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# Towards Adjusting Informatics Education to Information Era

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# Towards Adjusting Informatics Education to Information Era

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## Abstract

Since the very beginning of the modern computing era, the scientific and educational community in informatics has been in a continuous search for a proper philosophy, viewpoints, aims, contents, methods and tools. Advances in software, communication and hardware have played by that search the most influencing role, with theory advances having only secondary and declining impacts — in spite of the remarkable success of theory, quite well recognized by the community at large.

The recent developments and advances in computing, communication and informatization of the society point out strongly, that

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horizons of the field are much broader, and its impacts on the society are far larger than anticipated even by strong optimists . This brings new and strong impetus to reconsider again the aims, scope, contents and methods of education in informatics and in other areas.

In the paper we analyze: (a) needs to change education in informatics; (b) the current situation in informatics education; (c) a framework for a new approach; (d) steps to be done; (3) two case studies.

# 1 Why we need to change the education in informatics

There are two main reasons why the aim, contents and methods of informatics education should be challenged nowadays. Both of them have their roots in important recent developments as well as in growing experiences with the results of the current educational approaches and methods. The first one is associated with the emerging global/social needs informatics education is to respond to. The second one is related to the important internal developments within informatics itself.

## 1.1 New global and social developments and needs to which informatics education has to respond to

Informatization of the society is having a profound impact not only on tools mankind can use to solve its local problems and to meet its current needs but also on new global aims and problems the mankind can approach. This brings in turn new aims and requirements for informatics itself, and especially for its education, have to try to meet.

### 1.1.1 New global role of science and education.

After the remarkable impact of science and technology during the Second World War, the very basic philosophy about the role of science and research in the postwar period, and how they should be supported and organized, was developed in [Bus45]. This positional document established a doctrine how to view and support science and technology research that was followed by the most developed countries since then. The document was based on a belief in the enormous power of science, correctly, and created space for a large part of science and research to develop according to their needs and views. The other part of science and research have been tied up by the magic word *defence* and practically everything that could be put, somehow, under this umbrella, was almost blindly supported. Except the defence oriented part of science and research, the rest of society was given the chance and responsibility to utilize the outcomes of science. The doctrine was based on a belief that it is enough to care, for science and research supporters, that there are excellent results in science and technology and society will surely benefit out of it proportionally to the investment into the science and technology. This important part of the original philosophy on which the role of science in the society was based on did not turn out as well as expected. In addition, the enormous emphasis on science and research not only put aside education, especially at the "top research universities", but also adjusted its aims and methods to serve primarily to science and research needs.

[Gru93] represents an attempt to reevaluate the original philosophy on which science and technology have been based for almost 50 years and to outline a new role for science and technology in the society in general and propose new ways science should be supported and managed; with *national wealth* as a new magic word.[1] Even if some particular suggestions of that document can be questioned, it is getting increasingly clear that a significant part of science will have to care much more about its aims and usability of its outcomes. *Technology transfer* is the related key word. In addition, it is also getting increasingly clear that high level of education and educational priorities have to be established again. Informatization of society not only increases needs on the overall education of society but also makes a life-long continuing education and a preparation for it a necessity and a top priority.

### 1.1.2 Tasks of informatics as of a new fundamental and global methodology.

It is evident that in the course of time not all components of our society have succeeded to develop sufficiently well. Interesting enough, the degree of the development of various areas of society depends much on the

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[1] This includes such important tasks to take care of as *environmental protection.*

fact whether a given area had at its disposal a sufficiently sound methodology to deal with the problems that needed to be solved.

>From this point of view science and technology, and related areas, as medicine, have been developing fast due to the fact that they had two sound and complementary methodologies to their disposal: experimental methodology and theoretical methodology. However, also these two methodologies, though in principle very fundamental and successful, have been lacking the capability for dealing with the complex problems in an appropriate way.

Informatics, including information and communication technology, can be seen as providing science, technology, and actually all areas of society, with a new fundamental and extremely powerful methodology (see Section 3.4). For some areas, as for science and technology, this methodology is a third methodology, which in combination with two old methodologies qualitatively increases their potential. Of the large importance is also the fact that this new methodology has a global character — can be used to deal with problems in all areas of functioning of society — and presents a new, and for some areas actually the only one sound enough methodology so far, for dealing with complex problems in a powerful way.

There are several reasons why informatics should play a crucial role in all main programs of society. The main one is related to the fact that the major problems of mankind that need to be solved are of global and very complex character[2] and information processing and communication technology is seen as the main current technology with a potential to help to deal successfully with such global problems. It is also believed that progress in the area of information processing and communication technology will determine the rate of progress in all major critical technology areas.

With such an enormous role of informatics as a new (and sometimes even the single) methodology, it is of prime importance for informatics to develop fast and in depth this new methodology, and to concentrate its education, whether in informatics itself or in other areas, on presenting fundamentals and methods in a sufficiently sound and complete way.

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[2] For example, modelling and prediction of the behaviour of the earth system (including the climate, hydrological cycle, ocean circulation, growth of biosphere,and gas exchange between the atmosphere and the terrestrial and oceanic biota.)

### 1.1.3 Central role of the informatics education in all fields of education.

With informatics as perhaps the main methodology of the near future, it is of key importance for all areas of education to achieve that graduates understand the potentials of this new methodology and are able to apply it as needed. The existence of theoretical methodology resulted in having mathematics education as an indispensa ble ingredient for almost all science, technology, business, ... oriented areas of education. In a similar way laboratories have been used to a large extent to teach and learn fundamentals of the experimental methodology.

