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Computing and Information Science and Engineering: Quo Vadimus?

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Marc Snir

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Marc Snir[1]
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Abstract

We argue in this paper for a view of Computing and Information Science and Engineering as one broad discipline that is use-driven and that must take into account cognitive, social economic and legal constraints on the design of computing and information systems, as well as the impact of applications. We discuss implications of this view on computing and information education and on the organization of this field.

1 Introduction

Our generation is seeing the beginning of a major technological revolution, the *information revolution*. In January 1983, the Times Magazine chose the computer as “Machine of the Year”, announcing that “A New World Dawns”; this was four months after the introduction of the IBM PC. Since then, we have seen the explosion of the Internet; the growth of companies such as Amazon, eBay Yahoo or Google; and the growth in social networking (Facebook, MySpace, etc.). Today’s laptops have more compute power than the fastest supercomputers of 1982 and they can store more data than large mainframes of that age. The spread of personal computers has overtaken the wildest estimates made in that special issue of the Times.

IT has spanned large new economic sectors and has strongly affected existing sectors, both in developed countries and in developing countries such as India;ithasdoubled the rate of increasein labor productivity in the US, and increased productivity (to a lesser extent) in other OECD countries as well[23, 22, 1, 35]. Over two third of job openings in science and engineering in the coming decade are in IT [15]. It has affected many aspects of our daily life – especially for the younger generation: The ways we seek information, communicate, learn, get involved in political and community activities or entertain ourselves have significantly changed in less than a decade.

It is hard to overestimate the magnitude of the change enabled by IT. The industrial revolution started to change our lives a few centuries ago; it did so by using machines to extend our physical

[1] Illinois Informatics Institute, University of Illinois at Urbana Champaign, snir@illinois.edu.

capabilities: we could move faster, transport heavier loads, process and transform large quantities of physical materials and change our physical environment. A few centuries later, we live in a totally changed world, with vastly higher standards of living. However, as a possible downside, we lost much of our immediate experience of, and intimacy with, the physical world: we seldom create physical things with our own hands – "manufactured" has lost its original meaning of "hand-made", while "hand-made" has become a mark of quality.We also feel a loss of control over our physical environment and fear that machines more powerful than us will enslave us, rather than serve us[2].

The information revolutionis now starting to effect a more profound change than the industrial revolution; it does so by using machines to extend our neural system: Digital sensorsextend our senses and enable us to capture significantly more information than we could with our own eyes and ears; they extend our cognitive capabilities and enable as to process, transform and transport massive amounts of information almost instantaneously; they extend our reach in time and space, enabling instantaneous interaction with distant people and various forms of asynchronous communication. Digital technologies increasingly mediate our interactions with the physical world and with other people; and they change our cognitive environment, creating new virtual worlds that enhance or replace our physical world.However, as a possible downside, we become further removed from the physical world: not only we no longer manipulate it directly; we no longer perceive it directly. We feel the loss of our ability to perceive and comprehend our environment and fear that machines that are "brainier" than us will control us by distorting our perception of reality[3].

As a result of the information revolution, the value of products or services we consume is increasingly in information that is intangible, rather than in tangible matter. An increasing fraction of the value of manufactured products, from cars to cell phones, is in their design – in particular the design of the software embedded in these products. The explosive growth in services has been focused on information-based services, such as financial services – less on tangible services such as transportation. This shift to an information based economy has reduced the coupling between increase in income and increase in the consumption of raw materials: In OECD countries (including U.S.) the use of oil per unit of output has decreased by half in the last three decades[32, Chapter 4]. Intellectual property, rather than physical assets, has become the main mean of production: control over intangibles (patents, copyrights, etc.) are at the forefront of the national and international business agenda [31, 7]; investment by industry in intangible assets has overtaken investment in tangible means of production [20, 9].

The information revolution is far from having run its course: "machine-thought" is far from replacing "brain-thought", to the extent that "machine-made" has replaced "hand-made". One can be confident that the use of digital technologies will continue to spread; that more and more employees will move from the "physical economy" to the "information economy"; and that people will spend more and more of their work and leisure time creating, manipulating and communicating information. However, the continued growth in IT does not provide immediate guidance about the future of Computing and Information (C&I) in academia: The fast evolution of IT also entails a fast change in the types of jobs

[2] This fear is expressed in movies such as *Metropolis*: of F. Lang and *The Modern Times* of C. Chaplin.
[3] This fear is expressed in numerous science fiction novels and movies, such as S. Lem *Cyberiad*, and *The Matrix* movie trilogy.

enabled by the information revolution and a fast change in the type of technologies that are driving this revolution: we can expect not only continued growth but also continued change – perhaps fundamental change.

The fast evolution of the technologies we care about and of their uses has led the academic C&I community to periodically reexamine its education programs, its research priorities and its organization. We seem to be in one of these periods of creative uncertainty: many universities are establishing new schools and new research and education programs that are covering a broader range of sub-disciplines in C&I. Leading thinkers in our community propose a new vision of the intellectual tenets of our discipline[37]. NSF is rethinking the funding models for research in C&I, through the establishment of the Office of Cyberinfrastructure and the creation of programs such as CDI and CPath[26, 27]. The seeds for this evolution were sown many years ago: Some schools, such as the School of Information at the University of Michigan, or the School of Computer Science at CMU have had for many years a more inclusive view of C&I. But the trend seems to be accelerating in the last few years.

The debate on what our discipline is about and where it should go sometimes recalls the story of the blind men and the elephant: C&I is a large and varied field, and each of us touches a different part of it. In this essay, we attempt to see the whole. *We strongly believe that C&I is one broad discipline, with strong interactions between its various components*: a coherent view of the whole must precede any discussion of the best ways of dividing it into sub-disciplines. We strongly believe that the dominant discourse in our community should be about building a coherent view of the broad discipline, building bridges between its constituents, and building bridges to other disciplines we engage in interdisciplinary research.

We hope this essay will contribute to these goals. We shall first try to elucidate the nature and scope of our field and its relations to science and engineering. We shall next discuss the organization of research and education in C&I. Finally, we shall briefly touch on C&I as an agent of change in academia.

2 What is Computing and Information Research?

We are discussing in the essay the broad field of Computing and Information Science and Engineering: the study of digital systems that support storing, processing, accessing and communicatinginformation. The terms used to denote this broad field and its subfields, and the exact boundaries of the field, vary from institute to institute and from country to country. We spend much time in our community arguing about the precise boundaries of each of these subfields. These arguments should not obscure the fact that these subfields have large overlaps and what they share is greater than what separates them. To avoid a useless debate on terminology, we shall call this broad field *Computing and Information* (C&I).

