A PERCEPTION OF INFORMATICS

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> When you reach for the stars you may not get one, but you won't come up with a handful of mud either.
>
> *Leo Burnett*

1 Prologue

There are several important reasons, and some of them will be discussed below, why it is of large importance now to try to develop a new (though slowly implicitly emerging for a while), more adequate and more challenging perception of Informatics.

The main one is a growing understanding that Informatics in general, and information processing and communication technology in particular, have potential, and are expected to do so, to revolutionize and improve virtually every aspect of human and society life - especially that of science and technology disciplines. It is therefore in the interest of the whole society that Informatics develops in a proper way to fully meet its potential and that Informatics makes its potential known much better than so far to other academic disciplines and society in general.[1]

[1] In spite of unprecedented scientific, technological and, especially, application successes, barely dreamed about only few decades ago, even by very top experts and visionaries, computer science (CS) keeps having serious problems to identify and present properly and convincingly its scope, deepness, aims, unparalleled challenges and potentials. Because of that, CS has big problems to be perceived correspondingly not only by the whole academic community, by (potential) students at all levels of the education process, and by society at large, but also by the informatics community itself. (As pointed out, and demonstrated, in the report of van Leeuwen et al., for Informatics Europe, one of big problems of computer science in many countries (enrollment) is to a large extend due to the fact that neither faculty, (potential) students and nor society in general have a proper perception of the field and do not see it as a very attractive and challenging one, as many other disciplines and even most of them. In this report "enrollment crisis" is cited as one of the prime reasons why science in

Another reason, of a less general importance, but to be discussed here at first because of the context this paper is presented, is the need to design a strategy, or a vision, to develop the Informatics Section of Academia Europaea - perhaps the main European scientific framework where Informatics should act and demonstrate broadly its contribution to science, technology and society in general. To a society that starts to understand the importance of science and actually starts to believe that science could play a guiding role for society in the future and be a source of new resources for society, both intellectual and material, and that Informatics should play a prominent role by that.

The aim of this paper is to present and justify a position what a (perhaps provocative for some) perception of Informatics[2] should look like and by doing so to start/provoke a discussion on these issues. An attempt is made here to describe the intellectual substance and main challenges of Informatics in a new and compelling way and by that to initiate a new way of thinking about this so important area of science, technology and methodology. This is accompanied also by an analysis of the currently dominating perception of the discipline, that is to embrace what is usually termed as "computer science", "computing science", "computing" , "computational science(s)", "web science", "artificial/computational intelligence", "scientific computing" or simply ICT and so on.

On one side, this paper should therefore be seen as a challenge to those who perceive the field in a different way to express their positions.

On the other side, this paper is written with not too many technicalities in order to be comprehensible and of interest also to those from quite distant disciplines - so that inputs also from them can be expected.[3]

general is not profiting fully from the achievements of computer science, and why industry is not able to recruit even a fraction of the highly skilled information technology specialists it badly needs.) Informatics has actually big problems to be perceived even at least partially proportionally to its past outcomes, current impacts and already readily visible future goals and potentials. The main reason behind such a situation is that CS has tried for years to present its scientific and engineering scope, problems, tools, outcomes, challenges and long term goals, as well as history, starting from a much too narrow vision of the field - of its fundamentals, depth, broadness, achievements and power.

[2]Each perception of an academic discipline that is to be both fundamental and practically important has to be evaluated in the first order for its deepness, coherence, simplicity and elegance, but also for its utility.

[3]The paper presents Informatics as a very important and fundamental area of science and technology with a very broad scope (and as having not sharp boundaries with several other areas of science and technology) as well as huge impacts. However, this does not mean that (great) importance of many other areas of science and technology is not fully recognized. Moreover, many of the challenges of Informatics, as perceived here, can be clearly achieved only in a close cooperation with other academic disciplines.

2 History and Motivation

The first broadly communicated view of the disciplines behind modern computing, very clearly stated and still much dominating, can be traced back to the very well written, and much influential, paper of Newell, Simon and Perlis, published in Science in 1967, that fully captured the perception of the field at their time.[4]

The view of Newell et al. has been much supported, on the institutional and associational side, by the establishment of such powerful associations as the ACM and societies of the IEEE in North America and by the IFIP on the international scene. In both of these cases technology views of the field and interest of the industries behind have been quite dominating.

In connection with that the following observations can be of interest.

- In North America more scientific/foundational issues in computing started to play a quite important role already since 1960, by establishing such excellent and influential conferences as the FOCS[5] and the STOC. However, and unfortunately, these conferences have developed always with a strong concentration on "hot topics" mainly and advocated a quite narrow view of the foundations and the theory of the field. In spite of that, on the level on the top award of the field - the Turing award - foundational and theoretical outcomes quite soon got sufficient attention and for a while even dominated.

- Within the IFIP the situation was very different. "Theory" was strongly overlooked for 36 years and all attempts to create a special technical committee for theory were turned down till 1996 - due to the view that the only special theory behind "computer science" is the one that is behind programing, which was supposed to be covered by the Technical Committee on Programming - TC2. Only the establishment of the Technical

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In addition, the paper should not be seen as an attempt to claim novelty (of the most) of ideas presented here. It should be seen as an attempt to present a certain perception of Informatics in a systematic and a bit detailed way and also as an attempt to present the intellectual substance of Informatics in a (new) compelling way and by that to establish a more appropriate way of thinking about Informatics. The next version of the paper is to be also supplied with more detailed arguments and references.

[4]The basic ideas presented in their paper were: "*Whenever there are phenomena there can be a science to describe and explain these phenomena.*

Thus, the simplest (and correct) answer to "What is botany" is "Botany is the study of plants", and zoology is the study of animals, astronomy is the study of stars, and so on. Phenomena breed sciences. Since there are computers, there is a computer science. The phenomena surrounding computers are varied, complex and rich."

[5]Originally the Symposium on Switching and Automata Theory.

committee TC1, as the Technical Committee on Foundations of Computing, in 1996, after having the Special Interest Group on Foundations of Computing, SGFCS'14, established in 1989 (thanks to Dines Bjorner), has changed the situation.

- In Europe, the establishment of the EATCS was done outside of any technology umbrella, by visionaries, and helped to promote a much broader development of the field than in North America. Moreover, it has been mainly such a view of the field, supported also later by some theory of programming and formal methods visionaries, that have dominated the IS AE since its very beginning.

  The "EATCS" views of the field went also through a significant development. To the automata/complexity view, the logic/semantics view was added after a while and later also some other areas as cryptography and natural computing - both in a broad sense.

Starting with the last two strong, active and initiative chairs of the IS AE, the attempts have been initiated to see the field in a (much) broader way than before - more in the "IFIP-view" than in the "EATCS-view" to be short - and to have that reflected also in the membership of the IS AE.

Since the IS AE has been, and still is, very small, compared to other "comparable" sections of the AE and also compared to the needs of the AE - to have a strong voice and impacts in the European science - there is a space and the need to extend its membership and therefore there is the need to discuss such issues as "Who we are and where we go" and to develop a proper and visionary perception of Informatics that has a chance to stand the scrutiny of time in spite of its expected enormous development in breadth and depth and to develop the membership of the Informatics Section of AE correspondingly to that.

It is of course natural to ask what a (more) proper perception of Informatics should be and to see well why it is so much needed now. My first basic position is that such a perception does not need to be fully correct "in all details and in the limit" - that would be too much to ask and actually an illusion - one should see the field as still being in its (modern) infancy and as developing fast in both depth and breadth. My second and main position is that such a new perception should be visionary and should bring much broader and deeper vision of the field that would lead to really grand challenges and huge impacts - all other major areas of science have always gained much by taking such positions.[6]

[6]For example physics has been seen for a long time as *dealing with the stuff we can handle between fingers*. Quantum mechanics and the relativity theory have changed that

My last position on this issue is that any perception of an academic discipline should be much evaluated also by its utility, especially with the respect to the impacts on the research and education of the discipline, and to the overall perception of the field by the whole science and society in general.

I do believe that we need such a perception of Informatics that would much stimulate its proper development from the point of view of the interest of the whole science, technology and society and also because of our own interests and needs. A perception that would lead and inspire the discipline, for quite a time at least, and would attract very bright and ambitious students by its grand challenges and huge impacts.[7] Such a position, I feel, is justified much by the understanding that development in Informatics, as a science, technology and the methodology area, much influences development of all other sciences, technology areas, health and environment care, economy, education and actually the whole society.

Moreover, since it is getting almost obvious that in the foreseeable future one can hardly expect a very significant development in any of the areas of human activities where Informatics concepts, paradigms, methodologies and tools would not play one of the key roles, it is actually one of the main current social duties of informaticians, and especially of such institutions as the AE, to develop a sufficiently visionary perception of the field and to make it well understood by other academic disciplines and society in general.[8]

A historical observation: Men who fashioned modern science, mathematicians in their general methods and concrete investigations, were primarily speculative thinkers who expected to apprehend broad, deep, but simple, clear, and immutable mathematical principles either through intuition or through

very much and brought benefits also for our understanding of the "stuff we can handle between fingers". Considerations about Planck scale and superstrings living in the 10th dimensional space go even far, far beyond that. Observe that from such a point of view the perception of Informatics presented here is still very much modest.

[7]For any academic discipline, the progress in the advancement of the boundary of knowledge and in the discovery of very innovative solutions to scientific problems as well as a chance to deal with great challenges of the discipline depend very much on how the field is able to attract and support the brightest students. This is well known and many areas of science are very active from this point of view. This is currently a not easy task for Informatics at all because it has to compete with such attractive and promising fields as (molecular) biology, neuroscience, nanoscience, attoscience as well as with attempts to reach limits of our knowledge using huge Collider, new telescopes and space missions and so on.

[8]One should dare to say, without much exaggeration, and in short, that times come to see Informatics as a powerful servant, admirable and unifying Queen, or, to be less power and more spiritually oriented, a guru, for other academic disciplines and as the one capable and eager to keep learning from all of them.

observations and experiments.[9]

3 A Perception of Informatics

My basic position is that Informatics has four, very closely inter-related, components - scientific, engineering, methodological and application - exercising strong mutual impacts.

In the following all these four components of Informatics are discussed briefly and also some of their grand challenges.

3.1 Informatics as a scientific discipline

As a scientific discipline of a very broad scope and deep nature, both fundamental and applied, Informatics has many tasks and goals. Its main task is to discover, explore and exploit in depth the laws, limitations, paradigms, concepts, models, theories, structures and processes of both natural and virtual information processing worlds and to explore their phenomena as well as their interrelations, impacts and utilisation.

To achieve its tasks, scientific Informatics concentrates[10] on developing an information processing based understanding of the universe, evolution, nature, life (both natural and artificial), brain and mind processes, intelligence, information storing, processing and communication systems and tools, complexity, security and other basic phenomena of the information processing worlds.

The development and analysis of a variety of formal, descriptional, specification, computation, programming, interaction, communication, security and reasoning models, modes, languages and systems; development and analysis of (deterministic, randomized, quantum, genetic, evolutionary, neural, approximation, optimization, on-line, parallel, concurrent, distributed, continuous ...) algorithms, heuristics, protocols, processes and games are some of the main means of scientific Informatics.

Data, information, knowledge, formal languages and systems, logics, calculi, reasoning and proof systems, processes, resources, models (especially automata oriented) and modes of information and knowledge processing, communication and interactions are some of the key concepts behind.

Computability, efficiency, complexity (computational, communication, descriptional, ...), feasibility, universality, provability, learnability, validation,

[9]By John Herman Randall: *Science was born of a faith in the mathematical interpretation of nature.* Perhaps time came for a new vision: *New Science is being born of a faith in the information processing interpretation of the nature and society.*

[10]With the help of other sciences or by helping other sciences.

(formal) correctness as well as secrecy, confidentiality, privacy and anonymity are some of the key issues.

Information and knowledge digitalization, mining, analysis, sorting, comparing, searching, compression, representation, visualisation and transmission are some of the primitives of information processing.

In depth understanding of the fundamental problems and generalisation, as well as (semi)-automated implementation, of the basic methods are some of the main concerns.

In order to meet its goals, the scientific Informatics develops close relations to other sciences and technology fields - currently especially to physics, neuroscience, biology and chemistry, and also to electronics and optic-, micro-, nano- and bio-technologies. In the future, likely, also to atto-technology and quantum-technology.