Informatics as a methodology is very complex and it is only natural that a search for the ways how to teach this methodology are in the beginnings. Of importance it is to realize that this methodology is often identified only with some of its (software a nd hardware or communication) tools — and sometimes with very elementary tools only. At the same time this methodology develops so fast that even specialists can hardly follow all new developments in their area of expertise. Under these circumstances it is one of the main tasks of informatics to help other educational areas to see the potential of this new methodology and the ways this methodology should be understood and managed by their graduates.

### 1.1.4 Increasing emphasis on multi-disciplinary approaches.

Needs to support inter-disciplinary approaches and to focus education along these lines in general have been emphasized already for a while. With informatics providing a powerful methodology and tools to facilitate multi-disciplinary approaches the possibilities to pursue and develop this idea has a much more real base. At the same time, informatics itself should try to utilize fully the power of this new and multi- inter-disciplinary borders-bridging-methodology. Education in informatics has there fore to adjust to these quite new aims.

## 1.2 Maturing of the discipline

As an academic discipline informatics is clearly coming of the age. It is also a discipline with an extraordinarily fruitful interaction between academia and industry. This allows and also requires that also its ed ucation matures and increases quality of its graduates.

## 1.3 New internal developments — their potentials and impacts.

Several recent internal developments in informatics have much contributed to the needs to change the view of the field, and of its potentials and impact on society.

**Global networking:** The impacts of global networks are, even in their very beginnings, breathtaking and keep changing radically practically all aspects of society, including education. Information is becoming more and more valuable and more easily available commodity and global methods of obtaining, processing, communicating and presenting information are getting rapidly of an increasing importance.

**Cryptographic methods:** Not only global networking but also a variety of local and distributed information processing systems, such as smart cards, would hardly be possible without modern cryptographic techniques. Security of communication, data and authentication are the key issues of the information era. In addition to that, basic cryptographic concepts have turned out to be of large importance for various theoretical considerations in informatics and even for foundations of computing.

**Visualization and animation:** Enormous progress, that has been achieved, step by step, in the area of image generation, processing, transformation and in visualization and animation, has and it is expected to have, far reaching consequences on almost all areas of human activities.[3]

**Multimedia:** The progress obtained in digitalization of all basic types of information and in recording, combining, modifying and presenting such information, in ever more qualitative ways, is bringing an important new quality concerning the power and impacts of information processing.

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[3] One can speak even about visualization of mathematics as an important methodology to deal with some mathematical problems — what a contrast to the views presented by the Bourbaki school.

**Continuously increasing computational power and storage capacities:** In spite of various pessimistic forecasts it seems now quite clear that the existing progress concerning performance of computing systems will continue still for quite a while and can be expected to reach a new quality.[4]

**New computing paradigms:** Several new computing paradigms (randomization, parallelism, distributiveness, interactions, approximations) have significantly changed our theoretical and also practical views on what is feasible and brought also radically new concepts of hard to foresee importance. Randomization turned out to be a very powerful tool, especially when combined with interactions. This, in addition, resulted in development of radically new approaches to such basic concepts of science as evidence (proof) and such basic problems of computing as program validation, self-correction and self-testing. Parallelism and distributiveness, enhanced with the power of global networking, and allow to solve problems far beyond those imaginable only few years ago. (For example, integer factoring using tens of thousands of computers [Cal96].)

**Quantum, molecular and brain computing:** Though the very basic results obtained so far in the area of quantum, molecular and brain computing are still far away from having a larger impact on practical computing, and it is even far from clear what will come out of it eventually, there are reasons to assume that very important steps have been done concerning the representation and processing of information in quantum and molecular environment, and that information processing space is much larger than considered so far with potentials that may go far beyond those of nowadays.

These changes in the development of informatics mark a critical junction for the discipline and it is rapidly becoming clear that, although informatics education has enjoyed some success in the last decades, the ways of the past will hardly lead to success in the future.

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[4] For example, the recent "world record" of 1.06 teraflops operations per second by Intel is already not too far from the performance 1.4 teraflops that seems to be sufficient to model atom explosion or to decode human genom.

# 2 Analysis of the current situation in informatics education

The ways politicians and scientists choose research directions, priorities, problems, educational aims, and methods depend in general much on the overall understanding of the scientific base of the field as well as of its long term role and contributions for the society.

## 2.1 Short history of views on informatics and its education

It is natural that in the absence of some deeper and long term valid understanding of the field the views of informatics have evolved as the field developed, especially its technological base and main applications. It is interesting and useful to summarize some of such views. They can be put into several categories (see also [Bra87, Bra88, BBr89, Bra90a, Bra90b]):

**Folklore views.** They are more or less elaborated:

- **Basic folklore:** Computer science as a science is the study of the scientific problems related to the design, behaviour and utilization of computers.
- **US-Congress report (1992):** Computer science is a systematic study of computing systems and computations. The body of knowledge resulting from this discipline contains theories for understanding computing systems and methods, design methodologies, algorithms and tools, methods for testing concepts, for analysis and verification, and knowledge representation and implementation.

**General views.** They represent attempts to make a deeper abstraction of the field. Especially the first one was quite a significant step forward and for a while an influential one.

- **Simon [Sim69]:** Computer science is a science of the artificial that studies artifacts and contributes to the design theory and to managing of complexity.
- **Hopcroft-Kennedy's report [Hke89]:** Computer science as a science is, in the narrow sense, the study of symbolic representations

and manipulations of these representations and, in a broader sense, the study of representations and manipulations of knowledge.