The answers to the question that heads this section have varied over time. Some have taken a narrow view of the field (or fields). EdsgerDijkstra is famously quoted for saying that “Computer Science is no more about computers than astronomy is about telescopes”[4]. In his view, “Computing Science is not about computers, computing science is not about how to use computers in specific areas of potential application, computing science is about how to solve, with or without machines, the (scientific) problems posed by the existence of computers” [13]. Dijkstra was skeptical of experimental computer science, system research or application driven research. He was also skeptical of use-oriented research and of research concerned with pragmatics considerations; of research focused on the insertion of computing technology in society and user-interaction; and of interdisciplinary research and teamwork.

While few would debate the “is” in Dijkstra’s definition of Computing Science, many computer scientists would feel excluded by the “is not” – not to speak of faculty members in Computer Engineering or Information Science departments: research on the design of computers (computer architecture), research on the use of computers in specific application areas (e.g., bioinformatics or natural language processing), research on human-computer interaction and system-oriented research often involving large teams are the bread and butter of many CS departments (including the one at Austin where Dijkstra was on the faculty). Indeed, Dijkstra’s statement, while memorable, makes as much sense as saying “cellular biology is not about cells, it is about the scientific problems posed by cells”: Human-computer Interaction or computer architecture are posing scientific problems that require academic research; this research is part of C&I research. We shall return to this issue later.

Dijkstra clearly believed that “Computing Science” is a science, albeit one that is quite different from other existing scientific disciplines. Many computer scientistsstill feel the need to argue this point, perhaps feeling defensive about the quip that “any discipline with ‘science’ in the name isn’t”, or perhaps reflecting some lack of recognition in the early days of the CS discipline. As recently as 2005 J. Denning published in CACM an article entitled “Is Computer Science Science?”, arguing that “Computer Science meets every criterion for being a science, but has a self-inflicted credibility problem” [11]. This debate seems to reflect some implicit views about “hard sciences” in contradistinction to “soft sciences” or engineering – the former being considered superior. We discuss this issue next.

2.1 Science, Used-Base Science and Engineering

“Scientists discover fundamental truths about Nature; engineers build better mousetraps”: This is the implicit view that many of us were educated to. To quote voxpopuli (aka Wikipedia):

“Science is the effort to discover, understand, or to understand better, how the physical world works, with observable physical evidence as the basis of that understanding. It is done through observation of existing phenomena, and/or through experimentation that tries to simulate phenomena under controlled conditions. Knowledge in science is gained through research”.

“Engineering is the discipline and profession of applying scientific knowledge and utilizing natural laws and physical resources in order to design and implement materials, structures, machines, devices, systems, and processes that realize a desired objective and meet specified criteria.”

[4] I could not find a reference to this possibly apocryphal quote. On the other hand, Dijkstra did write that “speaking of ‘computer science’ is like referring to surgery as ‘knife science’”[13].

This leads to a linear view of science and engineering: Scientists seek knowledge, for knowledge sake; through a mysterious process, this knowledge turns out to have practical consequences and is picked by applied scientists, next engineers, and used to develop better technologies. This view is illustratedFigure 1.In this view, research is the methodology used by scientists, not by engineers. This view also encourages an implicit value system whereby basic science is seen as a higher call, an intellectually deeper pursuit, and the only true vocation for a university faculty member.

Donald Stokes, in his beautiful book “Pasteur’s Quadrant”[33] leads a powerful attack against this simplistic view of science. He points out that, over the centuries, fundamental research has been often motivated by considerations of use – by the desire to implement certain processes and achieve certain goals – not (or not only) by the desire to acquire knowledge for knowledge’s sake. His paradigmatic example is Pasteur, who founded modern microbiology, driven by the practical goals of preserving food and preventing illness. Indeed, examples abound of use driven science, from Archimedes and Hero to Papin and Carnot; use driven science has been the norm in medical research (Koch, Fleming, Waksman, etc.) and in modern synthesis chemistry (von Bayer, Haber, Ostwald, etc.). A recent example is provided byresearch in high temperature superconductivity. This is a quest with an obvious practical motivation (cost effective, liquid nitrogen cooled, superconducting power lines, magnets and other devices); a major breakthrough was achieved by two experimental physicists (Bednorz and Muller) – who shared the 1987 Nobel Prize in Physics for their work. The quest for a satisfying theory of high temperature superconductivity is still going on; this quest is as much motivated by the desire for a fundamental understanding of the phenomenon and for a solution to the puzzling discrepancy between current theory and practice; as it is by the hope that a good theory will lead to the discovery of new high temperature superconducting materials.

Thus, according to Stokes, research should not be described as a linear continuum from pure research to applied research, leading into engineering, but as a two dimensional space, as shown in Figure 2[5]: One dimension indicates whether research is motivated by pure scientific curiosity or motivated by considerations of use. The other dimension indicates whether research is driven by a quest for fundamental understanding, or purely focused on applications. Stokes further argues that “Pasteur’s quadrant”, namely use-inspired basic research, is increasingly prevalent in modern research institutes. Two of the Nobel prizes won by faculty in my own university, the prize John Bardeen won for the invention of the transistor, and the prize Paul Lauterbur won for his work on Nuclear Magnetic Resonance, are indicative of this trend.

