems represented by the Humanities. Finally the whole body of human knowledge, scientific and speculative is immersed in and impregnated by the cultural environment.

3.2 The Scientific Method

The scientific method is the logical scheme used by scientists searching for answers to the questions posed within Science. Scientific method is used to produce scientific theories, including both scientific meta-theories (theories about theories) as well as the theories used to design the tools for producing theories (instruments, algorithms, etc). The simple version looks something like this (see also Figure 4):

1. Pose the question in the context of existing knowledge (theory & observations).
2. Formulate a hypothesis as a tentative answer.
3. Deduce consequences and make predictions.
4. Test the hypothesis in a specific experiment/theory field.
5. When consistency is obtained the hypothesis becomes a theory. The results have to be published.
6. Theory is subject to process of ”natural selection” among competing theories. A winning theory is becoming a new framework within which observations/theoretical facts are explained and predictions are made. The process can start from the beginning, but the state 1 has changed to include the new theory/improvements of old theory.

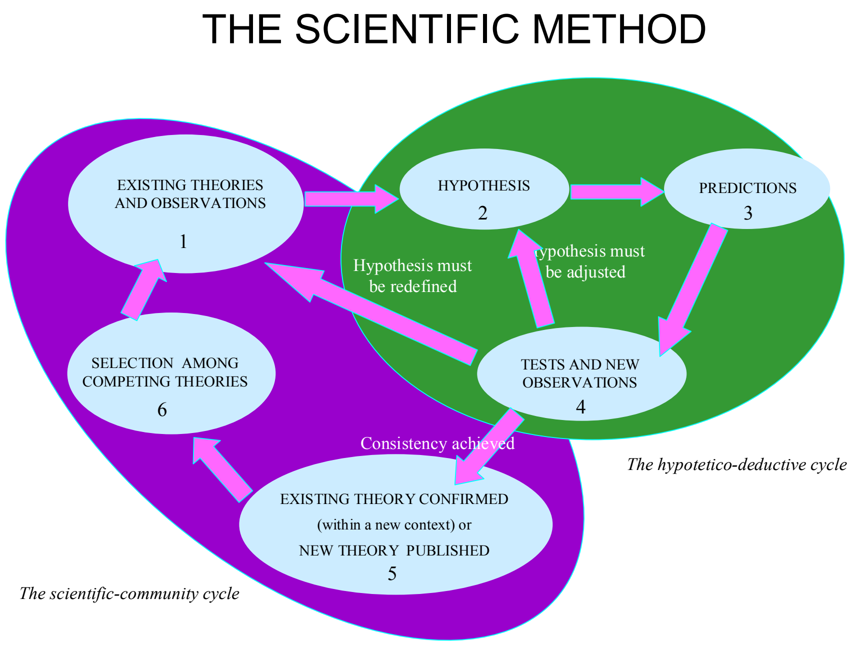

Figure 4 Diagram describing iterative nature of the hypothetico-deductive method

It is crucial to understand that the Logic of Science is *recursive*. Prior to every observation/experiment/theoretical test there is a hypothesis (2) that has its origins in the pre-existing body of knowledge (1). Every experimental/observational result has a certain world-view built-in. Or, to say it by Feyerabend [16], every experimental data is "theory-contaminated".

The scheme of the scientific method in Figure 4 is without a doubt an abstraction and simplification. Critics of the hypothetico-deductive method would argue that there is in fact no such thing as "the scientific method" [16]. By the term "the scientific method" they actually mean the concrete set of rules defining how to proceed in posing new relevant questions and formulating successful hypotheses. Of course, no such magic recipe exists!

The important advantage of the scientific method is that it is impartial:[2] one does not have to believe a given researcher, one can (in principle) repeat the experiment/theoretical derivation and determine whether certain results are valid or not (the hypotetico-deductive cycle of Figure 4). The question of impartiality is closely related to openness and universality of Science, which are its fundamental qualities. A theory is accepted based in the first place on the results obtained through logical reasoning, observations and/or experiments. The results obtained using the scientific method have to be reproducible.

All scientific truths are provisional. But for a hypothesis to get the status of a theory it is necessary to win the confidence of the scientific community (the scientific community cycle of Figure 4).

3.3 Sciences Belonging to Several Fields

The development of human thought parallel to the development of human society has led to an emergence of Sciences that do not belong to any of the classic types we have described earlier, but rather share common parts with several of these.