**Ullman's report [Ull92]:** Computer science is a discipline that deals with representation, implementation, manipulation and communication of information.

**Personal views:** They represent attempts to develop new views of the area on the base of strong personal experiences:

**Dijkstra[Dij89]:** Computing science is — and will always be — concerned with the interplay between mechanized and human symbol manipulation usually referred to as "computing" and "programming" respectively. It is located in the direction of formal mathematics and applied logic, but ultimately far beyond where those are now.

**Brauer[Bra91]:** Informatics is the (engineering) science concerned with theoretical analysis, organizational and technical design, and factual realization of (complex) systems of (autonomous, intelligent) individuals who communicate with each other and their environment where these systems are considered as subsystems of our human civilization which are to ameliorate the quality of life.

**Very general views.** They came first from cybernetics and later from artificial intelligence. Their common denominator was a too broad view of the field, without a sufficient justification and support by hard-core results, close to a science fiction. (In this connection it is worth of noting a remarkably well stated vision of A. P. Ershov about global networking and its impacts on society [Ers87].)

It is no wonder that the existence of such a variety of views, from which none seems to match fully the essence of such a key-to-be-area behind a so revolutionary informatization, led to the development of even more extreme positions. On one side there are attempts to be very cautious while coming up with a new definition (as it is the case of the report "Computing the future" [HLi92]). On the other side there are attempts to see informatics very differently. For example:

**Coy [Coy89]:** “Die Technikwissenschaft Informatik ist eine Wissenschaft und eine Technik, die sich vor allem anderen mit der (Re)Organisation von Arbeitsprozessen und Arbeitsplätzen befaßt. In diesem Sinne ist sie gemeinsam mit anderen Disziplinen Teil einer noch zu schaffenden **Wissenschaft der Arbeit**. Qualität der Arbeit und Qualität der Produkte sollen deshalb zu einer Leitlinie für eine praxisleitende Theorie der Informatik in einer demokratischen Gesellschaft werden.”

In addition, some computer scientists believe that computer science is deeply interwoven with engineering concerns and considerations and that it should concentrate more on the **how**, than on the **what** you do — which is more the focal point of physical sciences.

It is also only natural that the main views on education in informatics have always much reflected the dominating general views of the area and its role in the society. The attempts to come with model curricula played an important role for formulation of such views. A very significant was the ACM Computer Science Curriculum’68, mainly due to the fact that its designers had quite a coherent view of the area — from that period point of view. The second such a big attempt, much more controversial, has been the ACM-IEEE Computer Science Curriculum’92, which was as expected, due to the lack of such a unified and sufficiently deep view of the field at that time, what can be seen also from the following citation from an introductory paper [Den89]: “Old debate continues. Is computer science a science? An engineering discipline? Or merely a technology, an inventor and purveyor of computing commodities? Is it lasting or will it fade with a generation?”

In general, education aims, contents and methods have been very much under the immediate influence of the very last developments in software-hardware-communication technologies without a coherent and appropriate view of the scientific base of the field and without a sufficient vision of the future needs of graduates.

The views of the field presented above are in general too shortsighted. They see the scope and the methods of the field mostly too narrowly and the main aims of its scientific base often in a too utilitarian way (to serve and advice information processing and communication technology). In addition, programming and software have been seen mostly, misleadingly, as dominating the scientific and educational base of the field. Finally, the above views of the field are to a large extent influenced by a glorification of problem solving, reasoning and knowledge processing capabilities of humans and by the overestimation of the potentials of current and foreseeable computers.

## 2.2 Shortcomings of the current education and their analysis

In the course of time various general shortcomings of the current informatics education have been more or less identified. Some of them will now be first summarized and later analysed.

### 2.2.1 Global shortcomings.

Several of the general shortcomings have been identified in the Hartmanis-Lin's report [HLi92], where they analysed experiences of the application area with the computer science/engineering graduates. The degree to which they are valid can vary fro m one educational system to another. However, it seems to be clear that they represent strong points to pay attention to:

1. Computer science graduates are not prepared well enough to cope with the fast development of the field.
2. Computer science graduates are not trained enough to proceed systematically in solving problems and developing products.
3. Computer science graduates are not trained appropriately to use formal methods to derive and validate results and the rigour with which they approach and perform their tasks is in general not sufficient.
4. Computer science graduates do not have sufficient knowledge, insights, models, theories, methods and training in such essential engineering areas as system analysis, product validation, evaluation, testing, robustness, maintenance, and security.
5. Computer science graduates lack sufficient communication skills needed to cooperate in the identification, formulation and solution of problems.

6. Computer science graduates do not see well enough the importance of ethical problems and are not prepared to deal with them as needed.

There are also complaints from the research environment. There are even people that believe that if one wants to do research in computing, then it is better to study first either mathematics or electrical engineering or physics and then switch to research in informatics.

### 2.2.2 Analysis of the shortcomings.

On one side, one can say that some of the above critics are related to the fact that the application area requires too much from graduates concerning their immediate capability to perform perfectly even the jobs that require long term experiences and that the role of university education is to concentrate more on providing graduates with fundamentals needed for their job and for continuous education. However, in spite of that there are few points in such critics which can be summarized as follows (see also [Gru93, Gru93a]):

1. Fundamentals of the field are not well understood and are not usually taken broadly and deeply enough to create a coherent base.[5]
2. There has been a large progress in the development of all main areas of informatics. However, the degree of synthesis of knowledge and experiences in teaching and textbooks is far from sufficient.
3. Current education provides too much emphasis on analytical methods and too little on constructive methods.