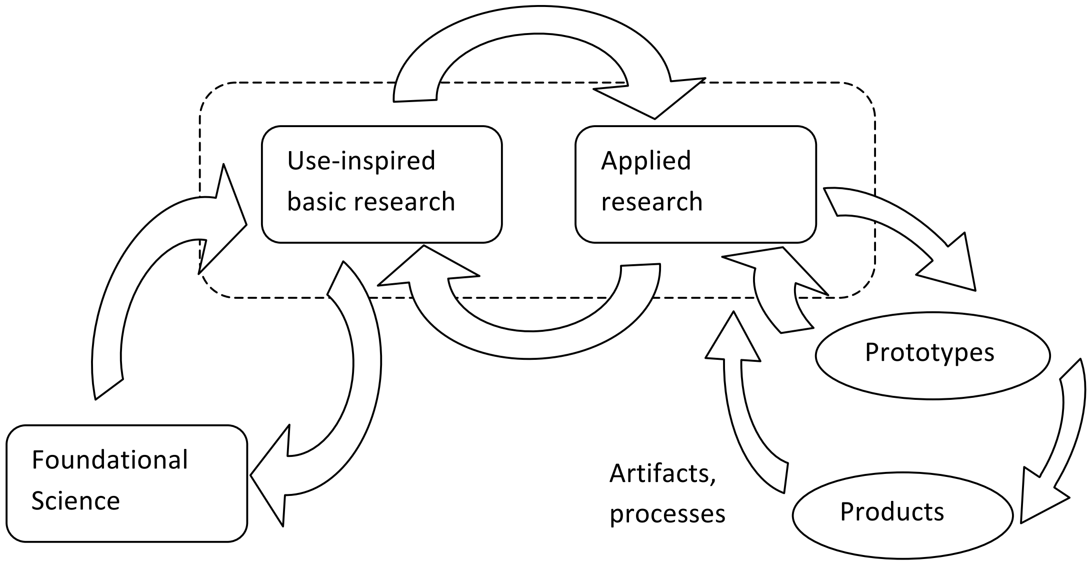
[5] Adapted from [33].

		Consideration of use? No	Consideration of use? Yes
Quest for fundamental understanding?	Yes	Pure basic research (Bohr)	Use-inspired basic research (Pasteur)
	No		Pure applied research (Edison)

The argument of Stokes strongly resonates with many researchers in C&I. Our work has a clear consideration of use: We ultimately want more usefulcomputing and information systems; we are also driven, on occasion, by a quest for fundamental understanding. To pick an example from my own research: Work on parallel computing is driven by the desire to leverage parallelism in an effective manner; it is also driven by a quest for a fundamental understanding of the constraints that communication imposes on computations. Without such fundamental understanding, we do not know whether difficulties in leveraging large-scale parallel systems are mere shortcomings of our current approaches, or inherent in the structure of the problems we try to solve.

At a more practical level, one can observe that any engineering department in a modern research university is a science and engineering department. This is often indicated by the department's name: Material Science and Engineering, Nuclear Science and Engineering, or even Engineering Science (at Oxford University). Even if "Science" is not part of the name, science is very much part of the pursuit of faculty members in academic engineering departments. While engineering departments educate engineers, namely people that will "apply scientific knowledge and utilize natural laws and physical resources in order to design and implement materials, structures, machines, devices, systems, and processes", faculty members of engineering departments pursue scientific research that has applications in the corresponding engineering area: Their best research is in "Pasteur's Quadrant". This is not necessarily detrimental to the education of future engineers: A strong scientific foundation is considered essential to their future career; and good engineering programs supplement the foundational education with courses, projects and work experience that provide the needed exposure to the art and practice of engineering and engineering design; this practical education often involves people with practical experience in the field.

Modern engineering departments are likely to subscribe to a view of themselves that is illustrated in Figure 3:



Faculty members perform basic use-inspired and applied research related to the applications of the engineering discipline; the basic research and the applied research interact with each other and enrich each other. The foundational sciences guiding their research are natural sciences: mostly physics (for electrical and electronic engineering, mechanical engineering, material engineering, aeronautical engineering, nuclear engineering, etc.), but also chemistry (chemical engineering), earth sciences (environmental engineering) and, increasingly, biological sciences (bioengineering). The use-inspired research in engineering contributes to the fundamental science and inspires new fundamental research problems. The practical goal of their research is to enable the production of better artifacts or better processes. The design of and experimentation with prototypes often is an essential step in the transfer of knowledge from research to practice, as they provide a proof of concept, a test and validation for theories and a platform to experiment with design alternatives. The problems encountered by the producers and users of these artifacts and processes, in turn, suggest new problems and motivate new research. It is the richness of the feedback loops between research and practice, and between basic research and applied research that best characterizes research in a modern engineering department.

It is interesting to think of the diagram of Figure 3 in connection to the definition of engineering given by Bill Wulf, the former president of the National Academy of Engineering[39]: He defines engineering as “design under constraints”, with science – the law of natures -- being one of the limiting factors engineers must take into account. Others constraints include cost, reliability, safety, ease of use, etc.Engineering research is focused on defining, refining or changing these constraints. For example, researchers may perform experiments and develop models to understand how much load a truss of a given design will bear, taking into account variations in manufacturing processes, material aging, rust, etc.; or, they may develop new materials that can bear heavier loads, or new truss designs. These will often require fundamental scientific advances – use-based basic research. They will also require the creation of a prototype of the new truss: Building artifacts or implementing processes is an essential part of engineering research.

The diagram in Figure 3describes not only engineering departments, but also other use-oriented disciplines such as medicine or agriculture. In each of these cases, the academic unit is organized around a use, an application domain, a set of practical goals: in the first case, the goal is to improve people health, in the second it is to produce more cheaply more valuable food; the unit educates future practitioners in the field: nurses, doctors or agronomists; and the unit engages in research inspired by the use it focuses on; some of it may be more applied, and some of it may be very basic, such as the research of Pasteur, or such as modern research in genetics and cellular biology. Last, but not least, this research can literally save millions of lives.Indeed, concern about impact and use, and research in "Pasteur's quadrant", are increasingly prevalent in science departments, be it life sciences, social sciences or physical sciences. Only a few purists would claim that departments are weakened by such concerns.

The cognitive, cultural, social, organizational or legal constraints of engineering design play an increasing role in the successful design of engineered products [6]: The difference between a successful consumer product and a failed one often resides in design, function or ease of use, not the underlying technology. Improvements in manufacturing processes, such as achieved by the famous Toyota Production System, require changes in socio-technical systems; as much, if not more, attention has to be paid to the social aspects as to the technical aspects. Yet almost all research in traditional engineering departments deals with the physical constraints on engineering design (industrial engineering being a partial exception). Engineering scientific education is focused on physics and other natural sciences; the engineering culture is suspicious of social sciences and dismissive of qualitative science. Yet many if not most non-physical constraints on engineering design are not amenable to quantitative studies. Engineering Departments that are only focused on physical constraints of products and production processes are relevant to a shrinking fraction of the economy.

2.2 Computing, Information and Engineering

Can we apply the diagram in Figure 3 to C&I? Our discipline is surely use-inspired: We want to build better computing, communication and information systems. This occasionally motivates deep, basic research, and it often involves applied research; C&I scientists use scientific methods in their research [10, 12]; and there is a continued back and forth between academic research in computing and information and the development of digital products and services by industry [8], with each enriching the other. So, the diagram seems to fit.