The basis of the relationship between Informatics and the natural sciences rests on an understanding that information carriers are always elements of the physical, biological or chemical world and, consequently, information processing is governed and constrained by their laws and limitations and also that information processes are an inherent part of the basic aspects of the nature and life - as discussed in more details below.[11]

Informatics as a science includes numerous theories much needed for its

[11] Two big discoveries led to an understanding that natural sciences are information processing driven. The first one was the discovery, by Francis Crick and James Watson, in 1953, of the twin-corkscrew structure of DNA and how genetic information is encoded into DNA - followed by a demonstration, due to Adleman, how DNA computing could be performed and that it has a potential for remarkable efficiency. The second one was the discovery of quantum teleportation and of the unconditionally secure quantum generation of shared random classical key, by Charles Bennett et al. in 1984-1993 - followed by the demonstration by Shor, in 1994-1996, that quantum computing could be performed and has a potential for remarkable efficiency. These discoveries changed views on physics and biology that started to be seen and explored as being, to a significant extent, information processing driven sciences. From that it has been only a natural and logical step to see other natural sciences in this way, as being to an important degree information processing driven - and a new revolution in the study of natural and also other sciences has emerged. All that, supported by the immense development of the power of information processing technology, has initiated various new attempts to deal with perhaps the main frontier of science - mind - and the attempts to understand it through a "reverse engineering of the brain" - what could, perhaps, lead also to dealing with such phenomena as consciousness that have been for so far considered as being out of the reach of (current) science.

Of interest is also the so-called *Landauer's principle* that say that *Each bit of lost information would lead to the release of an amount* $kT\ln 2$ *of heat, where* k *is the Boltzmann constant and* T *is the absolute temperature.* as well as slogans of J. A. Wheeler and D. Deutsch: *It from bit* and *It from qubit* that are to say/speculate that everything is designed from information.

development in depth and in broadness. Some theories are very abstract, others quite specific, and some theories are oriented on making better use of the outcomes of scientific Informatics to create a scientific basis of Informatics as an engineering/technology discipline and/or a new methodology.

To meet its scientific goals, Informatics has to develop a whole variety of subareas. Some are deeply abstract and appear to be, at the first sight, quite remote from the main tasks and interests of the current applied Informatics, yet they serve to develop deep insights into the key problems and powerful conceptual tools; others are either interdisciplinary or very applied.

In order to derive a deeper understanding of our real information processing world, Informatics has to create and explore a whole variety of other (virtual) information processing worlds[12]. By broadening so much its scope in this way, Informatics can also develop very powerful tools to deal with information processing related problems of our real world.

Observations, measurements, analysis, modelling, simulation and visualisation, as well as generalisations, abstractions and decompositions, constitute some of the main methodologies to explore information processing worlds.

3.1.1 Grand challenges of scientific Informatics

Let us start the presentation of some of the grand challenges of scientific Informatics with the most fundamental and abstract ones.

The first grand challenge is to work out ways to see our world as "a point" in a huge space of other related (abstract) [virtual] words and to come up with new ways to understand and deal with problems of our world through the investigation of and in this large space of worlds.[13]

[12] And to follow successfully this road is one of the big challenges of Informatics.

[13] Very technical examples along these lines are attempts to see theories of the classical and quantum mechanics as "points" in a larger space of possible theories that preserve some theoretical constraints and also possibilities of both of these theories. The attempt initiated by S. Abramsky and B. Coecke is based on abstracting the essential categorical features of classical and quantum mechanics that support such constraints and possibilities. Another approach is to go through various generalisations of the probability theory, through abstract state spaces, as done by H. Barnum, C. Brukner and others, or to study potential ("physical") worlds with correlations that are stronger than the quantum ones but still do not contradict the non-signaling restriction of the relativity theory.

Observe also that perhaps (one of) the highlight of the current science is to see the very basis of our reality - of the time, space and particles - in a (virtual?) [geometric?] 10-dimensional space with superstrings living there. It is believed that the superstring theory is not testable and therefore some consider it as not being physical. In spite of that some, actually many, top physicists view the superstring theory as a proper theory mainly on the aesthetic grounds as well as on its consistency and beauty (and also due to the fact that it

Another grand challenge of the scientific Informatics is to understand the laws, limitations, paradigms, processes and phenomena of the information processing that govern the evolution of the universe and life and play the key role in the development of nature in general and especially of living beings.[14] In short the task is to understand universe, earth, atmosphere, nature and life in information processing concepts, principles, laws, limitations and paradigms.[15]

As a sub-challenge there is the need to help biology[16] to answer two of its major questions: (1) *How a single fertilized cell develops into a multicellar organism? (2) How the central nervous system processes information?* Biology has itself no sufficient tools to deal with these questions alone - its tools to explain brain are not much different from those to explore stomach. Moreover, Informatics could help to answer a modification of the third major question: *What is life?*[17] and sub-questions as *How life began?* and *How could life*

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implies gravity). Some others support it on the basis of an understanding that many great ideas of physics are its spin-offs.

Observe also that some areas of science, as astronomy and cosmology, are much suffering due to the fact that there is only one real world to work in and it is not possible to make experiments in it from the outside. (Is this any longer true? Could virtual worlds help?)

[14] There are several reasons why the universe can and should be one of the basic objects of study for scientific Informatics. One of them is based on the view that the universe can be considered as a giant quantum information processing system and computational capability of the universe at its most macroscopic level is the key ingredient in the spontaneous arise of complexity at many levels and behind the design of all elements of the universe, earth and life - as argued, for example, by S. Lloyd.

[15] One of the major recent outcomes of scientific Informatics has been quite a convincing argument, using quantum computational complexity results, that quantum information processing could pay off. Physics had no tools at that time to see that clearly enough.

[16] Modern biology can be seen, at its deepest level, as the science exploring how cells use information contained in genes and information processing is seen, in a deep biological sense, as a part of life that is so important as eating and breathing.

[17] There is a variety of views what life, likely, is. One way is to see it as biomolecular and biochemical processes governed by quantum principles and laws - that are necessary to explain shapes, sizes and chemical affinities of biomolecules. For example, by Hameroff, in the book by Abbott et al. cited below, "Geometric distribution of non-polar π electron clouds can enable a collective, cooperative quantum processes - a unitary wave function - mediating perception and governing purposeful behaviour of living organisms". This does not seem to create much space for Informatics to get involved. However, in spite of the fact that practically everybody agrees that quantum processes are involved at some stage in the life processes, and quantum mechanics is of the large importance for the quantitative understanding of the basic interactions and processes, no one was able so far to demonstrate that quantum mechanics brings qualitatively new insights concerning the mystery of life. At least not to the extent that would made "biologist to jump to study it", and that one could see indeed some impacts of such deeply quantum phenomena as superposition, entanglement and non-locality.

begin?[18]

The third of the grand challenges of scientific Informatics is to create mod-

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The bottom-up approach to life, its study at the chemical and molecular level, has brought a lot of interesting knowledge about the very basic processes, but the more it does, the more seems to be puzzling what life really is. On the other side, there are characterizations of life by its organizational arrangements leading to a purposeful behaviour and reproduction: for example, through self-organisation, homeostasis, metabolism, adaptive behaviours, responses to stimuli, reproduction, evolution, ... This position gives not only a lot of space for having Informatics involved, it actually see information processing aspects as dominating. It creates also a space to consider as a semi-life or artificial life systems exhibiting some, or most, of the above properties what has been a basis for so-called artificial life research and developments.

At the top of life we can see the brain as an information processing system with hundred billions of neurons and synapses acting as simple switches that stores, retrieves and process information and knowledge in an amazingly perfect and efficient way which is still beyond our understanding. Even more surprising actually is that there are one cell organisms, as paramecium (from 50 to 350 μm in length), that do information processing par excellence in order to find foods, to avoid predators, to learn to find a mate and to have sex - without having any synapses. Concerning consciousness even much less is known, but, very fortunately and also surprisingly, using anaesthetics it is possible to switch consciousness off for a while and to make pain-less surgeries, what is actually a very remarkable success.

The idea that quantum (information processing) processes could play a significant role in understanding of life goes back to E. Schrödinger (1943) who challenged the idea, dominating at that time, that classical physics will be enough to understand basic features of life. One point behind was that the Darwinian/Mendelian nature of inheritance has its basis in discreteness (to carry genetic information), and discreteness is inherent only in quantum phenomena. Another point behind was that there are cases that different parts of brain, without recognizably direct neuronal connections, clearly work in parallel on processing the same perceptions and the outcome of this is a formation of a single compact conscious image. (See also the recent book "Quantum aspects of life" by D. Abbott, P. C.W. Davis and A. K. Pati.)

Since we have not been able to get a deep understanding of such phenomena as life, mind and consciousness within the framework of current physical theories and implications they have for information processing, it is natural to speculate that for making such a progress we would need other physical framework and due to it other information processing processes, principles, laws and limitations. This opens the door to leave our current physics framework, at least for a while, and to explore, using virtual information processing worlds, which of the not totally impossible physical frameworks would create platforms for understanding life, conscious mind and so on? Is this impossible? Is a better way visible/imaginable? One of them may perhaps be to assume that the reductionist approach to science, followed so far, did not create a framework to handle such complex systems as brain, mind and consciousness and so we could, perhaps, try it again with a new, Informatics driven, methodology discussed later in this paper.

[18] There have already been very successful attempts of Informatics to help biology. For example, Informatics methods and tools helped to assemble the human genome and the database of genomes is expected to have an enormous value in our understanding of life and evolution, in health-care and in the development of new drugs and so on.

els, theories and (especially formal) tools to help engineering Informatics to specify, design, verify, analyze and maintain (especially enormously large), concurrent and distributed (software) systems as well as embedded systems.[19]

Another of the big challenges of scientific Informatics is to create concepts models and theories for an understanding of intelligence and basics of intelligent behaviour, as well as consciousness (its origin, scope and functioning), and all that to such an extent that "highly intelligent information processing systems, devices and robots" become a reality.[20]

The fifth of the major challenges of scientific Informatics is to develop concepts, theories, models, methodologies and tools that would lead to the development of very powerful methods to search, mine, retrieve and derive information and knowledge as well as to make hypothesis and formulate theories and all that to such an extent that that could finally lead to *an engineering of the major science making activities.*

The sixth of the major challenges, to be discussed here, is to explore in depth inherent complexity of information processing, communication and interaction phenomena and to find ways for reasonable solutions of computationally very intensive, or even unfeasible, problems, in the current view of the issues, and of the problems requiring to process enormously huge data amounts or data streams.

[19] A part of this challenge is to improve (create) methodologies for design and maintenance of huge software systems, where sometimes several hundreds people need to work several years to create them and the systems are almost continuously modified and extended, to ensure their functionality (correctness), efficiency and security. Another part of this challenge is to develop new design techniques to ensure functionality and quality for embedded systems - systems with a special mixture/integration of hardware and software - that are becoming ubiquitous (95% of chips is curently in embedded systems) and should have several special properties - for example to respond with known and guaranteed delays, to be able to work autonomously and provide service at any time and so on. A way to deal with both of these "subchallenges" seems to be to go through the design of special formal systems and corresponding semi-automatic methodologies.

[20] Systems have already been developed that allow computers to perform activities that used to be considered as being only in the human domain, as hypothesis formation, theories development, proofs designs and checking - and all that to a remarkable (and ever improving) degree.

Observe, however, that it seems to be not the main goal in this area to try to mimic human intelligence by systems of Informatics. The more proper goal is to keep finding, step by step, tasks where such systems can (much) overcome human intelligence as we understand it nowadays.

3.1.2 Comments

The goals of Informatics as a science are much related to those of Physics. The main goal of *Physics* can be seen as to study laws, limitations and phenomena of the *physical worlds*. The main goal of *Informatics* can be seen as to study laws, limitations and phenomena of the *information worlds*. Physics and Informatics can therefore be seen as representing two windows through which we try to perceive and understand the world around us.[21] Informatics, in addition, explores also virtual worlds (created? or discovered? by us). One of the big problems is to explore which of these two worlds, physical and information, is indeed more basic, if any, and to study relations between the basic concepts of both worlds.[22]

The perception of scientific Informatics presented here sees the goals of this discipline in concentration on the study of the fundamental problems of information processing worlds that are, in principle, to a large extent independent of, though often motivated by, current and foreseeable information processing and communication technologies and their applications. The new perception of scientific Informatics considers scientific problems related to the design and application of current and foreseeable information processing technologies as a very important source of motivation and as one of the most important application areas.