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[5] [HLi92] "While introductory courses for most scientific and engineering disciplines exhibit a relatively high degree of uniformity in content and approach, university level introductory courses in computer science/engineering exhibit striking variations. Some emphasize new concepts in functional programming, logic programming, or object programming. Other teach no theory and are focused more on teaching programming languages than on programming itself, and still others emphasize theories of program correctness and programming methodology.

Some diversity at the introductory level is appropriate and desirable, as diversity results from informed choice on the part of faculty. But to the extent that this diversity reflects a lack of current knowledge about the field, it is undesirable."

4. Quantitative methods of complexity theory are much developed but their use is far from sufficient.

5. Quite often not yet sufficiently verified theories and methods, or even methods good enough only to solve toy problems are taught as a methodology to solve real problems. From this point of view there is too much unjustified and useless experimentat ion with students.

6. Too much energy is often lost in teaching and learning an enormous number of unessential details of far from perfect systems of far from a long term importance.

7. Practical work is not performed systematically enough.

8. Ethical questions are nowadays often emphasized without having a sufficient impact because the treatment of these questions is not an inherent part of all subjects.

The first reason behind the difficulties in establishing a proper educational program in computing is that the tasks the graduates should be prepared to deal with are very hard. Indeed, the graduates are to be prepared

- to deal with *immense differences in the scale of phenomena*; from individual bits in computers to billion operations per second and with highly complex software and hardware systems;
- to design and to deal with *many levels of abstraction*; to understand, manage, reason about the most complicated human creations;
- to achieve an *unprecedented precision*, because the underlying hardware is a universal computer and therefore a chaotic system;
- to overcome enormous difficulties one encounters in designing and managing of *complex software systems*.

The second reason behind various problems in establishing a more adequate educational program of informatics is that the aim of such an education does not seem to be clear enough. This is due to the fact that informatics graduates are finding jobs in ver y diverse areas where very different knowledge and skills are needed.

Actually, the main aim of informatics education, namely that

> graduates are capable to work along well established scientific principles and methods, have enough skill to enter successfully job market, and enough knowledge to keep themselves continuously up-to-date to ensure their lifetime successful career,

also requires to have a deep understanding of the field and to see the field in a long-term perspective.

# 3 Framework for a new approach

In order to develop a framework for dealing with the existing problems in informatics education we have first to formulate a new view of the scientific base of the field and its methodological impacts. In order to do that let us start with some very gene ral views on the development of mankind and computing.

## 3.1 Main eras of mankind and the essence of computing

In a very short but quite well pointed out way the global history of mankind can be seen as consisting of three eras:

**Neolithic era:** Progress was made on the basis that man learned how to make use of the potentials of nature to have *food* in a sufficient amount and desirable form whenever needed.

**Industrial era:** Progress has been made on the basis that man learned how to make use of the potentials and laws of nature to have *energy* in a sufficient amount and desirable form whenever needed.

**Information era** Progress is being made on the basis that man is learning how to make use of the potential and laws of nature to have *information* in a sufficient amount and desirable form whenever needed.

Also the essence of computing in the last two and in the next century seems to be quite well captured as follows:

**19th century:** Computing was seen as a brain process.

**20th century:** Computing is seen as a machine process.

**21th century:** Computing will be seen as a nature process.

The first of the above characterizations forms the basis for seeing the importance of informatics for society, the second forms the basis for searching for the essence of its scientific base.

## 3.2 A new view of the scientific base of Informatics

In order to develop a new view of some area of science it is useful to look into the history of science and to make a sufficient simple and powerful extrapolation of the current developments in that area (see also [GJu91, Gru93]).

### 3.2.1 A lesson from history.

The history of science shows that the success of a science depends very much on how large space, and at the same time an intellectually simple, smooth, and dense space is able to create and investigate in comparison to the space observable by human senses and the common sense.

There is a widespread belief nowadays that computing and communication technology is the one that represents the current and future progress, and therefore it should get the main attention, appreciation and support — both by scientists and education.

However, the history of mankind indicates that no matter how radically new a technology has been, it could have an immense impact on science, technology and society only when a very new way of thinking and seeing the world has already been emerging for quite a while — a view which could make a full use of this technology.

The history of mankind also indicates that the main long term contributions of such a new technology have been to help to develop further such a new view of seeing, understanding, and managing the world, and to make this new view of the world more coherent and powerful.

Those areas of science and technology that have been initiated by a new technology or developed a radically new paradigm then sooner or later started to shift their attention from the problems related to the development and utilization of the new technology to more general, and in long terms more important, problems. These issues were related to the development of a radically new understanding (and developing) of the world.

The same observations seem to apply to information processing and communication technology that could have been so successfully developed and applied to a large extent because a very new view of formalization and information processing has been developed since the very beginning of this century.

### 3.2.2 A view of the scientific base of informatics.

A new view of the scientific base of informatics, that underpins information processing / communication technology (hardware and software) was elaborated in [GJu91, Gru93]. Let us summarize the main points.

The science that has been emerging from the recent attempts to develop a scientific base for information processing / communication technology as well from millennium old attempts to capture and formalize understanding, knowledge, reasoning, computations, a nd to mechanize information processing, should be regarded, developed and taught as a new fundamental science that also affords a new fundamental methodology for science, technology and society in general.

This new science should be seen as having similar scientific aims (concerning the *information world*) as physics has had (concerning the *physical world*), and a similar fundamental methodological impact on society as mathematics has had.

This new science should be seen as a science that tries to develop a deep understanding of information (processing) world, its laws, limitations, elements, structures, processes, and so on.