What are the foundational sciences for C&I? The artifacts produced by C&I researchers and practitioners are algorithms, programs, protocols, schemes for organizing information; these are mathematical or logical objects, not physical objects. Algorithms, programs or protocol are useful once realized, executed or embodied in a physical digital device such as a digital computer. But they are studied as mathematical objects. This is true even of experimental research: the experiments often use simulations, and even if they use a physical setup, they usually abstract the physical properties of the system studied. Indeed, one might call much of Computer Science "Mathematical Engineering": it is focused on the creation of new mathematical objects under constraints, such as low (time and space) complexity for discrete algorithms;good numerical convergence, for numerical algorithms; and logical correctness constraints on the behavior of programs. The length of a proof is not a matter of concern for a mathematician (except for practical considerations of ease of verification); the length of a computation is a key concern for a mathematical engineer[6].

I recently found this view very succinctly and elegantly expressed in a somewhat eccentric blog[28]:

- Physics: The Laws of Nature
- Engineering: The Science of Building Useful Stuff Using Science (i.e., applying Applied Science to applied technology)
- Mathematics: Physics of Hyperreality
- Computer Science: Engineering of Hyperreality
- Computer Engineering: Combination of the Engineering of Hyperreality (architecture, software, architecture-level hardware) with the Engineering of Reality (physical-level hardware).
- Computer Programming: Construction work to implement Computer Engineering.

2.3 From Computer Science to C&I

Our previous discussion suggests an organization for C&Ias shown inFigure 4, similar to Figure 3.

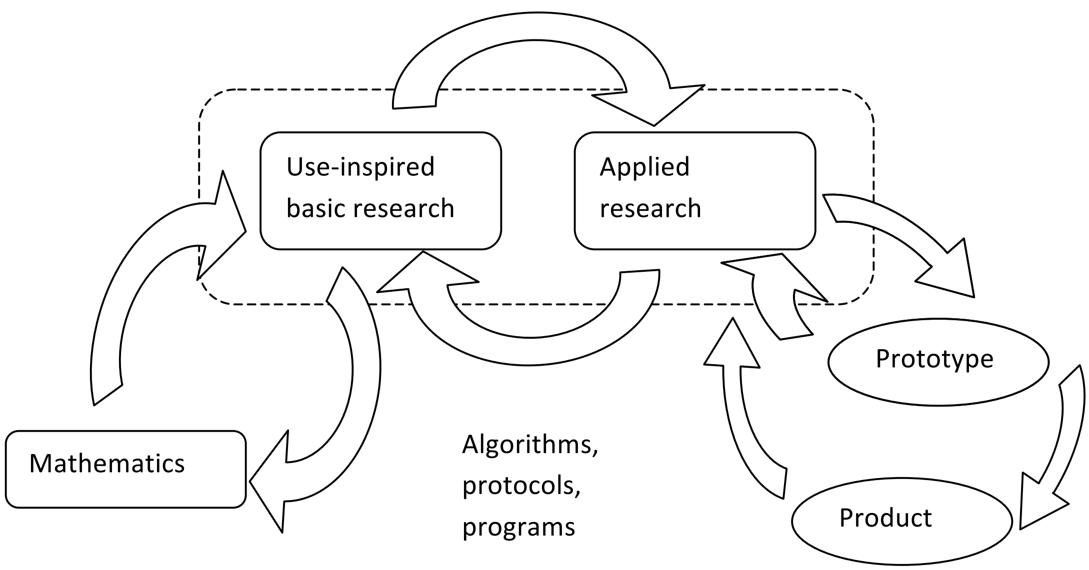


Figure 4. Computer Science -- a Purist View

[6] The view of computer science as mathematical engineering seems pretty much to be the view espoused by Dijkstra; see, e.g., [14].“Mathematical Engineering” is now used more restrictively as a synonym to “Scientific Computing”.

In this view, C&I starts where problems related to computing and information have been abstracted into mathematical problems; the abstraction process itself is left to practitioners, or to other disciplines – if it requires a scientific foundation outside mathematics.C&I researchers are building mathematical artifacts that solve these problems and analyzing them; they may experiment with these mathematical artifacts to acquire information that cannot be easily acquired through analysis.However, the artifacts are considered to be satisfactory if they solve the abstract mathematical problem; they use to solve the original problem is not a C&I issue.

While extreme, this view is not totally at odd with practice in Computer Science. Some of us will study quantum physics before pursuing research in quantum computing, but many are content to start with a mathematical formulation proposed by others. For example, some computer architects will study architecture design for low power using power consumption models and simulators designed by others – with little understanding of the basis for these models, their accuracy or their validity range.

The risk is obvious: Without a good understanding of the application domain, it is hard to know which part of the mathematical abstraction is solid and which is hypothetical, which aspects of the solution are essential and which are less important, which simplifying assumptions or approximations are reasonable and which are unacceptable. Therefore, one may end up building an elaborate castle in the air, a wonderful solution to the wrong problem. While some mathematics is deep in enough to be important on its own merit, most products of C&I research derive their value from the importance of the problem they pertain to solve, not from the sophistication of the solution.

Computer Science was lucky to develop early on useful mathematical abstractions to represent computing devices. For example, time and space complexity of algorithms provides useful information on the actual computation resources consumed by the execution of a code that implements these algorithms – to this day[7]. (This is less surprising than the "unreasonable effectiveness of mathematics in the natural sciences"[36]: models that may have been initially descriptive become, over the years, prescriptive.)But these mathematical abstractions represent only a fraction of the constraints that apply to software and digital systems.For example, Software Engineering research has strived for decades to define code metrics that represent how complex a code is (hence, what effort is required to program or debug it) – with limited success. Such a code metric would measure how hard it is for a programmer to comprehend a code. But this is a cognitive issue: It is highly unlikely that one can develop successful theories on this subject without a strong foundation in cognitive sciences. Unfortunately, much of this Software Engineering research was not rooted in Cognitive Sciences.