Informatics can currently be seen as the leading science and technology discipline, due to its enormous help to and impacts on all other sciences, technologies, medicine, health and environment care, economics, business, music,[23] liberal art and so on. Informatics serves and helps them, guides them and may even transform them and this way bring them to new heights. Informatics has therefore a large *duty* to take care for its proper development.[24]

[21] In a similar way we can see life-sciences and Informatics as providing two windows and tools with which we try to understand, imitate and outperform the biological world and its highlights - human brain, mind, consciousness, and cognitive capabilities.

[22] As beautiful examples of the discovery of surprising relations between different information processing worlds, let us mention two recent outcomes from quantum information processing. It has been discovered that every quantum computation is equivalent to a computing of the Jones polynomial of a particular braid at special values of its arguments (Due to Freedman, Kitaev, Larsen and Wang, 2001 - see quant-ph/0101025) and that every quantum computation can be reduced to computing the permanent of the weighted adjacency matrix of a certain simple graph (due to Rudolph 2009 - see arXiv:0909.3005). Along these lines are also several recent attempts to derive quantum mechanics from information processing axioms - see, for example, Dakić & Brukner, arXiv:0911.0695.

[23] Informatics' tools and methodologies have changed creation and performance of music especially enormously.

[24] There has always been a "Queen of science" with very broad impacts, also on education

3.2 Informatics as an engineering discipline

As an engineering discipline, Informatics concentrates on the specification, design, analysis, validation, verification and maintenance of natural and especially human-made (hardware) devices and (software) systems used for acquiring, mining, retrieving, storing, processing, imaging and transmitting data, information and knowledge, as well as on the development of tools and methodologies (for example specification and programming languages and methodologies) to make efficient use of such devices and systems.

Engineering Informatics also much concentrates on the design of more and more intelligent information processing systems and robots that could either simulate or even outperform that of living beings and especially of humans in various activities.

Information digitalization and (structured and concise) representation; abstraction representation and structuring; designs specification, developments, analysis, validation, verification and maintenance, and so on are some of the main issues.

Informatics as an engineering discipline concentrates, currently, mainly on the development of elements/components, hardware and software architectures and design methodologies as well as systems for storage, computations, imaging, reasoning, (human-machines and machines-machines) communications, networks, internet and web systems and services, social networks services, visualisation, images representation, creation as well as manipulation systems (computer graphics systems), animation, robotics and wide range of other services.

Transistors, VLSI technology, design platforms, chips, CPU, memories (RAM, special memories, memory discs, ...), peripherals, graphic and other cards, drivers and microprocessors are some of the main hardware elements. Pipelining, multicore memories, parallelism, concurrency and networking are some of the main information processing modes. Interface cards, switches, repeaters, bridges and routers are some of the main networks components.

Operating systems, database systems and compilers are some of the major general software systems.

Programs, protocols, syntax, semantics, types, objects, agents, clients are some of the key software concepts. Design techniques (from requirements

at all levels. Some examples: Medicine in Padua and at the same time Theology in Paris in 17th century; Philology during the Renaissance; Mathematics after Galileo's time due to its methodological impacts and partly also Physics in the 20th century mainly due its impacts on the industrial revolution. Informatics is quite fast replacing (expanding/extending) mathematics (that is seen here as being subsumed by Informatics, and the same holds for logic) in its Queen/servant role.

specification) and their (mechanized) support, documentation, architecture, verification, maintenance, portability, reliability, robustness, security, machine independence, reusability are some of the main issues concerning software systems.

Informatics as an engineering discipline concentrates also on theories and methods of information processing and communication systems specification, correct and efficient design, implementation, analysis, verification, evolution, evaluation, maintenance and utilisation.

Concentration is mainly on the development of the underlying theories, methods and tools that are either quite universal or at least relevant to many applications as well as on the use of scientific principles and methods to all stages of the design and maintenance of information processing systems.

Scalability, availability, adaptability, persistence, sustainability, performance evaluation, reliability, virtualization, safety and privacy, as well as assimilation of new supporting technologies and a symbiosis of information processing devices and humans, are some of the key issues.

Miniaturization, low-power consumption, design platforms, increase in performance and reliability, and bio-devices are some of other main current concerns.

3.2.1 Grand challenges of engineering Informatics

Perhaps the most complex, difficult and of the huge immediate importance for the whole society is the challenge to make network information processing and information processing systems secure, in a very broad sense, The objectives of computer and information processing systems security is, in general, to protect integrity and confidentiality of data in storage, during processing and transmissions as well as information processing systems, processes and services from disclosers, tampering, damage or collapse by unauthorized parties and activities (by hackers or malicious programs) or by unplanned events. Problems this challenge requires to deal with are very complex, negative consequences of breaking security can be really huge. It is therefore very unpleasant, and makes the challenge even more challenging, that in spite of a large effort in this area and many local successes, the overall situation can hardly be seen as getting much improved.[25] Security of huge software systems and communica-

[25] The challenges in this area are so formidable mainly due to the following four reasons: (1) Society increasingly depends on reliable functioning of huge software and communication systems (for example those that control major transportation systems for people, goods, energy, water, munition carriers, information, emails as well as in defence, finances, business and so on) and their collapse due to the "cyberattacks" can have enormous consequences; (2) Attackers are in principle capable (due to their larger motivation) to make a faster use

tions in huge networks should be seen as a very global problem of such systems and networks and to solve this problem it is not sufficient to ensure security of its basic components (processes/protocols) related to various security problems of particular data and users.[26] Quite promising, but still not sufficiently explored are the recent attempts to use quantum laws and limitations, such as the no-cloning restriction for quantum information processing, to bring a new level of security - so-called unconditional security, guaranteed by the laws of nature - for certain security tasks.

The second very specific and quite dominating challenge of current engineering Informatics is to develop methods and tools to specify, design, analyse, verify, maintain and make secure enormously and unprecedentedly large and complex software and hardware systems, often ever evolving, the state space of which is often far larger than the state space of any of the systems in the universe. This challenge inspires also much scientific Informatics and its outcomes. Formal systems are perhaps the main basis for the development of powerful and reliable methodologies, tools, systems and finally also skills. Evidence amounts that security issues have to be embedded into all stages of the design and maintenance of huge systems.

The third big challenge of engineering Informatics, again in cooperation

of the progress in sciences and technologies than are able to do so those developing such systems; (3) To achieve sufficient security is so difficult also because strategies and methodologies to achieve information processing systems security are much different from other computer systems design technologies. Moreover, unless security is taken care already in the design process, through so-called built-in security, especially into programming languages and operating systems, what is very costly and cumbersome, it is extremely difficult, almost impossible, to enhance security after the design is finished. To achieve computer security both hardware and software tools as well as the system administration policies have to be used; (4) One needs to achieve multilevel security across multiple networks and domains with a variety of distributed information sources and targets and web applications and to have in such a complex and ever evolving environment well working tools for automatic monitoring and managing security threads; (5) It is very hard to make users to cooperate and to behave in sufficiently security-concerned ways, in spite of the fact that trustworthiness, confidentiality, privacy and even anonymity of information is clearly of large importance..

There is nowadays a whole variety of ways security of information processing systems can be broken and also ways how "cybercrimes" and "cyberterrorist attacks" can be carried out. Viruses, worms, Trojan horses and "denial of services" as well as other malware (malicious software) and spyware, are perhaps the most known ones, but they represent only a small portion of the dangerous systems that have been already identified.

[26] Indeed, there is a lot of sophisticated techniques to ensure integrity and confidentiality of data in storage and during communications as well as identity, digital signatures, privacy or anonymity of users at simple and isolated communication schemes. However, all these problems get a completely different dimension in case of communication in huge (global) networks where it is hard to check or even know all channels information has to go through.

with several other areas of science and engineering, is to keep much improving, following the Moore law as long as possible, performance of information storing, processing, imaging and communication technologies as well as to create technologies to transfer and to reproduce sounds, smell and other sensual information (that seems to be needed to be transferred directly into human brains to create virtual reality). The search for new materials to replace silicon, low-energy consumption, fidelity and cost-effectiveness are the key issues by that.

Parallelism and utilisation of the fragile micro- and nano-world objects and effects, down to the quantum world objects and effects, seem to be the main current way to increase information storage and processing power.[27] Networking and related distributivness in storage and processing seem to be the other way to increase the overall information storage and processing power. There is also a clear need to search for a symbiosis of biological and fabricated information processing systems what could bring, in addition, a very new dimension into the problems of engineering Informatics.

DNA computing is one of the very promising directions concerning nano-computing. DNA can be seen as a quite predictable "digital programmable matter". Nature uses DNA[28] in certain ways, mainly using proteins. However, there is no reason not to assume that we can try to use DNA/RNA in different ways than nature and to build nano-devises including nano-computers. Indeed, DNA computing has been developed already for quite a while as a form of computing that uses DNA, biochemistry and molecular biology to do computation. There have been already quite remarkable successes in doing that. For example, in 2002 a programmable molecular computer composed of enzymes and DNA molecules was announced (by scientists from Weizmann Institute of Science in Rehovot); in 2004 a DNA computer was announced by, E. Shapiro et al., that was coupled with an input and output module which would theoretically be capable of diagnosing cancerous activity within a cell, and releasing an anticancer drug upon diagnosis; In 2009 biocomputing systems were coupled, by scientists from Clarkson University, with standard silicon based

[27]Let us mention some of the remarkable successes along the line of miniaturization. In 2008, scientists from the University of Manchester announced a transistor 1 atom thick and 10 atoms across; In December 2009 a working transistor was announced that was made of a single (benzene) molecule (attached to gold contacts) by a team from Yale University and from South Korea; In January 2010 Intel announced 25nm NAND flash.

[28]In order to give a picture of the role DNA can play in computing let us observe that DNA in each cell contains 3 to 5 millions of base pairs, can be seen as 2m long and 2nm thick and with 750 MegaBytes; in a human body we have 3 billions of cells, DNA as 5×10^9 km long and with 7.5 OctaBytes.

chips for the first time.[29]

In spite of the remarkable miniaturization DNA computing seems to offer, this is still in the framework of classical computing that is based on the laws of classical physics. The attempts to design quantum computers are one of the main driving forces of another very hot area - quantum information processing. The research community in this area is quite confident, but not sure, that this is an achievable goal.

The fourth main challenge of current engineering Informatics, again requiring very close cooperation with scientific Informatics, is to learn to design, analyse and manage global, ever evolving and geographically distributed computers (networks), capable to process, in an efficient, intelligent and secure (and privacy preserving) way, huge amounts or streams of data and tasks, as well as to store most (all) of information and knowledge all fields of science, technology, learning, scholarship, art, medicine and so on produced so far, and in such a way that all can be efficiently retrieved and used if needed.[30]

The fifth big challenge of current engineering Informatics is to design information-processing artifacts inspired by those nature has developed for information storing and processing. Developments in bio-chips, bio-sensors and in-silicon biology are steps in this direction. Cells- and brain-inspired computers are some of the most specific challenges and so are so-called molecular computers. Under intensive investigations are the already mentioned goals to develop powerful quantum processors that could make use of very specific quantum resources.

The design of systems capable of activities that used to be in the domain of living beings, especially concerning intellectual capabilities, and systems imitating behaviour of living beings is another big challenge of engineering Informatics in cooperation with scientific Informatics and several other areas of technology. Of a special interest is the design of robots, namely of robots capable to replace people in situations people can hardly operate in or their precision is not sufficient - in space and deep-sea explorations or activities,

[29] L. Cardelli's web site is one of the best places for informaticians to look for papers and talks on molecular computing.

[30] This challenge amounts, in a limit, to a creation of a heterogeneous, distributed and ever evolving huge computer network(s) (a global computer) accumulating all available knowledge and information producing and processing resources and tools. Design of such a global computer would result in a new synthesis of different areas of science, technologies, environmental and health care and so on with informatics products as a gluing and interacting substance. This challenge can be seen as a limit target of quite a distance future, but particular, and already very powerful sub-goals, huge networks of that type creating various collaboratories, are already on the research or even development agenda.

surgeries and so on.[31]

The design of ever improving virtual reality systems, especially virtual worlds,[32] is another big challenge of Informatics that can have enormous impact on the standards and style of working in many fields, including many sciences and technology fields, as well as on the way people live, develop and entertain themselves. To meet this challenge requires a significant progress in several other areas of scientific and engineering Informatics.[33] It seems that it is quite

[31]A lot of progress has been already done in designing industrial robots to be used in manufacturing, assembly, packing, transport, weaponry and so on. In a quite advance state is the design of artificial hands, walking robots and humanoids robots. Advances in the vision and simulation of other senses are of the crucial importance for that.