This new science should be seen as a science with enormous research space that puts no limits on its tools and methodologies; as a science that is developed to a large extent (if not primarily) by the needs to extend and deepen our knowledge (of the infor mation world).

## 3.3 Some problems with which nformatics as a fundamental science deals with

1. What are the **laws, limitations, elements, structures**, and **processes** of the information world and what are their properties?

2. What is **information**? What is **knowledge**? How to measure them? What are their properties? How much of them do we need in order to do this and that?

3. What is **feasible**? Namely:

    - What is **feasibly constructible, computable, solvable, decidable, learnable, expressible**?
    - What has a **feasible evidence, proof**? (And what is a feasible evidence?)
    - What can be **feasible and securely communicated**? (And what is a secure communication?)

4. To study the **space of information processing problems**, its structure, hierarchies, reductions, equivalences, hardest problems,. . .

5. To study the **space of information processing resources**. Which of them are important? What are their properties and power? Which relations and tradeoffs hold among them? How powerful are such resources as **time, space, randomness, interact ions, parallelism, alternation, nondeterminism, reversibility**,. . .?

6. To study the **space of information processing machines**, their power, mutual simulations, designs,. . . Machines that fit existing and foreseeable technology. Machines that fit classical physics, quantum physics. Machines that meet biological requirements,. . .

7. To study the **space of formal descriptional systems**: logics, calculi, theories, languages, rewriting systems, automata, . . ., especially methods how to design them and reason about them.

8. To study **inherent complexity** (computational, communicational, descriptional,. . .) of objects, algorithms, processes . . ..

9. To study **security** of communications, data,. . ., protection of intellectual properties,. . .

10. What are complex systems? How to specify them? How to reason about them? How to design, maintain and verify such systems?

11. How to develop **information processing models** and understanding of physical, biological, social and other worlds?

## 3.4 Informatics as a new methodology

Two basic methodologies of science and technology (but also of society in general) have been **theoretical methodology** and **experimental methodology**. Both of them have been very well worked out and very successful.

The new methodology, that is emerging from the achievements of theoretical investigations and technological developments in informatics is a methodology that seems to have enormous potential. This new methodology allows to enlarge the power of theoretica l and experimental methodologies, to bridge them and, in addition, to be a powerful tool in all the areas where the two basic methodologies have not really been fully successful.

The basic features of this new methodology can be shortly summarized as follows:

**Simulation.** A new methodology to obtain knowledge, to discover laws and to study processes. It allows to study systems with different physical or biological laws; to reverse, slow-down or speed-up time, ...

**Visualization.** It helps to see otherwise unvisible, to study nonlinearities, chaos, generation, growth, ... It helps to get insights and to discover laws — it can lead to conjectures which can then be addresses using classical methodologies.

**Algorithmization.** The design of algorithms is one of the basic methodologies for not only solving algorithmic problems but also for obtaining the very basic scientific understanding of various phenomena, problems and processes.

**Formalization.** The design and study of formal, description and symbol manipulation systems is an old methodology that has received a new dimension with the modern development of informatics, and symbol manipulation techniques.

**Complexity investigations.** The investigations of inherent complexity have revealed that formal objects and descriptional / algorithmic / communication problems / processes have inherent complexity and that a discovery of this complexity brings deep scientific understandings and pays large practical dividends.

**Study of the complex phenomena in a thorough way.** Till very recently the main strategy of science has been an *isolation and investigation of the very basic phenomena*, and little attention has been paid, and could be paid, to their interactions. Informatics brings concepts, methods and tools for such investigations. In this way informatics methods allow sciences to study much more complex problems than so far and it also allows technology and society in general to deal with global problems.

**Information processing models of the world.** The attempts to develop information processing models of physical, chemical, biological, economical and social world have turned into a new important methodology to deal with old and new problems that could not been handled before.[6][7]

In order to apply informatics as a new methodology a strong involvement of informatics graduates is needed because they have knowledge and experience needed to do the job. Specialists in other areas are often unable to deal well enough with computing aspects of problems they need to solve.

An application of informatics as a methodology cannot only help to solve otherwise unsolvable problems but may also contribute important intellectual abstractions and discoveries to other fields and to create new conceptual frameworks needed there.

It is also worth observing that **demonstrations** are an important phenomenon in informatics, and they may get so also in all areas heavily using informatics. Indeed, computer science advances are often made public by

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[6] One can even say that mass, energy and energy transformations, as the building ingredients of most of the current models of worlds are being replaced by information, computing and information transformation as new key ingredients of new models of worlds.

[7] An interesting and important example are information processing models of brain and their impacts on the study of human cognitive processes.

**dramatic demonstrations** and it is often that the (ideas and concepts tested in the) dramatic demos influence the research agenda in informatics.[8]

# 4 Steps to be done

A new view of the scientific base of informatics and of its methodological power, together with their envisioned role in the future society, create a basis for the formulation of some of the major steps that need to be taken in the informatics education.

## 4.1 Broadening of the aims and scope

The rapidly broadening scope of informatics applications and increasing sophistications of them require to pay large attention to ways how informatics education should adjust its aims and how to broaden its scope. The main idea to be followed is that the basic tasks of informatics are much beyond those envisioned by the current computing and communication technology and that its impacts may also soon be far beyond those envisioned nowadays. Some steps that seem to be needed are:

1. More adequate and deeper foundations are needed in four areas: discrete mathematics and logic, continuous mathematics, foundations of computing, foundations of information representation / processing systems design (programming, software,...). Foundations in some other areas (physics, biology,...) could also be considered as an addition. In all these areas of foundations a significant broadening of self-concepts is a need; otherwise foundations risk becoming increasingly irrelevant to computing / communication practice.