In the early days of computing, only few people interacted directly with computers: the psychology of programmers or users could be ignored without too much inconvenience: these few people would adapt to the computer. Today, the situation is vastly changed: billions of people interact daily with digital devices; it is not possible anymore to ignore the human in the loop. A major use of digital technology today is to facilitate collaboration and social interaction between people. The proper design of such technology requires an understanding of cognitive and social aspects of these interactions. Indeed, interesting research increasingly occurs at the intersection of the social and the technical. One

[7] While still useful, these simple performance models become increasingly inaccurate as communication (to memory, disk and network) replaces computation as the main performance bottleneck.

may well argue that the essential insight that enabled efficient web search and led to the creation of companies such as Google, is that the structure of the web carries information about the usefulness of web pages – a socio-technical insight. Progress in graphics and animation increasingly requires an understanding of human vision: otherwise, one makes progress in quality metrics that have low correlation to the subjective quality of an image; examples can be easily multiplied.Economic, policy and legal issues also have an increasing impact on Computer and Information technology: standardization processes, IP laws, and regulations on privacy are but a few examples.

Another important aspect of the evolution of our field is the increasing importance of applications. Precisely because software is so malleable and universal, one can develop very specialized systems to handle the needs of various disciplines: computer aided design systems, medical imaging systems, algorithms for DNA matching, auctioning algorithms for e-commerce – these are but few examples of application areas that have motivated significant specialized C&I research. This research cannot be successful without a good understanding of the application area; this research contributes to the application areas but also advances C&I.

Finally, the huge increase in the amounts of available data has a profound impact on our field. The cost of storing, transferring, and analyzing data continues to decrease. Massive amounts of data are gathered by modern digital sensors (telescopes, satellite imagery, particle accelerators, DNA sequencers, etc.). Experimental data in various disciplines is increasingly generated by massive surveys, and are widely shared; the relative advantage of a researcher or a university is no longer exclusive access to certain experimental data, but a better ability to analyze data and extract new knowledge. As business and social transactions are increasingly mediated by the digital infrastructure, detailed information on all these transactions is increasingly captured and stored. The ability to better analyze this data is a source of competitive advantage[8].

The organization of large collections of data for efficient information retrieval and the related social issues have been a main concern of Library Science for many decades. Library Science has also been traditionally concerned with the social, legal and policy issues that have a major impact on the ways data is acquired, stored and made available to various users; Library Science researchers have been more concerned with evaluation and more focused on the user. As more and more data is digital, the concerns of the (now renamed) Library and Information Science departments has a large and increasing intersection with the concerns of Computer Science departments.

This suggests a new view for the organization of C&I that is described inFigure 5: Mathematics is not sufficient anymore as a foundational science. For those working close to hardware, a good foundation in physics continues to be important. An increasing number of C&I research areas (Human-Computer Interaction, Social Computing, Graphics and Visualization, Information Retrieval, etc.) require insight

[8] For a contrarian view, see [4]. The article of Carr, “IT Doesn’t Matter”, and the ensuing book, have generated many rebuttals. However, the core message of Carr is important: IT is becoming an infrastructure technology, like railways or electricity. The competitive advantage is not in the infrastructure, but in better ways of using it. A similar conclusion is reached from the analysis of Bresnahan and Trajtenberg [3]: IT is a “General Purpose Technology”, a pervasive enabling technology where investments in the technology end up benefiting a broad, diffuse community, but not necessarily those that invented and deployed the technology. C&I researchers that prefer to focus their research on the IT infrastructure should keep this in mind.

from the social and cognitive sciences; human subject experiments become increasingly important for such research. In return, the work of computer scientists offers new ways of studying social and cognitive problems. At a more fundamental level, the development of artificial cognitive systems provides a better understanding of natural cognitive systems – of the brain and its function; and insights from Neuroscience provides better way of building artificial intelligent systems. Research in C&Iis strongly affected by the multiple application areas where Information Technology is used (Science, Humanities, Art, Business, etc,), and profoundly affects these areas. Finally, data repositories and methods for using them become an increasingly important product of the technologies addressed by our research.

3 Organization

The view illustrated in Figure 5 does not imply that each C&I researcher needs to be an expert in physics, psychology, sociology, biology, etc., in addition to core C&I; nor is each researcher in medical sciences expert in all disciplines that are relevant to medicine. Rather, it implies that C&I researchers with different disciplinary backgrounds will often need to work together – joining in a common goal to contribute to the design and implementation of better C&I systems and providing to their students the education needed to do so.