Many of the modern Sciences are of interdisciplinary, eclectic type. It is a trend for new Sciences to search their methods and even questions in very broad areas. It can be seen as a result of the fact that the communications across the borders of different scientific fields are nowadays much easier and more intense than before.

Computer Science for example includes the field of Artificial Intelligence that has its roots in Mathematical Logic and Mathematics but uses Physics, Chemistry and Biology and even has parts where medicine and Psychology are very important.

We seem to be witnessing an exciting paradigm shift:

We should, by the way, be prepared for some radical, and perhaps surprising, transformations of the disciplinary structure of Science (Technology included) as information processing pervades it. In particular, as we become more aware of the detailed information processes that go on in doing Science, the Sciences will find themselves increasingly taking a meta-position, in which doing Science (observing, experimenting, theorizing, testing, archiving,) will involve understanding these information processes, and building systems that do the object-level Science. Then the boundaries between the enterprise of Science as a whole (the acquisition and organization of knowledge of the world) and AI (the understanding of how knowledge is acquired and organized) will become increasingly fuzzy.

Allen Newell, Artif. Intell. 25 (1985) 3.

Here we can find a potential of the new synthetic (holistic) worldview that is about to emerge in the future.

4. Science, Research, Technology

The traditional Aristotelian sharp distinction between Science and Technology seem to fail when applied to contemporary Science, because the underlying concepts have changed over time. Today's Science is much more complex and heterogeneous than Science of the Aristotle’s time (that emerged as a part of Philosophy).

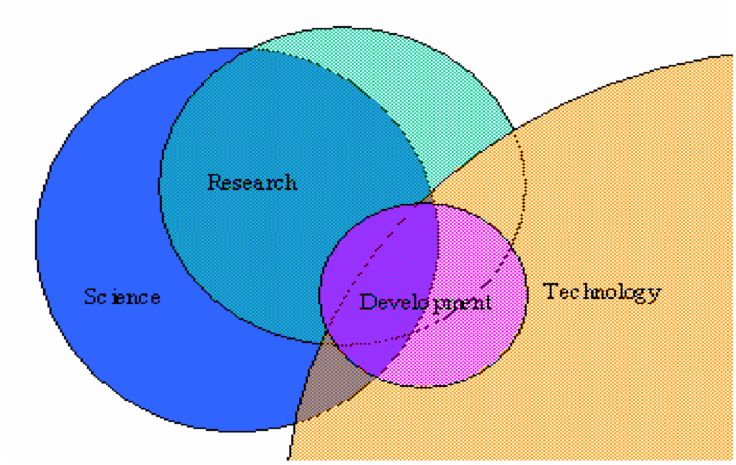

Figure 5 Relations between Science, Research, Development and Technology

The figure above illustrates the fact that there is an essential overlap between contemporary Science, Research, Development and Technology.

That is one of the reasons why Philosophy of Science is in vital need of a deeper, more realistic understanding of contemporary Sciences.

5. Problem with the Traditional View: In what way is CS a Science? AI example

Let us take as an example Artificial Intelligence (AI) that is a branch of Computer Science according to Computing Curricula [8].

AI is a discipline with two distinct facets: Science and Engineering which is the case for CS in general. The scientific facet of AI attempts to understand intelligence in humans, other animals information processing machines and robots. The engineering facet attempts to apply such knowledge in designing new kinds of machines.

AI is generally associated with Computer Science, but it has many important links with other fields such as Maths, Psychology, Cognition, Biology, Linguistics and Philosophy, Behavioral and Brain Sciences among many others. Our ability to combine knowledge from all these fields will ultimately benefit our progress in the quest of creating an intelligent artificial being.

The scientific facet, which has motivated most of the pioneers and leaders in the field, is concerned with two main goals (a) attempting to understand and model the information processing capabilities of typical human minds, (b) attempting to understand the general principles for explaining and modelling intelligent systems, whether human, animal or artificial. This work is often inspired by research in Philosophy, Linguistics, Psychology, NeuroScience or Social Science. It can also lead to new theories and predictions in those fields.

The engineering facet, which motivates most of the funding agencies and (consequently) younger researchers, is concerned with attempting to design new kinds of machines able to do things previously done only by humans and other animals and also new tasks that lie beyond human intelligence.