2. Students need to have more possibilities to tune their education in the last years of their studies in order to adjust to a variety of new applications.

3. Steps need to be done to support more multi-disciplinary studies with informatics as one part of the education.

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[8] By [Har92], among young computer science faculties **demo or die** is starting to rival the older **publish or perish**.

4. New types of informatics education programs should be formed. It seems no longer feasible to perform all education needed within one program. (However, with the same first part of their studies.) Computing science and engineering should get a more clear profile. Computational science, as an independent subject, is an alternative that is gaining a momentum.

## 4.2 Synthesis of knowledge and experiences

The amount of theoretically deep, and/or practically useful knowledge and experiences that have already accumulated in informatics is already so large that in order to meet aims concerning informatics education, stated in the previous point, a significant attention has to be given to providing synthesizing courses. Currently, in many areas of informatics courses of the undergraduate but also of the graduate education go often too much into details of importance mostly only for those few, perhaps, that intend to do research in that area. Synthesing courses provide a space needed for other subjects and can also lead to a higher level of the understanding of the subjects.

Synthesis is needed, and possible, not only in such specific areas as foundations (for foundations of computing see an attempt in [Gru97]),[9] programming languages and methods, software development, hardware, parallelism, security, but also, in many areas, theory, software and hardware education should be synthesized — also due to the fact that current computing/communication systems are a mixture of hardware and software. A particularly important step, of the large importance would be to develop curricula and textbooks for such courses as INFORMATICS I and II on such a level as it is in advance areas of science and technology.

## 4.3 Soundness of education

Basic education should concentrate on a sufficiently solid knowledge and sufficiently verified and systematized experiences, methods, systems and tools. There is no longer a justification to teach in basic courses, as it is

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[9] There is also no longer a good reason to separate teaching of calculus and numerical mathematics on one side and linear algebra and numerical mathematics or abstract algebra and symbolic computation on the other side.

quite often the case, especially in the area of programming, "software engineering" and artificial intelligence, the very recent ideas and products the potential and usefulness of which have not been sufficiently verified yet. There are enough deep and useful subjects and methods to teach. Moreover, education should systematize and not only demonstrate the sometimes ad hoc discoveries, inventions and artifacts that arise from the practical imperative. Some experimentation in teaching is needed but this should be restricted to well justified cases. Moreover, the number of non-scientific and non-engineering lectures in informatics itself should be put into minimum. Their positive impact on education is rarely proportional to the time consumed — even if they may contain ideas worth to read, to consider within more technical lectures, and to pay attention to in laboratories, projects and theses.

For education of engineering oriented graduates in informatics, and those is the majority, the main principles of good engineering should be taught: thorough analysis of problems, validation and evaluation of suggested solutions, efficiency, reliability, and security analysis,. . . and of those techniques facilitating them. (Projects, assignments and labs create the main space for doing that.) Graduates should be able to use science and technology to solve problems and to make decisions on technical terms. In particular, they should be equipped with a much broader range of solid validation techniques than a traditional mathematical proof. Moreover, graduates should be able to distinguish sound, scalable and already verified methods from potential-but-not-tested-yet methods and from alchemy type methods.[10]

## 4.4 Rigour and clarity

Education in informatics has to achieve that graduates understand importance of rigour and clarity and manage the basic techniques of achieving and maintaining it. This is due to the fact that informatics applications have often very large requirements on rigour and clarity because of enormous number of details and complexity of many products, especially software systems. Rigour and clarity have to be learned already in the introductory courses and reinforced through the whole curriculum - – this

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[10] In particular they should be able to understand that a method that does not scale well is actually not a method to be used in larger scale applications.

can not be taught as a mere addition in the later courses. Another way of teaching rigour and clarity is through a proper integration of theory concepts and methods with those of practice.

Rigour and clarity are of special importance when software specification and development tasks are to be handled in a disciplined and systematic manner — what is necessary for having systems which can be efficiently manipulated and analysed.

## 4.5 Profiling of graduates

As already mentioned, one reason that makes it difficult to discuss which topics are indispensable in the curriculum is the lack of a common understanding of informatics, especially its scientific base. This is connected also with the relatively small amount of "genuine" graduates / professionals in the field. As a consequence, only few people are acquainted with purely informatics professionals. And also at school only a small percentage has obtained an education in informatics - and often only in a quite obsolete form. This has retroactions to the self-confidence of the graduates and their weak identification with their profession.[11] Interesting enough, the difficulties with a clear image of the profession are (paradoxically) due to the big success story of informatics: Informatics plays such a significant role in so many application areas that the professionals are distributed over a wide range of companies, administration offices and research institutes (a fact which makes it easy to find a job also during an economical recession). On the other hand, the limited size of a "pure informatics industry" prevents many from obtaining a clear and simple image of the profession. (This is also valid for other sciences (e.g. physics) but they have a longer tradition and graduates are more successfully educated during their study to be proud of their original profession.)

In addition, the lack of the nationwide recognition of informatics professionals is another obstacle for a strong identification with this technology and science.[12]

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[11] It is not unusual that members of an informatics society leave it in case their job assignment has changed. Comparing with other professional societies, this is a different and strange behaviour.