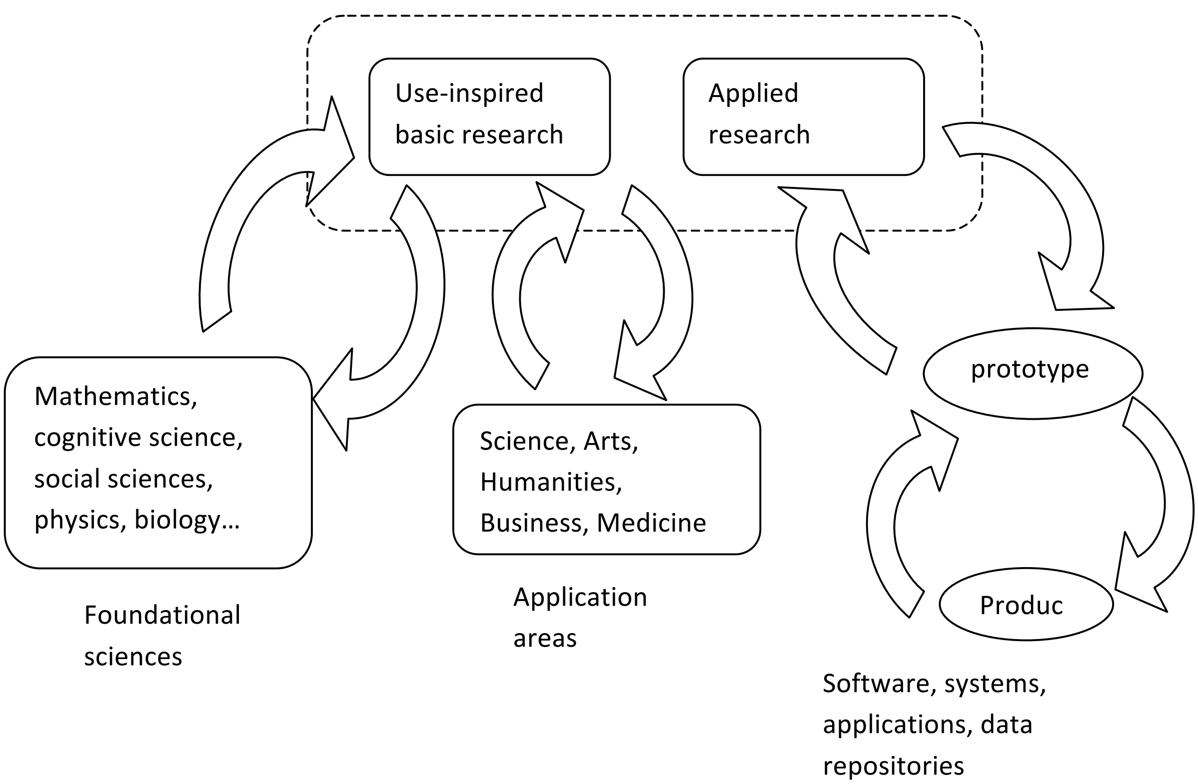


Figure 5 - Computing and Information – an Inclusive View

The need for these strong interactions has not resulted in a unique organizational model. Some universities (such as CMU, Georgia Tech, Indiana, Cornell and UCI) are establishing or expanding schools or colleges that bring under on roof Computer Science, Information Science, Applied Informatics (i.e. C&I research that is application domain specific) as well as interdisciplinary research and education programs. Interestingly, all these places have Computer Engineering programs that are not part of the C&I school[9]. In other places – especially places where Computer Science and Computer Engineering are joined, such as Berkeley, Michigan or Penn State, schools of Information Science are expanding to cover emerging areas in applied informatics and to broaden their work on the design of information systems and human-centered systems. These places seem to have few, if any, research and education programs bringing together Computer Science and Information Science. This is regrettable: Computer Science researchers are increasingly contributing to areas such as Human-Computer Interaction, Social Computing, Databases and Information Systems, Natural Language Processing, Trusted Systems, Bioinformatics and Games and Visual interfaces. These areas overlap with the research areas in Information Science; the lack of collaboration implies missed opportunities and unnecessary redundancies. As we pointed out before, there is a recognized need for a stronger focus on socio-technical systems in engineering; the almost total lack of physical constraints on the design of computing systems makes this need more urgent for Computer Science and Engineering: as computing and information systems are more malleable and as they serve as enhancers to our cognitive processes, they can and have to be more adapted to the human in the loop. A lack of strong interactions with social sciences and various application domains outside Science and Engineering is both hurtful to Computer Science and a missed opportunity for Engineering. While organization models will differ from university to university, it is essential that strong ties be established between Computing and Information, and between the engineering of C&I systems and the study of cognitive, social, economical and policy issues pertaining to these systems.

4 Undergraduate Curriculum

The diversification of research in Computing and Information implies a diversification in education programs: it is not possible for a student to get in four years good grounding in mathematics, physics, biology, psychology, sociology and the increasingly large number of C&I sub-disciplines. In addition, we see a tremendous diversification of the professional careers of people with an education in C&I. Less than half of students who graduated in Computer Science in 92-93 were employed in traditional Computer Science professions ten years after graduation (compared for 57% in engineering and 69% in health sciences)[5]. Those that stay in the CS profession(s) are employed by an increasingly diverse set of employers: In many top Computer Science departments, more than half of the graduating bachelors are hired by companies that are sophisticated users of IT technology in finance, services, or manufacturing, not by companies whose primary business is IT products or services; this is were most of the growth in IT jobs is expected to be [15]. The labor market recognizes multiple specializations within computing: the Bureau of Labor Statistics tracks a dozen of different occupations within computing [15] (although its categories are somewhat obsolete). A recent Gartner report [25]suggests

[9] Engineering at Indiana is at a separate campus.

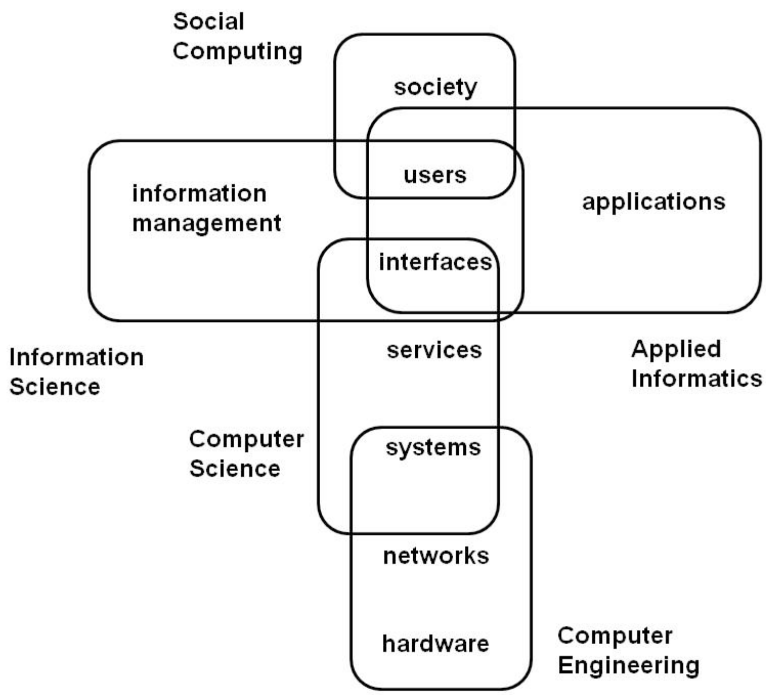
that the IT profession will split into four distinct professions: technology infrastructure and services, information design and management, process design and management and relationship and sourcing management.

Different academic units organize their education programs according to different principles. Professional schools (e.g., Business) tend to be organized according to professions; their programs are often accredited and the accreditation criteria define what a professional education consists of. Science schools (e.g., Life Sciences) tend to be organized according to scientific sub-disciplines. Engineering departments are using a hybrid model – with an implicit assumption that different professions require a different scientific foundation.

Currently, ABETaccredits Computer Science Programs and Information Science programs; ACM has developed recommendations for five curricula: Computer Science, Computing Engineering, Information Systems, Information Technology and Software Engineering; and ALA accredits masters in Library and Information Studies. These disciplines do not reflect the richness of our field: technology and professional specializations are evolving fast; accreditation organizations tend to bless existing practice, not to promote new practice. Therefore, anorganization of education according to professions may not fit our needs.

Another approach is to cluster the increasingly large body of knowledge in computing and information science and engineering into coherent clusters: In this view, the domain of Computer and Information extends from hardware and networks to system software, middleware, applications, user interaction and social context. Computer Engineering focuses on the lower layers of this hierarchy, Computer Science focuses on the middle layers, and Information programs focus on the top layers. In addition, some programs focus on informatics applied in different areas (bioinformatics, medical informatics, digital arts, digital humanities, etc.) and programs that emerged from Library Sciences have a strong focus on information management. This leads to a view of education programs that is shown in Figure 6[10].As we have observed, no one school or college seems to span this entire spectrum of programs, but the newly emerging colleges of information that include Computer Science cover almost all of it.