[32]The term virtual reality/environment refers to computer-simulations of places and activities in the real world or in imaginary/fantasy worlds. The first basic problem for the design of such systems is to simulate basic sensory experiences with high fidelity and cost-effectiveness. Quite advanced, and believed to come to a very satisfactory state soon, are simulations of the sight and sound (even 3D) experiences. On the experimental level are simulations of the smell experience and cost-effectiveness seems to be the main issue by that. Significant advances have also been in the simulation of the touch experience. For other senses simulations seem to need to manipulate brain directly what is currently on the initial experimental level. The second basic problem is to simulate realistically advanced sensory experiences, especially to handle their changes, of the potential inhabitants of virtual reality, so-called avatars, as they move, handle objects and interact with the environment and other inhabitants. This includes a simulation of locomotion, balance senses, gravity, feelings, facial expressions, gestures and so on.

Virtual worlds are virtual reality systems in which a user (or users) can interact with the environment, with other users and other inhabitants, use and create objects and perform various activities (social interactions, business, shopping, financial and so on) and socialize. One can then talk also about virtual economy, real-estate business, properties and their values, and also advertisements for real worlds in virtual worlds.

Virtual worlds are fast growing in importance and impacts. There have been estimates that the number of people using virtual worlds has been increasing much every month. It has been estimated, for example, that more than 600 millions of people used, at the beginning of 2010, a virtual world and that their uses will be soon so widespread as are that of internet.

[33]Virtual realities can be also seen as systems that create a sufficiently good, for a given purpose, illusion/impression of being either in the current or in one of the past or potential future real worlds or in an imaginary world. The illusion should be good enough, from the point of view of our senses, and impacts of "being" in these worlds on human brain and bodies should be (almost) indistinguishable from those in the real world.

Virtual reality systems currently available are already successfully used in various design and training activities because they are faster, cheaper and allow easily to perform various tests and actions. Museums and galleries as parts of virtual realities are quite clearly within the reach of foreseeable technology as well as visits of various interesting places of nature (as caves) or archaeological and our heritage places. Potential uses of the virtual reality systems for training and education (for example of drivers, pilots, surgeons,[34] parents and so on) and for treatment of various behavioural anomalies and diseases as well as social interaction problems has been also already tested.

possible to fool our vision. More difficult it seems to be to create an illusion of reality that satisfies our hearing and especially our other senses as smelling, touching and various feelings, say those of the movements. Problems are also with making "virtual people" not only to look, talk and move realistically but also to gesture and express feelings and interact convincingly. The main problem is to develop an understanding how much realistic an imitation should be, and into how many details it should go in order to create a sufficiently good illusion of reality.[35]

The design of global warning systems is another big challenge of engineering Informatics that requires a broad cooperation with other areas. The task is to develop theories, methodologies and tools for design, maintenance and updating of global, economical and efficient information systems that would allow in several areas, using proper detectors and sensors, monitoring and surveillance strategies, and methods to process information obtained, to detect signs of potential natural disasters or health emergencies (as pandemics) or bio- as well as chemical terrorist attacks. The task is also that such systems should be able to provide not only early enough warnings, but should also be helpful to implement immediate countermeasures in case such a disaster occurs. That would likely require also to build huge databases cataloging potentially dangerous situations and implementing methods of comparing current situation to those in databases. All that raises the design of huge and reliable software systems and the development of similarity detecting methods as well as networking to new heights. An enormous challenge is also to protect such surveillance and warning systems against misuse of information available and against security attacks.

Another global challenge is to develop Informatics based strategies and tools for personalized (e)learning that would be aimed to increase learning outcomes using systems tailored to specific learning capabilities and motivations of individuals. The goal of scientific Informatics at that is to get a deeper

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The possibility to switch to virtual reality and to live for a while in different parts of the world or even in a different era can bring fascinating personal experiences, enhance people's internal life to new heights and bring also into a new dimension a variety of behavioral and social sciences. Moreover, the possibility to live in virtual worlds as a non-handicapped inhabitant can be of the immense value for handicapped people. The same is true for ill people with limited possibilities to move.

There are already no doubts that design of virtual realities is one of the ways Informatics should go. Less clear is where the limits are such designs can and should go and where limitations are for being useful to do that.

[35]When the idea of having virtual worlds is pushed to its ultimate possibility, the whole range of very specific philosophical, ethical, economical and even human rights and law issues seem to be arising. Boundaries between real and virtual worlds may also be blurry for some.

understanding of the learning processes and on this basis to develop an understanding of ways to improve learning by making it more personalized in a proper way. The goal of engineering Informatics is to develop methodologies and tools for personalized learning and for making these tools easily accessible/deliverable.

Development of the entertainment Informatics is also an important challenge for several reasons: Informatics tools allow to make education entertaining and entertainment educational in the extent that far overcomes what used to be so far - this is not only to improve the school education, but also, and maybe especially, the life long education. The potential for interactiveness and individual fitness are some of the most specific features of the Informatics based entertainment. The entertainment is becoming increasingly more and more important way to enhance life of individuals and to influence the overall development of society. Moreover, the entertaining Informatics has a potential to make also mass entertainment more personal and interactive. In addition, entertainment Informatics is a very important source of particular challenges for other areas of Informatics, especially artificial intelligence, virtual reality and worlds, computer graphics, robotics, human-computer interactions and so on.

The last big challenge of engineering Informatics to be mentioned here is to create information systems to improve health care by making it global and to make also medical treatments more personalised. There is a variety of sub-tasks to deal with in order to meet this challenge: (a) To develop a compressed representation of general biological and medical knowledge; (b) To develop global databases and archives of authorized medical information about individual patients, diseases, treatments as well as of the outcomes of medical research with build-in mechanisms for reliable updatings; (c) To create systems to standardize, store, archive and update authorized medical information in a way that allows its thorough analysis and fast retrieval as well as a protection against loss of confidentiality and misuse; (d) To integrate all kind of networks with medical information (in doctors offices, clinics, regional, national and global) to allow to share medical information; (e) To design systems for tele-diagnosis, for helping in general in medical diagnosis as well as during various treatments and surgeries; (e) To design individual patient-tailored models of human body in order to make better diagnosis and more personal medical treatment; (f) To design micro- and nano-scale robots being able to infiltrate human body for information retrieval and for medicine supplies and treatments; (g) To create systems to guide/replace surgeons and to perform tele-surgeries.[36]

[36]An impressive illustration of the potentials of robot-assisted tele-surgeries was demon-

3.2.2 Comments

- It would not be an exaggeration to say that every significant technological innovation of the 21st century will require to use some, more or less sophisticated, Informatics based theory, technology and methodology. This means that we are facing era in which computing (Informatics) will be central to innovations in nearly every area. In the past, but far, far less, such a leading role had been played only by the steam engine technology and later by the electricity based technology.

- Informatics as a science concentrates on gathering of knowledge. Curiosity and search for knowledge for its own sake should be its main driving forces. Informatics as an engineering discipline has as its main concern demonstrable utility. Improvements of performance and reliability, as well as economical success, should be some of its main driving forces.

  One can also say that the goal of science used to be seen as the quest for knowledge; the goal of engineering used to be seen as the quest for skills. Informatics as a methodology and tools blurs to a large extent this distinction between the goals of scientific and engineering Informatics.

  Current science is often seen as being engineering driven and current engineering as being science driven. The key fact behind is that Informatics paradigms, methods and tools play such a key role in both, in science and engineering. They allow to pursue the quest for knowledge in such a way that engineering outcomes are a natural consequence of it. On the other hand, current top engineering depends much on the scientific outcomes transformed mostly into the informatics driven/supported products.

- The history of Informatics, as an area of technology and science, should be seen as being very old - actually the oldest of technologies and sciences.[37] In order to see properly the history of Informatics as a science,

strated already in September 2001 when a surgery was carried out by a robot in Strasbourg and the surgeon guiding the robot was in New York. A similar challenge is listed in the below mentioned document *Grand challenges of engineering*.

[37] To see the roots and history of Informatics well is of the large importance for seeing properly the essence and, likely, also the future of Informatics as of an area of science, technology and methodology. A proper view of the history of Informatics creates an adequate intellectual framework for an understanding of the long term aims and scope of the modern Informatics and leads to an understanding that the advent and development of modern information storage, processing and communication technologies represent just another important milestone in the history of Informatics. A milestone which has brought new knowledge, insights, tools and challenges, all that of immense importance, but which is actually only one of the milestones in the overall history of Informatics.

it is important to realize that the "twin science" to Informatics is not only mathematics but all (natural) sciences.[38]

In order to see properly the history of Informatics as an engineering discipline, it is important to realize that the "twin technology" to Informatics is not only electrical engineering, but all engineering.

The history of Mathematics should be seen as a (very important) part of the history of Informatics.[39] A very crucial part of the history of biological systems should also be seen as a part of the history of Informatics. Concerning history of information processing devices created by the nature, we are nowadays actually only in the very beginning of its understanding. Similarly, we are still in the very beginning of an understanding of the development of the universe and life as (quantum?) information processing systems.

Distinctions between scientific and engineering Informatics are in many aspects blurry. Engineering Informatics is much helping scientific Informatics in many ways to deal with its main challenges and attempts to explore information processing worlds and our physical and biological nature. Design of various models and simulations as well as virtual worlds is one of the ways to do that. On the other side, engineering Informatics has to tackle specification, design, analysis and verification problems of such a dimension that without the insights, results and tools of scientific Informatics that cannot be handled. Scientific and engineering Informatics are therefore, and should be, developed as partners in the quest for dealing with the most fundamental questions and also with the most difficult design challenges.

[38]This also implies that Informatics can learn much from other sciences and also use their methodologies to study its phenomena. For example, a global computer, or such a global network as the internet, can be seen, in many aspects, as a sort of "living creatures" and can be, and also has to be, explored using also observational and experimental methods of natural and social sciences. In general, Informatics has been designing many other systems that are so huge and ever evolving in a not much coordinated distributive way, as silicon compilers and so on, that they need to be studied by observational and experimental methods of natural and social sciences. That brings Informatics closer to these disciplines. All that also creates a space for influencing Informatics development on the basis of laws, limitations and findings of natural and social sciences. As another example, the so called *scattering theory* of physics has inspired the design of a surprising quantum random walk algorithm to solve the well known game theory problem (of evaluation of so-called NAND-trees) in an asymptotically more efficient way than any classical algorithm does.

[39]The perception of Informatics presented here actually considers mathematics, in a broad sense, as a very important part of Informatics. However, this point is not elaborated more in this (short version of the) paper.

It is well known that progress in science has been much influenced not only by great new ideas but also by great new instruments, Actually, our view of (natural) sciences and their (achievable) challenges has always been much shaped by available instruments as telescopes, microscopes, accelerators and so on. Telescopes and microscopes have changed astronomy, cosmology, biology, chemistry and physics - they increased much information gathering power of our eyes - high energy accelerators allow us to get to the bottom of the matter. The possibility to turn the enormous information processing power of modern computers via sophisticated algorithms and carefully designed software into new powerful instruments has actually much increased frequency of the design of new powerful instruments and by that the development of science and technology, medicine and so on.

- The history of mankind teaches us that no matter how radically new a technology has been, it could have an immense impact on science, technology and society at large, only when a very way of thinking and seeing the world had already been emerging for quite a while in science and society that could make full use of this technology. The history of mankind also demonstrates that the main long run contribution of such a technology has been to help to develop much further this new way of seeing, understanding and managing the world, and to help to make this new view of the world more coherent and more powerful.

3.3 Informatics as a Basis of a New Methodology

Informatics, as a symbiosis of a scientific and an engineering discipline, gives rise, develops and also explores potential and limitations of the basic components, in addition to theory and observations/experiments, of the third, basic and fundamentally new, methodology of the large importance for all sciences, engineering disciplines and society in general.[40]

This new, Informatics-based, or Informatics-driven, methodology provides a new way of thinking and new languages for science, technology and other areas of human and societal activities, extending the Galilean mathematics-based approach to science and technology to new heights.[41]

[40]The existence of a new methodology for science based on modern information processing technology has already been recognized for some time. This has been reflected, for example, by the existence of the "third branches of some sciences", usually called *computational* - for example, computational physics, mathematics, chemistry, economics,....