[12] Moreover, for a man in the street it is not yet easy to realize to which amount informatization influences his daily life. Indeed, computers may be considered as electrical engineering products, embedded computer systems in cars and other devices are (mostly)

## 4.6 Technology transfer experiences

Improving technology transfer is one of the general and important problems of the current society. Informatics methods and tools should and could play an important role by that. In order to facilitate this it is desirable and even necessary to take care that graduates of informatics are prepared as much as possible to play by that a progressive role. In order to achieve that the following steps need to be done:

1. Students should learn to work with very modern concepts, methods and tools.
2. Education process should systematize new methods and tools in such a way that graduates are then able to contribute to the improvement of these methods and tools.
3. Students should participate on ambitious projects attacking basic theoretical and practical problems of computing. Even if such particular projects are often far from being able to produce useful products, students learn their lesson and the experiences obtained allow them often to come later with much better solutions and already useful products.
4. Students should get involved as much as possible into multi- and inter-disciplinary projects.

## 4.7 Curricula and textbooks

It is to emphasize that the whole problem of informatics education in an area is far more complex than that of what and how to teach. For example, of an increasing importance is nowadays an active involvement of students and the amount of their contacts with faculties.

Another important issue are (model) curricula. The lack of stimulating model curricula seems to be an important and urgent problem of informatics education. The experiences with the latest ACM/IEEE attempt to create such a curriculum seems to indicate that the task to create model curricula is currently beyond possibilities of a single country (where needs to adjust to various local interests can hardly lead to an innovative and

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invisible, and the same holds even for computer networks such as internet.

stimulating curriculum). An international effort in this direction seems to be needed.

Textbooks also seem to be a big problem. A trend pushed so much a couple years ago, namely, that computer science education should be not too hard especially for those with not too much inclination to mathematical reasoning and engineering thinking, resulted in the production of "story telling textbooks"[13] that can also hardly have a positive impact on informatics education and also hardly contribute positively to a good reputation of the field among other scientific and engineering disciplines.

# 5 Case studies

Three areas of informatics education will now be analysed in more detail.

## 5.1 Fundamentals of computing

As already mentioned, one can distinguish four main types of foundations: discrete mathematics and logic, continuous mathematics and numerical mathematics,[14] foundations of computing, and foundations of designing, reasoning (programming, software engineering),... (Foundations of physics, biology, and so on, should be seen as an additional option.)

In the area of discrete and continuous mathematics the main task is to adjust education to informatics needs by choosing proper subjects and examples and by bridging theory education with using modern computing tools to solve problems far beyond the pen-and-paper framework.

We concentrate here on foundations of computing. Bridging these four types of foundations is the next problem, and not an easy one.

Education in this area seems to need new aims, contents, methods and impetus because in its current form it is loosing respect of graduates, recognition of importance of faculties and interest of students — and there

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[13] In which one can find on 50 pages what could be clearly written on 5 pages.

[14] Unfortunately, too often too little attention is paid in computer science / engineering education programs to continuous mathematics in spite of the fact that such mathematics is of key importance not only for some particular areas of computing (as robotics), but also because multi-disciplinary approaches and many applications require from graduates a very solid knowledge of concepts and methods of continuous and numerical mathematics.

are no objective reasons for being so. Just the opposite is true— with respect to the achievements and impacts of foundations.

In general, the basic educational aim and scope in this area of foundations has been set up, so that the education is good for those graduates going to do research in this area. This is no longer justified — this is the role of some special and not obligatory courses, theses and so on. The education in the area of foundations of computing should concentrate on subject all graduates should learn and most of them need. Interesting enough, this change in the educational aims does not need to have a negative effect on the quality of education in the area of foundations of computing (see [Gru97]).

Larger attention needs to be devoted to demonstrate the relations between very fundamental concepts and results and practical problems. It has to be illustrated that basic concepts of foundations should be seen as intellectual tools that can provide directly only guidance and that in order to get out of them something more practical, these concepts often need to be twisted, modified and “industrialized". However, if this is done, then surprisingly powerful tools can arise. Fortunately , there are already quite a few examples that can be used to illustrate it on a theoretically interesting level and practically important cases. (Let us mention the concept of weighted finite automata and transducers and their use for image compression, modification and generation — see [Gru97].)

The view of foundations of computing keeps developing. The old view has concentrated on computability, grammars, formal languages and automata, as the main subjects. This is still quite often so. In spite of the fact that all these areas still have their unreplaceable place in foundations of computing, their role has changed and therefore the way they are to be taught has to be changed (and what is to be taught from these areas has to be revisited). Teaching of some of the old subjects is no longer justified and new subjects and viewpoints have to be added.

More modern view, slowly gaining a momentum, is based on emphasizing efficiency and complexity considerations (computational, descriptional, communicational), randomization, approximations, parallel and distributive computing, communication systems, security foundations, and so on. This provides foundations for computability, complexity of problems, efficiency of algorithms, parallel computing and computers, security, interactions, formal systems, rewriting systems . . . Further extension in the direction of radically new modes of computing as quantum, molecular and brain computing are also to be considered.

In order to include a variety of new subjects a high level of synthesis is needed and possible in all four areas of foundations. An attempt to provide a synthesis in the area of foundations of computing is in [Gru97].

Of a special importance would be to develop curricula and textbooks for such synthetizing courses as FOUNDATIONS I and FOUNDATIONS II to combine foundations of computing with foundations for programming and system designs. However, such a synthesis should not be on a naive level but on a level as in advanced areas of science and technology. Such courses could be a base to develop courses INFORMATICS I and INFORMATICS II, mentioned above.

Several areas of foundations offer already a possibility and also a need to bridge the theory, software, hardware and application areas. For example finite automata, parallel computing, computational complexity, cryptography, and so on.