[10] Adapted from M. Pollack, personal communication



16 A more radical view is provided by the new computing curriculum developed by Georgia Tech [19]. This curriculum organizes the body of knowledge into eight threads: Computational modeling, Embodiments, Foundations, Information Internetworks, Intelligence, Media, People, Platforms; and organize career paths of students into four roles: Master practitioners, Entrepreneurs, Innovator and Communicator; an undergraduate program of study consists of the combination of two threads, shaped by the view of a future role.

Another approach that, apparently, has not been yet followed, is to organize education programs according to the combinations of foundational sciences that a student may acquire: In addition to core C&I, some programs may have an emphasis on natural sciences (possibly subdivided into physical sciences and life sciences); others on social sciences; yet others may emphasize economy and management; and some may just focus on the mathematical foundations of C&I.

These different views lead to an increasing balkanization of our discipline: It is fair to assert that we are still more concerned with differentiating the various programs than to define their common content. In particular, should there be a core common to all (or most) programs in C&I?

Let's clarify: A common core is not about what every student in C&I must know: most of the specific knowledge we teach will be obsolete long before our students reach retirement age. A common core is about C&I education, not about C&I knowledge[11]. It is about educating students in ways of thinking and problem solving that characterize our community and differentiate us from other communities: a system view of the world, a focus on mathematical and computational representations of systems, a

[11] "Education is what remains after one has forgotten everything he learned in school" – A. Einstein.

focus on information representation and transformation, a focus on problem solving via abstraction, etc.The selection of courses for the core will not be based (only or mostly) on the usefulness of the facts taught, but on the skills and concepts that are acquired by the students.For example, an introductory course in programming need not necessarily use the most widely used programming language, but the language that best exemplifies the fundamental principles of programming we wish to teach and best match the interests and abilities of the students taught; a compiler course may be added to the core, not because many people develop compilers, but because such a course uniquely leads from abstract mathematics (formal languages) to the implementation of a complex software system (a compiler). Also, a common core is not necessary the same as a set of common courses; it is possible to teach the same set of concepts in different ways in order to accommodate different student populations.

I believe that such a common core is extremely important for our discipline. It is, to a large extent, what defines a discipline: You can expect a student of physics in most departments to take a sequence of physics courses that start with mechanics and end with quantum physics: this is not necessarily what those students will need in their future career, even if their career is in research; but those courses define the physics canon. If we take ourselves seriously as a discipline, we should be able to define the C&I canon. Like physics, this core should be concise – say four courses: A common core does not preclude variety in junior and senior years.

5 Computational Thinking

The information revolution is also changing the conceptual paradigms used by other scientific disciplines. Mechanics was the leading science in the era of the industrial revolution, and biological or social systems were understood as mechanical systems: the heart is a pump, the limbs are levers, etc. In the era of the information revolution, we conceptualize biological or social systems as information processing systems. Biologists use the paradigm of an information processing system to understand genetic and cellular mechanisms:DNA is a code, with letters (codons) and words (genes); cell metabolism is understood as a graph of metabolic pathways; etc. The computer becomes the analogy that philosophers use to attack the mind-problem problem[18]; and Information Theory plays an increasing role in Physics; some attempt to base Physics on computational paradigms [38].

Educated people of the industrial revolution era would study mechanics: Newton's theory was a popular topic of discussion in the salons frequented by Voltaire. Today, an understanding of the basic concepts of computation and information are an essential component of a well-rounded education. Unfortunately, computing teaching in high schools and universities is more often a vocational subject – seldom a subject with any intellectual depth. While learning how to use computers is as important as learning how to drive, learning how computers work is more important than understanding how a four-stroke engine works. In a not too distant future, an understanding of computing and information will be a mandatory component in the education of each college student. It is our responsibility to ensure that this will be an education to exposes students to computational thinking[37], not "computer driver ed".

6 The Future

We come back to the question in the title of our essay: Where is C&I going?

I think it is quite clear that the field will continue to grow and to broaden. Increasingly, it will need to address the cognitive, social, economic, legal or ethical constraints in the design of digital systems; increasingly it will need to think of the human or the social group as an integral part of system. This is true of engineering, in general [6], but especially true of C&I. The need for a broader approach to C&I will lead to the creation of larger academic organizations – schools or colleges – that bring under one roof the multiple research and education strands.

But we should think beyond pouring new wine in old bottles. Information Technology has a profound impact on the way the information economy works: It enables fast dissemination of information, thus enabling flatter and more flexible management structures.It enables a different way of accessing services and information that is more a pull model than a push model: I can shop or use banking services via the internet when and where I want – not at opening hours at fixed locations; I can find information I need when and where I need it. It enables the bazaar model of the open source community where people from different organizations and different geographies can work together to create impressive software systems, with no formal agreement binding them [29, 30].

It is often said that the use of information technology in an organization goes through two phases; the first, when it is used to automate existing processes, which brings few productivity gains, if any; and the second, when processes are changed, to take full advantage of the possibilities of the new technology. It seems that the use of IT technology on campuses has not gone beyond this first phase. “The shoemaker usually walks barefoot”: The inventors of the information revolution may well be the last ones to be revolutionized by it. We still teach as we taught many decades back – we only replaced blackboard with hand-written transparencies,next PowerPoint slides. We still have the same organization of colleges, schools and departments, and the same ways of organizing research and education programs. Of course, Universities have been along for centuries, and see themselves as preservers of proud academic traditions: the fierce attacks on academic traditions in the 60’ies have had little impact – we have now programs in Gender and Afro-American studies – but little else has changed. Information Technology may force a more profound change [16].

This change is partly driven by economics. William J. Baumol famously observed more than 20 years ago that that there seem to have been no labor productivity increases in classical music for hundreds of years: it still takes four musicians to play a Beethoven string quartet. This has become known as “Baumol’s cost disease”: some sectors, such as music performance, are labor intensive, and technology does not increase labor productivity. Salaries increase, on average, faster than inflation – more so the salaries of highly qualified people. Thus, an economic sector where the main expense is the labor cost of highly qualified personnel, and where technology does not improve the labor productivity, will see costs increasing faster than inflation. This is true for higher education: As long as a main measure of the quality of higher education is the student/faculty ratio, labor productivity in higher education cannot increase; as long as faculty salaries are increasing faster than inflation, the cost of higher-education will grow faster than inflation. Such a situation will lead to the same pressures we see now in the health sector, and will force major changes.Information Technology is, in many sectors, the cure for Baumol's disease[34][12]; will it be in higher education?