[41]The existence of a new methodology for sciences, as the one based on the modern information processing technology, has already been recognized for some time and that has

This way Informatics concentrates on developing new, Informatics based, tools for understanding the universe, evolution, nature, complexity, life (both natural and artificial), mind and brain processes, intelligence, security, and other basic phenomena of the information processing worlds.

Let us now summarize some of the main features of the Informatics-driven methodology:

- Modelling (computer/computational)[42] - theories and methods of design, validation and verification of models for different areas, especially of very and ultra complex human-made and nature-created systems and processes.[43]
- Simulation (computer/computational) - theories and methods of design, validation and verification of simulations, as well as of the display of outcomes using imaging, visualisation and animation tools[44]

been reflected in a realization that there are "third branches of some sciences", usually called *computational*. For example, computational physics, chemistry, mathematics and so on.

[42] J. von Neumann nicely formulated that modeling is an important scientific methodology: *The sciences do not try to explain, they hardly try to interpret, they mainly make models. By a model is meant a mathematical construct which, with the addition of certain verbal interpretations, describes observed phenomena. The justification of such a mathematical construct is solely and precisely that is expected to work.* A more modern and more appropriate statement could be obtained from the above claim by replacing the word "mathematical" with "informatics".

[43] Some of the most basic questions concerning modelling: For which phenomena can we design models that are simpler than phenomena we want to model and are still very useful? How to validate and refine models?

[44] Modelling and simulations are two of the most powerful tools to study objects and processes in various areas of natural sciences, such as cosmology, physics, chemistry, biology, material- energy- and earth-sciences; for such disciplines as medicine, health and environmental care, economics . . ., but also for social and behavioral sciences, archeology and so on. In addition, for all major areas of engineering and technology, as well as for the design and manufacturing, in order to produce and test various objects and products. Using simulation one can follow processes that are too risky or invisible because of being too small, or too slow, or too large or too fast. (For example, in molecular dynamics simulations have been reported with billions of atoms and in attophysics simulations involving electronic changes in the attosecond scale.) It is worth to note that an understanding that quantum phenomena cannot be efficiently simulated on classical computers was the first impulse for the idea to design quantum computers and the question which quantum processes can be efficiently simulated on them (and also on classical computers) is one of the most fundamental questions in that area. Problems of limitations and pitfalls of modelling and simulations, both from the feasibility point of view and the point of view of obtaining deep scientific knowledge, belong to the most acute and difficult ones. Simulations of battles, impacts of natural or men-made disasters, earth and atmosphere processes and so on belong to the ones requiring the largest computer power available; simulations for entertainment industries, especially

- Visualisation and animation theories, methodologies and tools;[45]
- Virtualization, formalization, digitalization, (multilayer) generalization, (structural) composition/decomposition, reduction as well as approximation and other abstraction-driven methodologies and tools the importance of which has been verified in the development of mathematics;
- The design of virtual reality systems including virtual worlds.
- The design of (productive, clever, cooperative, emotionally intelligent and trustworthy) robots and other intelligence intensive systems;[46]

motion pictures, computer and video games, belong to the most interesting, stimulating and challenging ones. Improvements in the area of computer technology, but also in the design of algorithms and software systems, open usually new domains where modelling and simulations are feasible. Observe that the first large scale and influential simulation was done in 1953 by E. Fermi, J. Pasta and S. Ulam in Los Angelos laboratory - to understand behaviour of large non-linear systems and their supposed tendency to decay to states of ever greater disorder.

[45] It is quite obvious that visualisation helps much to better understand very small and very large objects, as well as very fast or too slow processes. Less obvious is that visualisation can help to get deep insights into phenomena where there seems to be nothing to visualise. Fractals are perhaps the most widespread example of this type that have shown incredible complexity behind apparently extremely simple processes. Visualisation becomes an important tool also in such anti-visual areas, at the first sight, as pure mathematics. 3D visualisation and animation start to be of the key importance in (molecular) chemistry, biology, medicine, but also for the entertainment industry.

Observe also that visualisation and later de-visualisation of mathematical objects used to be important steps in the history of mathematics. Visualisation has played an important role at the birth of science, in the Golden era of Greek science - they concentrated their "scientific effort" mainly into the study of geometrical objects that could be visualised. Later, formula languages to express algorithms of algebra and calculus had enormous impacts on their developments because they made thinking about them much more efficient and more precise. On the other side, the algebraisation of geometry, in the 17th century by Descartes and later the Bourbaki's approach to mathematics can be seen as very important de-visualisation steps that paved the way to larger abstractions in mathematics. One of the reasons for that has also been the fact that tools for visualisation at that time were quite primitive. This has changed recently and so we can witness a rebirth of visualisation also in mathematics.

[46] The point is that powerful and universal (information processing) artefacts provide by themselves often also important means to understand phenomena of the nature through the study of the (simplified) phenomena occurring at the design and use of these artefacts. Indeed, many of the most general and powerful discoveries of science have arisen not through the study of phenomena as they occur directly in nature, but, rather, through the study of phenomena in the human-made artefacts, in products of technology as well as of phenomena in virtual worlds. All that is also one of the main reasons why we should try to design powerful quantum computers - to understand better mysterious and often counter-intuitive phenomena of the quantum world.

- An application of data mining, pattern matching, information retrieval, knowledge discovery and hypothesis formation as well as learning systems to huge sets or streams of data provided by sensors or obtained due to the digitalization processes.[47]

- The design of systems for (automated) problem solving, reasoning, theories creating, proof checking and theorem proving and of other systems to deal with the tasks that used to belong to the human domain only;

- The development of methods to specify, design, analyse, verify, modify and maintain very complex, parallel and distributed (information processing) systems.

- The development of methods to design algorithms and protocols, to analyse their performance and to explore the inherent complexity of computational, communication and description problems, as well as to study complexity classes and their mutual relations - as a way to get a deeper understanding of various phenomena concerning efficiency and their interrelations.

- The development of methods to design, analyse and compare descriptional languages and systems and the relations between objects and their specifications.

- The development of methods to replace hard to deal with algorithmic goals by more easy and still good enough ones. One of the key practical (theoretical) concept behind is that of practical (polynomial time) distinguishability. The goal to design an object O can be replaced by the goal to design an object Q that is, for all practical purposes (in polynomial time), indistinguishable from the object O. The replacement of the goal to do something for sure by the goal to do that with as high probability as we need used to be another extremely important step along these lines - to make theory less idealistic and still useful enough.

The new methodology can therefore be seen as a toolbox of more or less correlated intellectual tools and products of technology that serve various purposes and can be used to handle a large variety of problems.

The power of the new methodology is, mainly, in the following:

[47] Such techniques allow us, in addition to other advantages and uses, to discover sometimes otherwise hardly noticeable phenomena and relations and to inspire new theories.

- New methodology brings a new dimension to both old methodologies;[48]
- It subsumes and much extends the role mathematics used to play in helping and guiding other disciplines;
- It provides a powerful alternative to so far dominating reductionism in science as its main methodology.[49]
- It brings into new heights an enormous power of modelling (mainly mathematical before) and simulation;[50]
- It allows to utilize better an enormous power of visualisation and animation;
- It utilizes the potential virtual worlds bring for an understanding of the real world and also for enjoying living (in the real world);
- It allows to make use of the old observation that the designs and study of information processing models, systems, as well as simulations/imitations of life and living systems, such as robots and other

[48]For example, computer simulations nowadays far exceed what could even be imaginable when former paper-and-pencil simulations of mathematical models were used.

[49]Reductionists view the entire universe, from its beginning in time and from particles (or the Planck scale) to galaxies, as being governed by so simple rules/laws that they are comprehensible by human mind. Telescopes and microscopes, which allowed to see and study macrocosmos and microcosmos, their increasing performance that culminated so far with gigantic high-energy accelerators, and discoveries due to them much supported the reductionist view of science. That led to the view that physics is the only fundamental science, chemistry is an applied physics, life is created by complex chemical reactions and various particular steps in the biological evolution, as speciation and emergence of humanity, are only due to various random events. The non-reductionist (holistic) position is to a large extent based on the possibility of computers to model interactions of a huge number of simple elements and to build computer models so complex that they are not understandable by human mind and that this brings very new tools for science to ask and to answer new questions, to study emergent phenomena and to formulate new hypotheses and theories. On a more theoretical level, it is believed that there are "emergent" phenomena exhibiting properties that cannot be explored/understood by examination of the system's parts. This is especially true in quantum information processing, where it is of key importance that some states (so-called entangled states) of a composed quantum system cannot be composed of states of its subsystems. (Quite surprisingly, exactly these states seem to be behind the fact that quantum algorithms can be for some tasks more efficient than classical ones.)

[50]The scale of events that can be now simulated far exceeds anything even imaginable when only paper-and-pen simulations were possible. One of the most fundamental questions concerning simulations is which processes can be simulated sufficiently well by systems that are (much) simpler than systems to be simulated.

"intelligent" systems, can bring a deeper understanding of the life and nature phenomena;

- It seems to have a big chance to make hard sciences from some (many) [most of] soft sciences;
- It brings a new dimension to the study of complex and chaotic systems.[51]
- It provides a deeper reason why fluency with the basic information processing tools should be considered as a basic skill that needs to be learned and taught at all levels of education.
- It provides a basis for the development of *computational thinking*, at various levels, as a new fundamental thinking framework, tools and skill sets to enhance capabilities of individuals and the society to bring their intellectual, social and economic well-being into new heights.
- It creates a basis and a potential to develop new quality scientific and engineering tools and skills to make science in general, what is another great challenge of Informatics.
- Informatics methods and tools show us new aspects of reality be it of the nature, society or people.

The power of the Informatics-based methodology is not in all aspects based on a fluency with information processing technology, but it can be in many aspects much enhanced by that.

The Informatics driven methodology is starting to have big impacts also on the philosophy of science. On the way we see goals of science, the character of scientific research, scientific methods, ways knowledge is produced, the character of knowledge and of the scientific truth, the level of precision we drive for and is sufficient for us and so on. For example, one of the basic assumptions of science was the belief that natural sciences should concentrate on the study of simple systems that can be sufficiently well specified by very few qualitatively different parameters and so they can be handled by human mind. Physics has been then the most successful natural science because many important physical phenomena could be described by equations with only few parameters specifying their qualitatively different features. That was actually all human mind, unaided, could handle. However, the nature and society contain also systems, as human body or brain, that are clearly not of that type.

[51] An important outcome of computer simulations has been the discovery of the deterministic chaos and of various (even strange) attractors.

The number of distinct parameters needed to specify them well can be huge and such systems the pre-Informatics science could not even consider as the subject of the real interest.

Observe also that at the birth of modern science there had been the shift from the purely logical to mainly mathematical description of nature. In a similar way we can see the birth of Informatics driven science as being represented by the shift from the mainly mathematical description of the nature, life and society to a more adequate information processing description. Observe also, in this connection, that it is much due to the use of Informatics based methodology that biology, medicine and neuroscience are currently at the frontier of the research interest.

In the rest of this section we deal in more details with some of the important features of the Informatics-driven methodology.

3.3.1 Knowledge creation and dissemination

The Informatics-driven methodology is in its full power behind various new ways knowledge, especially scientific and engineering, is obtained and disseminated.

To the most basic ways belong those fully utilizing, in a quite straightforward way, an enormous information processing power of a modern information processing technology combined with various searching engines, and information and knowledge detecting, mining and retrieval methods when applied to huge data and information sets. This includes patterns and similarities detection tools; hypothesis formations; automatisation of some of the key intellectual knowledge formation processes as well as the performance of intellectual processes not tractable by humans.[52] These methods and tools can be used especially in such huge data sets driven areas as astronomy, particle physics, earth-sciences, material-sciences, energy-sciences, life-sciences, archeology, economics, social sciences, history and so on.

To the more sophisticated features of the Informatics based methodology belong: design and analysis of models, simulations, visualisation, virtualization, ...

To the most sophisticated ones, and often to the most powerful ones, belong those that are information processing technology independent and allow to transform fields by new ideas through asking new types of questions.

The potential of the Informatics-driven methodology for knowledge creation depends so much in many areas on how much of the available information and

[52] For example, some computations and also proofs are co complicated that they cannot be done and checked without computers and proof checkers.

knowledge is digitalized and stored in a properly structured form and on the truth-worthiness of such information and knowledge.

