Discovery and Innovation in Science and Technology:

Inter- and transdisciplinary in cognitive learning

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***Abstract*—The modern approach to research cuts across traditional boundaries. In order to obtain maximum benefit from research effort globally, Universities need to adapt their approaches to the management and organization of research and teaching, to foster cross-discipline working and promote global mobility for the next generation of students.**

Keywords—research; teaching; interdisciplinarity; transdisciplinarity

I. Introduction

This millennium will see us enter an era of revolutions in a range of technologies from medicine to transport that will have transformational effects on society. With new tools, new insights and understanding, and a developing convergence of the disciplines of physics, chemistry, materials science, biology and computing, we will realize novel and superior products and systems that were, until the 21st Century, the stuff of science fiction. This will not be possible without collaborative links between disciplines.

"It is not enough to value the links between experiences, disciplines, creativity and ideas. One has to develop methods, strategies and practices that will transform those links into real connections. We have to recognize interdependence in order to actualise it and we have to know how to act once we have developed that recognition."[1]

Up to now, academic education has been strongly oriented towards specific academic disciplines. In this, it is often overlooked that most of the problems that research and education are supposed to help us solve are not defined in terms of disciplines, and these problems are precisely the ones that are particularly urgent: examples are the environment, energy, and health. There is an disconnect between the development of problems and the development of disciplines, and this disconnect is growing to the extent that disciplinary development is increasingly determined by specialisation.

As an example, *Cognitive Information Processing* and *Cognitive Computing* will be important technologies of the 21st Century and will require the input of researchers from solid state and organic chemistry, biology and medicine, physics and mathematics, information and computing sciences, and engineering if their potential is to be fully realized. In this context, the need for an inter-disciplinarily approach is often mentioned. But inter-disciplinarity, a cooperation between disciplines with a finite duration, is not enough. The development of the problems tackled by today's science assumes that inter-disciplinarity is more a short-term approach to a specific issue rather than a fundamental new instrument of science and research.

Global developments have progressed in revolutionary steps, starting with agriculture, followed by the industrial and information/communication revolutions. Nanoscience and nanotechnology are the fourth revolution in the 21st century: all industrial sectors will be affected and there will be widespread and beneficial societal impacts. Nanotechnology – from nanomedicine to nanoagriculture – is a showcase for where inter-disciplinarity is vital for discoveries and innovation.

At present, there is no recognised "single" discipline that encompasses biomedical science, information systems, and electronic engineering, but such an approach may be required in the future to address industrial and societal needs. There is a challenge for Universities in addressing this, in forming degree programmes that do not lose intellectual depth in addressing the range of material required, and/or do not lead to multiple pathways to the final qualification that is confusing for both students and academics. That said, the growing fields of nanotechnology, bio-intelligent materials, biomimetics, cognitive informatics and cognitive computing etc., will not prosper without intensive crossover and interaction between disciplines.

The University has to change: because its environment (social as well as institutional and regulatory) is changing, and because science and research, that shape internal structures and processes, are changing. Similarly, many conventional jobs will disappear in the near future, by the time that children currently in primary education have graduated. Others will transform radically and many new jobs will be created. Hence industry, government, and the services sector will, in the future, look to recruit candidates with flexibility and an open mind.

The historical development of the universities has been greatly influenced by government intervention in the last fifty years. Fifty years ago governments showed little interest or interference in universities, unless they propagated anti-government views. Governments were content that universities should be seats of learning, pure research, and scholarship; and would provide funding if affordable. Universities around the world had similar structures, with essentially independent departments.

In the last fifty years the world has fundamentally changed.

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[1] R. Burnett "Disciplines in Crisis: Transdisciplinary Approaches in the Arts, Humanities and Sciences", http://www.eciad.bc.ca/~rburnett/

Many governments now realise that new scientific knowledge holds the key to our future wealth and health: many new medical drugs and industrial products are based upon discoveries made in universities. The industrial hubs in the USA have moved away from the steel centre of Pittsburgh and the car centre of Detroit to high-technology companies based around MIT and Silicon Valley companies based around Stanford University and the University of California. If Europe is to compete successfully with China and the USA then it has to focus on high-technology products and the ideas and materials for many of these will originate in our universities. Hence governments around the world are now intensely interested in their universities.

However, the structure of our universities has changed little in the past fifty years. The majority of Universities still tend to have relatively small, independent departments. A key feature of the university-of-the-future must be flexibility: we must make it easy for an engineer to learn Chinese or an Indian language, history and culture without this being an additional burden Concerning research, we must acknowledge that much of the most exciting and useful research is occurring at the boundaries between traditional disciplines. Many biologists who design new medical drugs to attach to specific protein molecules have been trained as physicists. Many new materials for next generation mobile phones, computers, cars and planes are designed and developed by materials scientists working with chemists, physicists and engineers. However, University departmental structures often impede rather than facilitate multidisciplinary research.