## 5.2 Parallel and distributed computing

There are two reasons why it becomes necessary to include a teaching of parallelism into any informatics educational program.

- Main nature and society systems are basically parallel and distributed and therefore parallel computing models, modes and methods are actually more natural than sequential ones;
- Parallel information processing is going to play an increasing role in every-day data processing, also because such systems can have better fault tolerance and higher reliability.

As it is often the case, we understand under the parallel computing both parallel and distributed computing, i.e. tasks executed by parallel computers (by multiprocessors or array processors or pipeline computers) or by distributed computers (networks of processors).[15] (Although the last

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[15] In the extreme cases, as it has been done in dealing with so called “RSA challenge” [Cal96], such a distributed computing can involve tens of thousands of processors and one can speak about a “metacomputing”. Such problems and methods to deal with them are, however, far beyond the needs and possibilities of most of the graduates and therefore we do not suggest to include such topics into the basic education about parallelism yet.

one, in the ultimate form denoted as metacomputing, may play a significant role and have had already impressive results, for example meeting the so-called “RSA challenge” (see e.g. [Cal96]), in factorizing large integers, we will not discuss it in more detail now because a "normal user" will hardly have at hand thousands of processors, and because we try to restrict the topics as narrow as possible). As obligatory we consider three courses and one laboratory:

- Models of parallel processing;
- Parallel algorithms;
- Architecture of parallel computers.

Each of these courses should be a one semester and two hours per week course. In the last course one type of parallel computers should be treated in detail. For the other models only basic features and properties should be discussed (see e.g. [Hbr89]). The content of the second course should depend on possible application areas students can be exposed to at the corresponding university but some basic parallel algorithms (e.g. graph theoretical ones) should always be demonstrated (see e.g. [Qui94]). In the more theoretically oriented first course, besides the main simulation and complexity results for basic parallel models also the limitations of physically realizable parallel devices should be analysed. In the laboratory students should learn how to program and use an existing parallel computer — the type of the computer (shared memory or message passing) is secondary. Optional courses, of importance for applications may also be offered (for example, in parallel numerical algorithms).

However, ideal would be to make a synthesis of all the three courses suggested above. The resulting course could be large but smaller than all three courses together.

Many people seem to be convinced that teaching of parallel computing should start only after students master sufficiently well sequential computing. However, this does not seem to us to be the best approach. There should be a synthesis in teaching of seq uential and parallel computing (see views in [Nev95] and a presentation in [Gru97]).[16]

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[16] For example, once a tight lower bound is established for the sequential computational complexity of a problem, time comes to discuss the idea of a wor k optimal parallel algorithm for the same problem. On the other hand, in the basic foundations of computing course cellular automata can be used as a model of universal computers.

## 5.3 Informatics education for non-informaticists.

Informatics concepts, methods and tools are of key importance for all sciences, especially engineering, and also for other areas of education. The degree of their importance may vary, but it is in any case substantial.

Some of the computing / communication skills all undergraduates have to have, and as early as possible during their studies, are clear: working with PCs, text editing systems, operating systems, spreadsheets, email; to use and search through internet; to make simple programs and to use data bases. However, it seems quite sufficient to train such skills in a learning-by-doing manner.[17]

The above skills are, on the other hand, not sufficient. A course has to be set up in which students learn, in a way that depends on a particular area of education, the very basic ideas concerning:

- potentials and limitations of the computers (see [Fey96] as an example of such an approach for physicists), and algorithmic approach;
- potentials and limitations of numerical methods;
- basic concepts concerning computational efficiency and complexity; feasibility and unfeasibility, and basic ideas how to handle unfeasible problems;
- very basic concepts concerning cryptography and information security;
- very basic concept concerning software validation methods and problems;
- principles of data base and expert systems.

Of course, in different disciplines some other courses are either desirable or a must. For example computer graphics is necessary for various design oriented engineering areas. In the same way a course on robotics may be appropriate for some engineering a reas. A simulation / visualization course may be of importance for some science education programs.

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[17] In addition, one can soon expect that most of the freshmen will have already quite a sufficient knowledge / practice in such subjects.

In addition, all graduates should be able to distinguish which types of problems could be attacked using computers and with what effort, and how to find and evaluate appropriate tools for doing that.

In general, emphasis should be on teaching and learning basics of informatics as a new methodology.

The key point behind is that whereas intuitively grounded insights and very basic experience with computing technology were often sufficient in the past to lead to a substantial progress in most of the application areas, this will no longer be the case in the future. As the complexity of applications and of computing grows, so also has the need for well-understood concepts and theories and for systematic approaches with which to manage this complexity. It is therefore imperative that education in all areas of education concentrates on the best knowledge and insights that has to offer if informatization is to reach its full potentials within society.

# 6 Conclusions

The paper deals with some general problems concerning informatics education. It is based on the conviction that the current problems of informatics education have deeper, even philosophical, roots and are not only on the level how to improve particular technical aspects of education.

The paper is also based on the conviction that the problem of improving informatics education is of a large importance for society that depends increasingly on its capability to manage the potential informatics and information processing/communication technologies offer. Various general analyses and particular suggestions have been made in the paper concerning the education in informatics.

A final observation. A natural evolution of the field and its educational programs would eventually lead to an implementation of steps advocated for in this paper. However, such an evolution seem to be a very slow process requiring decades and this is hardly acceptable with respect to the potentials informatization has for the society and with respect to the needs education in informatics has for the success of the whole process of informatization.

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