A big challenge of Informatics is therefore to deal with huge scientific, engineering and methodological problems related to the task of digitalization and storing, for various areas, of all available information (for example medical information and records) and knowledge in a proper (and compressed) form that allows its searching, mining, retrieving and verification by anyone, from anywhere and anytime in a reasonable time. The development of the procedures for ensuring and checking truth-worthiness of information in such global memories, as well as of its updatings, is another big challenge of Informatics.

The last two challenges are much related to the new ways knowledge is disseminated, taught and learned because all these processes depend in an increasing way on information and knowledge in globally accessible memories.[53]

3.3.2 From *computational thinking* to *Informatics thinking*

The basics of this new, Informatics-based, and ever evolving methodology and the use of the related tools should be taught, in the corresponding form and proper contents, at all levels of education in order to develop so-called *Informatics thinking* - a new (and much broader and deeper) perception of the so-called *computational thinking* that is currently under various considerations, as discussed below. The impacts of the development of Informatics thinking could be summarized as follows.

- A better use of the potential of information processing and communication technologies.
- A creation of a basis for life-long (self)-learning of ever newer and more sophisticated information processing concepts, methodologies, technologies and skills.
- An increased interest of potential students in the study of Informatics, what should be in the overall interest of society.
- An increased capability of individuals to be more mature in thinking in many disciplines because thinking in these disciplines, from the basic paradigms to the most powerful methods, is going to be much influenced and shaped by Informatics thinking.

[53] For example, information and knowledge presented in such encyclopedias as Wikipedia and their trustworthiness have an enormous impact on the whole education process and actually on all intellectual processes.

- An increased quality of work force in general and especially in all areas of science, technology, economy, health- and environmental-care, and so on, that would lead to an increase in the potential of society to handle its problems.

- An increased quality of life of individuals by increasing their capability to act intelligently and efficiently as well as their capability to enjoy living not only in the real but also in virtual worlds.

- An increase of the overall problem understanding and solving, systems designs and analysis as well as complexity managing capabilities of individuals and of the whole society.

In short, the basics of the new methodology would enable personal empowerment leading to a new quality in the intellectual and social well-being of individuals.

The goal of the education in Informatics thinking can also be seen as an expansion of human capabilities through new abstract concepts and tools as well as through information and knowledge inquiring, processing and communication tools to help to manage complexity and allow automatisation of tasks.

Informatics thinking, as a way to enhance thinking by using paradigms, insights, concepts, methods and tools of Informatics as presented here, can therefore be seen as a proper basis for currently under consideration a very important effort to enhance our educational processes by new features often labelled as *computational thinking*.[54]

To summarize, Informatics thinking can be seen as a capability of individuals to use knowledge provided by Informatics as a science, thinking paradigms and methods provided by Informatics as a methodology and a contemporary technology provided by engineering Informatics to deal with a broad range of personal, job and society problems. A deeper understanding of the concepts, potentials and limitations of the all above mentioned features of Informatics thinking and the capability to consider related cost/benefits trade-offs as well as to apply correctness checking procedures in general are another key

[54]The attempts to see the scope and the nature of "computational thinking" in the recent workshop *The scope and nature of computational thinking*, organized by the National Research Council of the National Academies in USA, have been based almost exclusively on old, more narrow, less deep and actually diverse views of *Computer Science*. It is therefore of a little surprise that intersections of the views of almost any two participants of the meeting, concerning the nature and the scope of computational thinking, were very close to being disjoint. This can be seen as a certain indication that the whole (so important and well intended) effort has been still missing the point.

aspects of Informatics thinking. In addition, one can see Informatics thinking as providing a variety of new cognitive tools for a broad range of intellectual activities.

Informatics thinking includes a variety of features of diverse complexity. The most advanced ones are oriented to the scientific and engineering communities; others to professionals in non-technical fields including social sciences, humanities, art, music and so on. The most basic ones are oriented to all members of society and some of them, like programming[55], in a very general sense, should be taught, in a proper form, even during the pre-school education processes.

One of the practically important questions concerning Informatics thinking is how to teach it and especially what a proper sequence of educational steps in order to develop Informatics thinking. This is a question that does not have a simple answer. In this connection it is of importance to point out that frequent attempts to compare Informatics thinking to such skills as reading, writing or arithmetic are missing the point. More to the point are attempts to compare Informatics thinking to scientific and engineering thinking and actually to see Informatics thinking as a more complex one than both of the last two. A proper combination of basic educational programs in scientific, engineering and methodological Informatics and a demonstration of them on applied tasks is, likely, a general way to proceed. Some aspects of Informatics thinking should be formulated and demonstrated during teaching processes of all subjects.

To conclude, scientific, engineering and methodological Informatics provide a unified framework and language to develop Informatics thinking.

It is also worth to observe that the new methodology creates also a new class of scientists - in addition to theoreticians and experimentalists we have now also scientists that understand and master the Informatics-driven methodology, have a different approach to knowledge acquisition and use also different tools for that.

3.3.3 Case study I - Modelling and simulation

On a pragmatic basis, modelling and simulation of very complex phenomena are some of the main driving forces of current Informatics. Especially modelling of the earth, atmosphere, nature and environmental phenomena such as climate and weather, but also of battles, economics, financial systems,

[55]By programming it is understood here the capability to describe unambiguously a process as a sequence of elementary steps fully understood by an agent that is to perform the process.

molecules, human organs and especially of the brain and cells as discussed below. To demonstrate that let us notice that the far most powerful current computer system, Roadrunner, with a theoretical (demonstrated) performance 1.7 (1.1) petaflops and occupied space 260 m^2, has been developed by the IBM for Los Alamos National Laboratory to model the decay of US nuclear arsenal.

Observe also that modelling and simulation environments, such as LOGO and NetLogo, suitable to explore emergent phenomena, are some of the most elementary ways to educate in Informatics thinking on the very basic pre-school level.

On a more foundational level, modelling is in the heart of the new, Informatics-driven, methodology in the following sense:

In classical ancient Greece, methodology in science was driven by philosophy. The underlying assumption was that phenomena of the nature are not under the control of Gods, but that human mind is powerful enough to discover basic qualitative axioms (truths) and deduction rules. The goal of science was to understand the *causes of phenomena* of the nature. Since the Galilean time, methodology was driven mainly by mathematics. The underlying assumption was that God created mathematically expressible world and let it run according to simple and mathematically expressible rules. The goal of science was to discover such rules (and to demonstrate by that God's geniality). Understanding developed that it is not absolutely necessary to know the causes of phenomena, but that is to a large extent sufficient to know explicitly the most important *relations* among some quantitative characteristics of the phenomena, because they can be sufficient to make useful and important predictions concerning the behaviour of the phenomena of physical nature.

In the current, post-computer, era, methodology in science and technology is driven by Informatics. The underlying philosophical assumption seems to be that we do not always need to know explicitly neither the causes of phenomena nor all relations between their important quantitative characteristics. It is sufficient to design a (static or evolving (with potential of learning)) oraculum, that is a mathematical or information processing *model of the phenomena*, especially if it is a system of mutually interacting parts, that can be used, especially through simulations, to provide, or even visually display in an inspiring way, outcomes and answers to various important questions of interest about the given phenomena.[56]

Modelling and simulations are the key methods in such disciplines as earth-sciences, environmental sciences, behavioral sciences, (system) biology, (molecular) chemistry, (particle) physics, material- and energy-sciences, economics,

[56] In this connection it is worth to mention that the Gödel's incompleteness theorem denies us the possibility of constructing a complete and consistent description of the nature.

social sciences and so on, where one needs an understanding of the complex phenomena produced by large amounts of interactions of various simple processes and/or neighbouring elements.

Simulations and modelling provide a completely new view of reality that is often the closest one to reality we can have. The more complex and the more modifiable these systems are, for example by changing (or even reversing) the flow of time, or by zooming, or by changing the flow and amounts of various resources, the better understanding of reality can be obtained that way. In general, modelling and simulations allow us to use virtual worlds in a very effective way to get deep insights into the real world.

Computer modelling and simulation of big molecules and their dynamics is one of the big success stories in the area with big impacts on design of useful molecules and drugs. Several factors are behind. Powerful (parallel) computers, good sets of test data and deep knowledge and expertise available. All that opened new windows to see the world of molecules and gave rise also to new fields such as protein dynamics.

Modelling and simulation of the human brain is another very challenging task for modelling that is expected to bring huge benefits for medicine (to treat brain diseases and disorders via drugs and implants, to deal with memory, hearing and vision problems and so on) and also for Informatics (to inspire the design of computers with novel types of parallelism and also the design of artificial intelligence systems of a novel type).[57]

Another of big challenges of modelling is to understand cells - an important information processing devices - at least to such an extent that would allow to diagnose their malfunctioning and then to cure or repair them. Cells, and biological systems in general, can be seen as well-organized autonomous systems of many discrete interacting components and biology accumulated often huge amounts of knowledge about their basic components. This is especially true for the main components/macromolecules of cells: nucleic acids polymers - DNA and RNA - proteins and membranes, but all that provides very little insights into how cells work as a whole and how they process information. What is needed is to understand cells and their main components, and also other biological elements, as systems of interacting components that abstract from their chemistry. To do that through continuous mathematical models would require to simulate huge amounts of differential equations and that is unfeasi-

[57]The Blue Brain project of the Brain and Mind Institute of École Polytechnic in Laussane, which started in 2005 and aims finally (in 10? years or so) at the simulation of the entire human brain down to the molecular level, is of a special interest and importance in this context. The overall goal of the project is to study the brain's architecture and behavioral principles.

ble. A way out seems to be to create automata models of cell behaviour in the form of several discrete, concurrent, asynchronous and heterogeneous models of interacting elements, to study its behaviour and emerging properties and to try to improve the models on the base of new discoveries of biology and also to put before biology, on the bases of simulation outcomes, new questions to answer by a biological research. The interaction models of the above type are some of the most difficult for Informatics to handle and analyse, and so deep results of the concurrency theory and of other areas of scientific Informatics need to be used. A good idea is also to make such models as programmable ones and that then requires to create appropriate programming languages and methodologies. A huge problem is how to validate such models and how to find out in general when a model of biological systems is sufficiently good. At another extreme would be modelling of large animals. To deal with such models is the goal of the new interdisciplinary research area called system biology.[58]

Potentials of modelling and simulations for getting knowledge about the phenomena of nature have been for a long time questions for hotted debates. At the extreme is likely the question how much they can help at discovering the origin of life - of the ways life could arise - in the case it has not been imported to earth, as well as at understanding of the evolution.[59] In spite of the fact that modelling and simulations may have their limits concerning the possibility to find the full truth, they are surely a way to show weaknesses

[58]For more details see L. Cardelli's *Abstract machines of systems biology.* System biology is also a very good example to illustrate some basic problems of informatics-based modelling. The idea to complement the reductionist approach to biology, which concentrates on taking complex systems of interacting components apart and then studying their components, by a concentration on modelling of complex systems and interactions in them as a whole, had appeared already before 1970. However, it has not been much successful until an understanding has developed that not only classical mathematical models can be used, but also computational, automata-like, models can be the more proper ones. In addition, until ways have been found to obtain much more and much higher quality data and also more powerful computers started to be available to design, validate and refine more realistic models and to perform larger scale simulations sufficiently fast in order to explore interesting emergent phenomena and to create on their basis new interesting and testable hypothesis and to test them then by experiments.

[59]There have been strong views that modelling and simulations (alone) cannot provide sufficient evidence for the origin of life. However, simulations can allow to work with much more complex models than are real phenomena one is able to create in laboratories. This could perhaps be used to explore potential ways life could emerge because it seems to be quite likely that it has emerged and sustained under quite complex circumstances valid for quite a while. Modelling of interactions of various chemical and biological substances under complex conditions and with complex environments could lead to plausible hypotheses and predictions that need to be then verified and tested. Stuart Kaufman has been perhaps the first attempting to do that though much more complex models may be needed.

of some hypothesis and to suggest new plausible hypothesis. Modeling and simulations may also be not a way to get deep insight into the phenomena, and to have by that a great explanatory power, because models can be much too complex for human mind to comprehend and the nature too complex, but these models may be anyway sufficiently good because they may have a large predictive power and so be very useful.[60]

Of a special interest is modelling and simulation in the research in computational/artificial life. This research is believed to be able to put at least new light on some of deep problems of biology and to create systems that help us (using a new type of slaves) to solve some of our problems. The attempts to separate the view of life by what it does from the one by what is made from is surely an interesting and well justified field of research and it only remains to see how much useful will come out of that. One can also say that the goal of the artificial life research is to help to broaden the empirical database of biology as a science.