There is another engineering application of AI: using the results of the scientific facet to help design machines and environments that can help human beings. This may, including the production of intelligent machines.

Table 1

Sub-fields of AI	Related Fields
Perception, especially vision but also auditory and tactile perception, and more recently taste and smell.	Philosophy, Cognition, Psychology, Mathematics, Biology, Medicine, Behavioral Sciences, Brain Sciences
Natural language processing, including production and interpretation of spoken and written language, whether hand-written, printed, or electronic throughout (e.g. email).	Linguistics, Psychology, Philosophy, Logic, Mathematics, Behavioral Sciences, Brain Sciences
Learning and development, including symbolic learning processes (e.g. rule induction), the use of neural nets (sometimes described as sub-symbolic), the use of evolutionary algorithms, self-debugging systems, and various kinds of self-organization.	Logic, Philosophy, Mathematics, Biology, Medicine, Behavioral Sciences, Brain Sciences
Planning, problem solving, automatic design: given a complex problem and a collection of resources, constraints and evaluation criteria create a solution which meets the constraints and does well or is optimal according to the criteria, or if that cannot be done propose some good alternatives.	Logic, Mathematics, Philosophy
Robotics: is sometimes studied for the purpose of producing new kinds of machines, and sometimes because designing complete working robots provides a test bed for integrating theories and techniques from various sub-areas of AI, e.g. perception, learning, memory, motor control, planning, etc. I.e. it is a context for exploring ideas about complete systems.	Philosophy, Cognition, Psychology, Mathematics, Biology, Medicine, Behavioral Sciences, Brain Sciences

Table 1 suggests how complex the field of AI is, and how many connections to other scientific and further cultural phenomena it has. For a more comprehensive survey see [20].

6. Conclusions

Computer Science is a new field and its object of investigation (Universe) is a computer, which is an ever-developing artifact, the materialization of the ideas that try to structure knowledge and the information about the world, including computers themselves. Already the subject of investigation of CS suggests that the traditional Science paradigm may not apply for CS.

However, in spite of all characteristics that differ the young field of Computer Science from several thousand years old Sciences such as Mathematics, Logic, and Natural Sciences we can draw a conclusion that Computer Science contains a critical mass of scientific features to qualify as a Science. CS has a traditional core of "hard" (exact) Sciences.

From the principal point of view it is important to point out that all modern Sciences are very strongly connected to Technology. This is very much the case for Biology, Chemistry and Physics, and even more the case for Computer Science.

The engineering parts in the Computer Science have both connection to the hardware (physical) aspects of computer and software.

The important difference is that the *computer* (the physical object that is directly related to the theory) is not a focus of investigation (not even in the sense of being the cause of certain algorithm proceeding in certain way) but it is rather *theory materialized, a tool always capable of changing in order to accommodate even more powerful theoretical concepts*.

Computer Science in general and especially its field of Intelligent Systems show methodological and thematic features that are essentially different from Physics and other traditional Sciences. There are two alternatives at present:

1. deny the Computer Science the scientific status

2. accept CS as Science of a special eclectic kind that incorporates both "hard" and "soft" scientific traditions and even inherits common questions, themes and methods from such fields as Linguistics, Psychology, Anthropology, Philosophy or even other Arts.

Actually, taking into account the present development within different scientific fields, the above dilemma appears rhetoric. Science is simply not the same thing it was in the last century.

For Computer Science students in order to be able to perceive the holistic view of their field it is essential to be educated in Theory of Science that takes into account reality of contemporary Science. The time is ripe for paradigm shift in Philosophy of Science!

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[1] This is obviously a gross simplification. For e.g. computational biology and bioinformatics is mathematics the very essence of the field!

[2] *Impartial* is used here as synonymous for *objective, unbiased, unprejudiced, and dispassionate***.** Note, however that this is the statement about *science, not about individual scientists* whose attitude to their pursuit is on the contrary as a rule indeed passionate**.** The fact that science is shared by the whole scientific community results in theories that are in a great extent *free from individual bias***.** On the other hand the whole of scientific community use to share *common paradigms***,** which are the very broad concepts deeply rooted in the *culture. Paradigm shift is a process that occurs in a very dramatic way, partly because of cultural (not strictly rational) nature of paradigm, (Kuhn).*