Another drive is the new approaches to scientific research that are opened by Information Technology. The main obstacle to progress in research in the past has been the effort needed to collectfacts. Now data is bountiful – Research increasingly needs the ability to integrate and analyze information from diverse sources, in order to study complex systems, such as climate and its impact on our environment, or the human body. Social networking infrastructure enables large citizen science projects, where many volunteers collect data and contribute to research: For example, the Audubon Christmas Bird Count aggregates the contributions of over 40,000 self-reporting birders, spread over all the U.S. The mobilization of citizens for such project requires not only a technological infrastructure, but a strong motivation and sense of ownership into the research by the citizen scientists. Social networking infrastructures enable the Wikipedia – the collective creation of more than 75,000 contributors, with more than 10,000,000 articles in more than 250 languages. The Wikipedia is a trusted reference used by more than 600,000,000 people every year, including faculty and students. These two examples point to a profound democratizing effect of IT on the research enterprise: amateurs and citizen scientists are (again), essential partners in research; and the monopoly on authoritative knowledge held by academia is sapped.

Finally, it becomes extremely hard to enforce on students that are immersed in the Web old ways of imparting knowledge: The idea that one must attend a lecture at a particular place and time in order to obtain a particular piece of information seems as antiquated as the idea that one has to come to a particular bank office branch at a particular time in order to withdraw cash from a checking account. The notion of a sequential narrative that stretches over fifteen weeks is strange and antiquated to people that are accustomed to maintain multiple simultaneous dialogues, to jump from topic to topic at seconds interval and to explore that highly non-sequential World Wide Web. We can regret the good old days and bemoan the short attention span of today's student, but we must educate today's students.

Several modest examples will illustrate the possibilities:

More and more universities are installing reporting systems to collect information from faculty on their research, education and public engagement activities. These systems are used by administration to gather statistics and compute various productivity metrics, to facilitate information gathering for various accreditation activities, and to support performance evaluation and promotion and tenure processes. This clearly is a "phase I" automation step: a manual process is automated (and labor is shifted from administrative personnel to faculty), with no change in existing information flow. However, it is not too hard to think of more innovative uses: a good system should help faculty manage their academic portfolio, manage their public persona (web site, blogs, etc.) and support their own activities (grant writing, student recruiting, etc.); it should help faculty, students and administrators locate expertise on campus: A "phase II" system will be focused on creating new, horizontal information flows, and further empowering faculty, not in improving the vertical flows, and further empowering administration. We can design such a system.

[12] It still takes four musicians to play a Beethoven string quartet, but digital recording enables us to enjoy the music where and when we want to hear it.

We all pay lip service to the need for diverse measures of research impact in the evaluation of academic performance; yet, we all focus on publications in top journal and conferences as the main, if not unique, measure of impact. As a result, the perfect paper that drives the last nail in the coffin of a well studied problem is given more weight than the imperfect draft that opens new research vistas. Reference counts, while better than paper counts, still suffer from well-known biases[17]. The community that developed such effective ranking algorithms for web search should be able to develop better measures of impact for academic research.

The study of Richard J. Light, at Harvard, indicated that participation in a small student study group is extremely important for academic success: such participation is a stronger determinant of success in a course than the teaching style of the instructor[24]. As departmental libraries close and as students make less use of libraries and of instructional labs, students in large universities have fewer opportunities to socialize with other students in their program. Can we use social networking technology to encourage students to study in groups and to facilitate group creation? More generally, students spend twice as much time studying on their own than listening to lectures. Yet, many studies on the use of IT in higher education focus on improving the lecture hall experience. How can we use technology to make self-study more productive? The experience gathered in successful online learning programs is very relevant, since successful programs are fostering a learning community and use using technology to multiply the interactions channels between students and between students and faculty[21]. C&I researchers could also contribute to the development of better assessment methods so as to provide continuous progress assessment and feedback, without devoting too much time to exams and quizzes (and to grading), and without limiting team work.

As the half-life of knowledge growth shorter, it becomes less important to impart specific knowledge to students (and to test them on this knowledge) and more important to teach them how to learn, how to handle new knowledge in areas they are not expert in, how to identify and leverage sources of knowledge and expertise and how to collaborate with experts in other areas, creating collective knowledge. Yet our education is still strongly focused on acquiring domain specific individual knowledge; and studentsmostly collaborate with other students that have similar expertise. Projects and practicums that involve teams of students from different programs, with different backgrounds,couldrefocus education so as to train more foxes and fewer hedgehogs [2][13]: Theywould teach students to respect expertise in other domains and require them to understand the distinct vocabulary and concepts used by such experts. Projects, practicums and studio courses can be more open ended, encourage more student initiative and involve students in a critical assessment of other student’s work; such collaborative learning-by-doing empowers students, increases motivation, improves retention and teaches skills that are essential for success in the information society. A skillful use of IT technology,

[13] “The fox knows many things, but the hedgehog knows one big thing.” Sir Isaiah Berlin distinguishes between hedgehogs – thinkers “who relate everything to a single central vision”, and foxes – thinkers who “pursue many ends, often unrelated and even contradictory, connected only in some de-facto way”. Although the essay of Isaiah Berlin focuses on Russian writers, I see “foxiness” as being very much the tradition of American Pragmatism. Both types are needed in our society, but “hedgehogs” who prize the hedgehog way of thinking seem to dominate in academia, especially in Science and Engineering.

both for supporting course activities and for assessing teaching and learning, can facilitate this education style.

Predictions are very hard, especially about the future, said Yogi Berra. It is hard to know exactly how Information Technology will affect the University. But it is not hard to predict that the effect will be profound: the previous examples barely scratch the surface. Therefore, we should not only explore new research and education directions in C&I; but also be open to different ways of organizing the C&I research and education enterprise. Computer Science has suffered in the not too distant past from a lack of recognition of its legitimacy as an academic specialty. It would be ironic if our profession was to become conservative at reject new research and education directions as disrespectable. Indeed, it would be the beginning of the end for our discipline as an amazingly vibrant, continuously renewing intellectual pursuit.

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Illinois Informatics Institute (I^3)

University of Illinois at Urbana Champaign

Siebel Building, 201 N Goodwin Ave.

Urbana, IL 61801