Computer modelling is very successful in the areas with deep knowledge of the phenomena consisting of an interaction of several simple components under quite well understood rules. This is often the case for phenomena in physics and chemistry. In such cases models and their simulations can deepen our knowledge of the phenomena. The other case are the phenomena where we still do not have deep knowledge and the goal of simulation is to use the enormous information processing power of computers to analyze a lot of data and by that to create a basis for the discovery of various patterns and for generation of hypothesis - in such cases we talk about phenomenological models - as it is the case in such areas as social sciences, psychology, economy and so on.

There are views that the information processing viewpoint of the physical reality cannot explain what could not be explained in traditional terms. This is, however, missing the point. The information processing view of the physical world creates a new framework or perspective to think about the real world and allows to derive knowledge that can otherwise be hardly obtained. For example, the complexity theory considerations can rule out some physical theories by proving that they would imply the possibility to make feasible problems feasibility of which the results of the complexity theory (practically) ruled out.

Some complex phenomena of nature and society cannot be dealt with using

[60]Behind the belief that modelling and simulations could, perhaps, help to discover the origin and evolution of life is not the old idea that general mathematical principles or rules may underlie the patterns of nature, but the idea that information processing principles, which have randomness built in and its laws and limitations "under control", may underlie the patterns of nature.

experimental methods due to practical or even ethical considerations; modelling and simulations are then the main available methodology to deal with them.

3.3.4 Case study II - Algorithmic and complexity considerations

1. Discovery of a new data structure or an algorithm can revolutionize the way scientists think about a problem and can also be an impulse for creation of a whole new research area or even of a research paradigm. Some examples:[61]

- Schnor's exponentially faster matrix multiplication algorithm showed that natural goals to find most efficient algorithms for given algorithmic problems may lead to very unexpected outcomes and to deep insights into the whole class of problems.
- Discovery of the **NP**-complete problems by Cook created a new way to look at a huge variety of algorithmic problems in almost all areas of science.[62] .
- Freivalds' randomized algorithm for matrix multiplication testing in 1975 (and discovery of some other fast randomized algorithms for important problems, such as primality testing) much contributed to the understanding of a huge information processing power of randomness as a computation resource and created a brand new paradigm in information processing.

[61] It may seem as "carrying woods into forest" to emphasize the importance of algorithms nowadays. One of the reasons for such a position is that history is full of important algorithms and algorithmic methods: starting from algorithms for elementary arithmetical operations and square root, Euclidean algorithm, solution of quadratic equations, Runge-Kuta method, Gauss elimination, Newton approximation method, Fast Fourier transform, Ford-Fulkerson algorithm, Knuth-Morris-Pratt algorithm, Simplex algorithm, Quicksort, Metropolis algorithms, Grover algorithm, divide-and conquer, dynamic programming, Monte- Carlo methods and so on. Less known is that it has been a period in not too much distant past when even the word "algorithm" denoted products a real (pure) mathematicians could hardly be proud of. All that went so far that mathematics considered algorithm design as a so insignificant or even meaningless methodology that one of the main, and in many ways excellent, books about the history of mathematics with many deep insights - due to M. Kline (1972) with 1253 pages (a 1990 edition) - does contain only a single occurence of the world *algorithm* - and only as a part of a hard to express otherwise name - Euclidean algorithm (to compute the greatest common divisors).

[62] There are, for example, by Google Scholar, more than 4700 (3200) [500] papers in physics and chemistry (economics) [music] only referring to **NP**-completeness.

- Shor's quantum factorization algorithm gave the main boost to the important field of quantum information processing and Bennett& Brassard quantum protocol for unconditionally secure generation of shared classical keys gave rise to an important field of quantum security/cryptography.

2. The study of the inherent complexity (computational, communication and descriptional) of phenomena and especially of the feasibility issues is also an important methodology to influence and guide research directions. Some examples:

- Quantum information processing. It was mainly due to the quantum complexity outcomes that the scientific community started to believe that this area may have a big potential and one of its main goals - design of powerful computers - could be worth of a (very) large experimental and design effort. The complexity theory keeps having deep impacts on the whole development in quantum information processing and communication. One can even say that one of the goals of the quantum complexity theory is to challenge our basic intuition how the physical world behaves.[63]
- Using computational complexity theory reasoning it has been possible to show that various modifications of the current quantum theory are extremely unlikely to work because that would allow to solve in polynomial time problems that are complete for complexity classes believed to be far larger than the class **P** of even the class **BPP** of feasible problems. Moreover, using communication complexity reasoning it was possible to show, by van Dam, that so called PR-boxes, exhibiting stronger correlations than quantum ones, cannot exist.
- Computational complexity considerations play the key role in modern secret key and also public-key cryptography and actually in all other areas of security. secrecy, anonymity, privacy and trust.
- Definition and study of complexity classes and their relativized versions is an important way to find some order in the very complex world of complexity. There are so many complexity classes defined and investigated so far that one can talk about a ZOO of complexity classes with at least 500 interesting classes.

[63] Such key quantum complexity concepts as **QMA**-completeness, a quantum analogue of the classical **NP**-completeness, start to play the key role in the understanding of complexity and feasibility of various very basic quantum processes.

3.3.5 Philosophy of science

A big challenge for scientific Informatics as well as for Informatics as a methodology is to revitalize the philosophy of science and to find out what the goals, methods and tools of science are in the new, Informatics driven, era of science.

Revolutions in physics and biology at the end of the 19th century were accompanied by intensive philosophical discussions concerning the goals, methods and tools of science. At the end of the 20th century the philosophy of science was almost dead. It was not fashionable to talk about science. The mood shifted to doing science. Now, with the new scientific methodology available, most of the old questions come up in a new setting.

For example, the goal of science was to get an understanding of nature through fully understandable models and reductionism was the main method. It is getting clear that some key phenomena of nature and society are so complex that any reasonable and useful model of them has to be too complex to be fully understandable by people. It seems that our goals have to change - we can be, and have to be, in some cases satisfied with models that are too complex to be fully understandable by people in the case we would be able to work with them, with the help of computers, and to make a predictive use of them or to be inspired by the outcomes of their simulations.

Another questions of importance are: What are big challenges of science?[64] Really big challenges had always a science fiction flavour.

3.3.6 Comments

Informatics with its tools and methodology keeps slowly revolutionizing the overall situation and style of work in all academic disciplines. The present role and future promises of theory keep much increasing in all areas of science and technology because using Informatics methodology and tools (a) theory can make much faster than before new knowledge to be useful; (b) it can much faster than before produce new knowledge; (c) it can create much faster than before new challenges and can open new frontiers for the experimental/observational research and (d) it can much faster than before react to new discoveries of experimental research and to come up with innovative theories or explanations of new mysteries revealed by experiments. Theory can now also much better help to create and control experiments. All that has very much amplified the outcomes and applicability of the theoretical research in

[64] Physics brought the view that only an understanding of time, space, the origin of the universe and the origin of life are really big scientific questions. The rest was seen as "stamps collecting" Is that still true? What are the main challenges of science in general in information processing worlds? Can machines be better scientists? Soon?

general. On the other side, Informatics keeps bringing also the experimental research into new heights by providing it with new facilities to realize much more sophisticated experiments and to process fast enormous amounts of data obtained from experiments. To summarize, Informatics creates a powerful bridge between theory and experimental/observational parts of sciences and much contributes to the increase of the pace of discoveries across all scientific fields. Moreover, Informatics concepts and tools developed due to the motivations and needs of one academic discipline find nowadays very often and fast use in different academic disciplines what again increases their importance.

Informatics with its methodology and information processing tools brings also a new view of theory in many academic disciplines that see theory as consisting of three much interrelated parts: (1) conceptual theory - a part creating proper concepts, theories, insights and paradigms; (2) computation-intensive theory - a part concentrating on producing algorithms, protocols and so on and using computers to obtain knowledge, hypothesis, theories, proofs and so on; (3) modelling and simulation - to design, analyse, validate, use and refine models through their simulations.

3.4 Applied Informatics

The main applications of Informatics in academic domains consist in an infiltration of its concepts, paradigms, methods and tools to other academic disciplines. This allows not only to solve problems in these disciplines that were out of considerations before the so powerful information processing and communication tools were available. The most important is that Informatics thinking, results and tools allow to ask new questions in all academic disciplines, questions that could not be asked before and especially questions the answers to which may revolutionize thinking in the field because these questions are of a different type as those which used to be asked so far - more sharp and questions where quantitative answers are possible and needed.[65] In-

[65]For example, it is quite clear that there are questions that cannot be answered unless huge amounts of data are collected and processed. This is the case in astronomy, earth sciences, material sciences, particle physics, biology and so on. Less obvious is that there are special types of Informatics-driven questions that can have other enormous and fundamental impacts. For example, questions about the information processing power of quantum phenomena revealed an enormous power of quantum entanglement and non-locality. That is of the features that used to be seen as strange, counter-intuitive and useless and only as impacts of a not perfect mathematical formalism that could not fully capture the physical substance of quantum phenomena. Questions about the information processing power of quantum phenomena arised also new fundamental scientific questions as is the following one: *Is our world polynomial or exponential?*, as stated by S. Aaronson, As another obser-

filtration of Informatics thinking is expected to be so deep that (almost) any academic discipline X can be expected to have soon, as one of its most important sub-disciplines, X-Informatics.[66] Similarly, researchers in any major area of science are already being identified as either theoreticians, experimentalists of computational/Informatics specialists.

Applications of Informatics are ubiquitous and not only in the academic disciplines - almost everywhere. The evidence is mounting that no other area of science and technology has so widespread and so important applications in practically all areas of human and social activities. Moreover, one of the key features of the future society is expected to be a symbiosis of humans and intelligent information processing machines and systems. It has also been slowly understood that paradigms, concepts, methods and tools of Informatics will deeply penetrate most of the basic human activities to such an extent that under serious considerations is the idea how to promote and incorporate into basic educational processes basics of the corresponding Informatics (computing) thinking - as already discussed.

Informatics is aware of its potentials for applications and takes special, and quite unique, care to facilitate its applications, especially in the following ways.

1. Informatics makes fast and successful steps, in cooperation with other areas of science and technology, to achieve its goal that information processing "energy" is available easily, anytime, everywhere, to everyone and from everywhere.[67]

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vation along these lines, let us realize that it is still not clear whether quantum information processing attempts to have powerful quantum computers will not fail because it still may turn out that there are some deep, so far not yet discovered, physical limitations for having powerful quantum computers, and all that could lead, due to the Informatics based challenges, to the discovery that our best theory of nature needs a revision - or even a substantial improvement. Would this be the case, that would be the most important (so far) case how Informatics-inspired challenges changed another science. Actually, there are already theoretical groups trying to develop some alternative theories to quantum mechanics and also experimental groups trying to test alternative theories based on various collapse models. In addition, it would actually be very surprising would Informatics did not have even larger impacts on other scientific theories, especially on biology and so on.

[66] For example, to advance health-Informatics has been identified recently, in the above mentioned *Grand challenges of engineering*, as one of the 14 grand challenges for engineering.

[67] In this connection, it may be worth to mention the following view of the history of mankind as consisting of three (overlapping) eras:

Neolithic era: Progress was made on the basis that men learned how to make use of the potentials provided by the biological world to have **food** available in a sufficient amount and whenever needed. (With religious and philosophy as *"sciences"* in behind)

Industrial era: Progress has been made on the basis that men have learned how to make use of the laws and limitations of the physical world to have **energy** available in a

Design of global sensors-, surveillance- , as well as computers networks, through the development of grid computing, peer-to-peer computing, wireless- and mobile- as well as cloud computing, ...; development of better and better web services (as the semantic web promises) and search engines, are some of the main current steps towards that goal.

In all these areas goals are so ambitious that one starts to talk about global computing on one side and on "dust and clay computing" and molecular computers to explore human cells on the other side.

2. Informatics makes fast and successful steps, in cooperation with other areas of science and technology, to achieve that data mining and information/knowledge retrieval devices, as well as information processing and providing systems, penetrate "everything and everyone" - that information processing is so ubiquitous that it is thoroughly integrated into many objects and activities even of our everyday personal and domestic life.

Design of embedded systems, developments in so-called ubiquitous/pervasive computing, as well as in the so-called ambient intelligence, are some of the main current developments towards that goal.

One of the most ambitious sub-goals is to embed nano-scale monitoring, data retrieving and drugs delivering systems (to proper places) into human bodies. A perhaps bit less ambitious goal is the design of domestic ubiquitous computing and robotic environments.

Nano-scale miniaturization and low-energy consumption are some of the main issues in this context. Embodiment, environment/context-awareness, adaptivness and anticipation are some of the main concerns.

All that goes so far that one starts to see large parts of medicine as being soon developed as applied robotics and to consider entertainment industry and show business as being soon Informatics, especially robotics, animation and virtual worlds driven. It seems to be also only a question of time when this will be the case also for sport industries.

3. Informatics takes special care for improving human-computer, computer-computer, computer-human and human-human communication and interaction.

Developments in the area of wireless networks, mobile computing and com-

sufficient amount and whenever needed (With mathematics and physics as sciences behind).

Information era: Progress is and will be made on the basis that man learns how to make use of the laws and limitations of the information world to have **information** (processing energy) available in a sufficient amount and whenever needed (With informatics and life sciences behind).

munication on one-side, as well as a concentration on the development of the user/human-centric information processing devices and voice- as well as brain-driven computing, are some of the main developments in that directions. Under explorations are also human-computer interfaces based on gestures, mimics, body postures, emotions and so on.

4. Informatics takes special care for putting humans and society well being in the centre of its interests.

Developments in the area of human-centered computing and services oriented computing are some of the main steps along these lines.

5. Informatics, in cooperation with other sciences and engineering disciplines, takes special care to enhance human-computer-human and also computer-computer communication not only to be practically in real time but also to be secure in a broad sense, and to preserve anonymity and privacy wherever and whenever needed. By doing that it has a chance to create a society where not-detectable physical crimes are practically impossible and by that to create society with the level of security hardly imaginable in the 20th century. To achieve that, especially through global networks, is an enormous challenge scientifically and technologically.

6. Informatics starts to take special care that its methodology will be massively used and actually will penetrate human reasoning to such an extent that "information processing dissolves into behaviour" and "behaviour will be driven to a large extent by information processing paradigms, tools and outcomes". Attempts to analyse so called "computational thinking", its impacts and ways to incorporate it into all spheres of the education process, are an example of activities along these lines though still often in a quite narrow and naive form. Attempts to push education concerning *fluency with information processing technology* into all forms of education are another step in this direction.

7. Informatics takes special care to develop theories, methods and tools to make better use of the so-far accumulated information and knowledge in learning, scholarship, science, technology and so on and also and products in sciences, technologies, medicine, archeology, music, art and so on.

This is done, on one side, by developing techniques of (also semantics driven) searching through enormous amounts of texts, images and also through more dimensional data. A search for similarities play by that the key role and represents a big challenge of the field.[68]

On the other side, this leads to the design of digital encyclopedias, (global)

[68]Development of the corresponding theories and methods can have very broad applications and especially medicine and life sciences could profit enormously out of it. Archeology, history and music are other areas that could be much changed by such techniques.

digital libraries, galleries, museums, archives and so on.

The main outcome of that could be an enormous enhancement of personalized learning and also of personalized entertainment.

3.4.1 Comments

Applied Informatics builds on one side on the outcomes of scientific and engineering Informatics, as well as on the progress in the Informatics driven methodology. On the other side, it inspires developments in all of them and keeps putting before them great challenges again and again. All that inspires development of a variety of new theories, enabling technologies and also a search for a deeper understanding of their potentials and impacts.

Enormous potential impacts the developments in applied Informatics may have on our psychological, social and cultural phenomena and life require that several areas of humanities and social sciences start to explore these impacts. The impacts can be so large that some restrictions on the use of the information processing technology may be needed so that the increasing potential of information processing devices to enhance and replace some intellectual potential of humans does not go too far to jeopardise a "healthy" development of society - whatever that means.[69]

4 Why to go from current vision of *Computer Science* to a new perception of *Informatics?*

Old, actually current, mainly computer-, software- and programming-centered view of the field[70], is much too narrow, missing the main points and therefore getting obsolete. It is harming the development of the field, the formulation of proper grand challenges and also the attraction of the brightest minds/students to the field.

The new perception of the field is based on the following:

- An understanding has slowly emerged that it is needed to liberalize computer science as a science from (a) particular hardware and software

[69] People are slowly loosing capabilities to do more complex arithmetic, spell-checking and so on, for example.

[70] It is the view that sees computers and software systems and their designs as the central objects of study and algorithmic thinking and programming as the central intellectual activity of the field. It is the view that does not take into consideration the fact that in spite of the fast growing importance of such systems and such intellectual activities, they keep representing an increasingly smaller sub-area of the field.

technology; (b) particular hardware, software and communication architecture; (c) particular types of programming and algorithmic issues; in order to ensure that the discipline develops properly.

- It has slowly become clear that very sophisticated, and of vital importance, information processing activities have been going on for ages in the nature and that an understanding of these processes and their carriers, as well as of their laws and limitations, is of the key importance for the development of many other (almost all) areas of science. Quantum- and bio-information processing systems are perhaps the main examples along these lines.

- It has slowly become understood, at least by some, that the way to the understanding of the universe, its evolution, as well as of life, may be based, to a large extent at least, on the study of the underlying information processes.

- It started to become quite clear that the study of a variety of information processing phenomena is one of the key ways to understand such natural sciences as physics, biology and chemistry. All of these sciences start to be seen as being, to a significant extent at least, information processing driven.

- An understanding has emerged that an addition of sophisticated information processing systems is a way to go from the design of powerful machines to the design of powerful and intelligent machines.

- It started to be understood that a new, much more challenging, perception of the field is needed to attract the brightest young people and in general to increase interest in the study of Informatics, what is in the overall interest of the society.[71]

[71]By Bill Gates (2007): *The percentage of college freshmen planning to major in computer science dropped by 70% between 2000 and 2005. In an economy in which computing has become central to innovation in nearly every sector, this decline poses a serious threat to American competitiveness. Indeed, it would not be an exaggeration to say that every significant technological innovation of the 21st century will require new software to make it happen.* Moreover, as has been pointed out, and demonstrated, in the recent report of van Leeuwen et al., for Informatics Europe, one of the big problems of computer science in many countries (enrollment and education) is to a large extend due to the fact that neither faculty, neither (potential) students and nor society in general, have proper perception of the field and do not see it as a very attractive and challenging one, as many other disciplines and even most of them. In this report "enrollment crisis" is cited as one of the prime reasons why science in general is not profiting fully from the achievements of computer science, and why industry

- An understanding has started to be developed that what used to be called "computational thinking" should penetrate all levels of education. However, currently still a very narrow view of the field can be seen as the major obstacle to develop a sufficiently powerful position on this issue. A position that would have a chance to receive a broader consensus.

- One of the most unpleasant consequences of the current perception of the field, as hardware- and software-centered computer science, is that for researchers in many of the frontiers of Informatics it is so unacceptable to be labelled as computer scientists that they prefer to present themselves, their research and its outcomes as belonging to other fields such as cybernetics, mathematics, neuroscience, physics, biology and so on, or to some areas of engineering, and also it is so unacceptable for some of the most attractive and challenging areas to be seen as a part of computer science, because their goals are far from a concentration on computers, that they prefer an emigration "or a divorce from the mother field in order "not to *loose a face*. All that damages not only Informatics, but actually the whole science and, consequently, the whole society.

- An understanding has developed that a wrong perception of a science/technology discipline usually leads to: (a) wrong emphasis on the main goals, methods and value systems within the given area of science; (b) wrong support of the discipline by society and by money granting agencies; (c) not strong enough position of such a science discipline within the whole academic community.

- An understanding has developed that the more money goes to science, the more tough is the fight how money should be distributed. Informatics is hardly getting the portion of money that corresponds to its impacts.[72]

5 Problems to overcome

There are several obstacles that need to be overcome so that such a new perception of the field is sufficiently well accepted.

is not able to recruit even a fraction of the highly skilled information technology specialists it badly needs.

[72] The usual reasons are still questions: *Who are you? What are your scientific goals?* and comments *You are not a science. You have no clear vision and deep as well as broad scope. Computer science may disappear and dissolve into other areas, ...*

- The importance of information processing and communication technologies, as well as the complexity of the problems of their utilisation for solving very complex problems, is still fast growing and represents the focal point for the immediate interest of the field from the application point of view - in spite of the fact that from the perspective presented in this paper, the overall tendency, especially for scientific Informatics, is far from that.[73]

- The scope and goals of Informatics, as well as its methods and tools, as presented in this paper, overlap in many important aspects with those of other areas of science and technology. That may be seen as attempts to take away from these areas such topics, especially in cases when contribution of Informatics can be very large. This "ownership" problem is very non-trivial, as well as sensitive, and needs to be handled appropriately. Mathematics has a lot of experience with that, but in case of Informatics the situation seems to be much more complex.

- Most of the teachers and researchers in the field have grown up within the old vision of the field and have hardly enough motivation, interest and also potential to switch to the new perception of Informatics. A generation of them has likely to "die out" so that the new perception is well accepted.

- One can expect resistance from the currently dominating information processing technologies as well as from several sciences fearing that Informatics tries to take the cream from their piece of cake.

- Most of the top people in the field are willing to accept only such a perception of the field in which they play an important role. This has

[73]During the last half century we have witnessed an enormous increase in such computation resources as the speed of computation and the size of memories as well as of such communication resources as the speed and the bandwidth of communication links. One can even say that we start to live in the digital peta-age - with petaflops performance computers already coming and with petabytes of information available. Moreover, we can expect that we are still in the initial phase of such a process of increasing information processing and transmission potentials. (S. Lloyd has derived in his book *Programming the universe*, using the so-called Margolus-Levitin theorem, that no *ultimate laptop*, as the one that has weight 1 kg and volume 1 liter, can perform more than 10^{51} very elementary particle operations per second and that in case performance of computers would keep increasing according to the Moore law, no laptop can reach that performance sooner than in 2205. He has also estimated that universe during its overall existence could not perform more than 10^{122} elementary bit operations and could not produce and store more than 10^{92} bits.) All that is behind of a certain glorification of the information processing and communication technology.

always been the case in science.

- Non-professionals keep having problems not only with such an advanced view of Informatics as presented here, but also with down-to-earth vision of computer science. Troubles with technology, fears of the technology with the potential of taking jobs and fears of "cybercrimes" on one side and fantastic predictions about what one can expect in the excellent future on the other side are behind of such mixed feelings.

6 Conclusions

1. An attempt is made in this paper to describe the intellectual substance and main challenges of Informatics in a new and compelling way and by that to initiate a new way of thinking about this so important area of science, technology and methodology.

2. Informatics is presented here as a very deep and broad academic discipline consisting of four closely interacting components, scientific, engineering, methodological and application. It has as its main goals to help to deal with some of the major problems of science, to produce products and tools to help to deal with some of the main goals of engineering and produces a methodology that brings science and technology, and also all other major areas of society to new heights. Its applications are ubiquitous and of enormous impacts.

3. The outcomes of scientific and engineering Informatics, as well as of the Informatics-based methodology, are seen here as influencing not only all academic disciplines, but actually all areas of society. For academic disciplines, they especially influence the ways how knowledge is created and also how knowledge is put to use through applications. They also influence the ways knowledge and skills are learned and taught at all levels of the established and also personal education. As a consequence, they are bringing deep changes for the whole education process making it Informatics driven and global in the life-time and world-space. A big scientific and engineering challenge is to make all ingredients of these processes truth-worthy.

4. The paper is a short version of a much more elaborate one under preparation, on a new perception of Informatics, in which all aspects of the new perception are presented, justified and analyzed in a much more detailed way. An attempt is also made there to learn much from the history of other sciences and technology fields and to go more deeply into its very old history.[74]

[74]The perception of Informatics presented in both of these papers is actually based on the ideas originated in the following papers: J. Gruska, H. Jürgensen: *Maturing of Informatics*,

Comments and suggestions concerning the perception of Informatics presented here are much welcomed.

in *Images of programming*, edited by D. Bjorner and V. Kotov, Elsevier, 1991, and in J. Gruska: *Why we should not any longer only repair, polish and iron current computer science education*, Proceedings of IFIP WG3.2 Working Conference "Informatics at university level: Teaching advanced subjects in the future", ETH Zurich, 1991, Education & Computing 8, 1993, 303-330. As the closest to the perception of Informatics in this paper seems to be the views presented recently by Ch. Papadimitriou and P.J. Denning.