A major concern is the increased administrative burden being placed on Universities by government regulation and reporting. There is often a disconnect between the administrative functions of a University and the primary activity of research and teaching.

II. ENHANCING THE EDUCATION, RESEARCH, AND INNOVATION BASE

The social, scientific and technological conditions for the development of ideas, knowledge, and solutions to problems have changed dramatically over recent decades. The globalisation of information, of work, of ecological considerations, to mention just a few, have made a tremendous impact on our life. Problems have become more complex and their solutions require new thinking that has to consider influences from multiple sources in our world.

University education plays a vital role in the welfare and well-being of global society, and it is recognized that good education systems underpin prosperity and stability. The challenges are to provide a trans-disciplinary education that is recognised and transferable around the world.

A. Multi- Inter- and Transdisciplinary Education

A *Discipline* is a sub-field of science, engineering, humanities, etc. with a specific approach, fundamental concepts, language, methods, and tools, that aims to analyse, understand, and describe parts of Nature.

Multi- disciplinarity is where several disciplines come together in parallel to tackle one subject.

Interdisciplinarity is where the concepts and methods of one discipline are used in the work of another discipline.

Transdisciplinarity is a holistic approach that sees all aspects of the world inter-related through patterns of interdependent systems. These include natural, social, economic and political systems. Transdisciplinary integrates knowledge and methods from any source that can be of value in addressing a particular problem or research question. Essential requirements for any transdisciplinary work are curiosity and patience; and understanding of other disciplines and their languages takes time and commitment. Transdisciplinary research and teaching do not respect traditional boundaries.

B. Challenges for Inter- and Trans-disciplinary activities

- *Language*: Each discipline creates its own jargon. I/T-disciplinarity requires the appropriation and accommodation of different languages, meaning communication of I/T-disciplinary research and teaching can be difficult since it requires the use of technical terms borrowed from one discipline but that are not well understood by the specialists from the other discipline.
- *Methods*: Disciplines are often devoted to their own methods of investigation. This may lead to misunderstanding and opposition.
- *Institutional constraints*: Institutions are mostly disciplinarily organised, creating barriers for I/T-disciplinarity; though strong, well-defined disciplines are necessary as any interdisciplinary activity starts with a deep understanding of single disciplines.
- *Cognitive constraints*: It is very difficult for an individual to become expert in two or more disciplines. An in-depth knowledge of different disciplines is however the requirement for genuine I/T-disciplinary research. This raises the question of the impact of these difficulties on education and on the institutionalisation of interdisciplinary training programs.
- *Assessment*: Experts (reviewers) for evaluating the results of M/I-disciplinary research and education are lacking. Standardised bibliometric information is scarce and not representative. New ways of quality assessment need to be developed.
- I/T-disciplinarity requires mastering of more than one discipline in depth. Superficial learning of several disciplines does not lead to meaningful I/T-disciplinary research and corresponding solutions of complex problems.
- Experience has shown that learning the essentials of several disciplines has to be done consecutively, not in parallel: for example, doctoral studies in one discipline and post-doctoral work in another.

C. Importance of Inter-Trans disciplinarily for Universities

Inter/Trans-disciplinarity matters because, in the real world, most scientific, technological, and social problems do span different disciplines: so in future, graduates have to operate in a multi-disciplinary environment, very different from what has existed in the past. The present generation of students must be convinced that they will have good careers if they take a research route in their early years, and that University research leads to careers other than in academia. Whilst today, someone with inter/trans-disciplinary expertise might be viewed as a generalist, in the future this could be regarded as a specialism. For example, a graduate with three Master's degrees in biology, informatics, and engineering, may, in future, be better off than with one PhD in biology etc. Interdisciplinary degrees need to be defined in a sensible way that does not simply double the workload and content. It should be possible to opt for a full MSc inter-disciplinary degree enveloping various Faculty disciplines. This change in culture to an inter/trans-disciplinary approach can be created only during the training of researchers and must be part of their curriculum. University courses must be broader and open to related disciplines thus giving to the students the predisposition to interdisciplinary work after Graduation. Industry will be keen to hire graduates who have mastered the challenge of studying different fields with success and who will also be able to perform trans-disciplinary work and research

The real need is for the next generation of scientists to know how to move forward when faced with a real-world problem on a technical topic they have never met before, on a realistic time-scale, and with a realistic budget. Future research is aimed to solve problems where many traditional disciplines are involved and where an interdisciplinary approach is essential. For example, the rapidly emerging field of biomimetic, intelligent, nano-materials and systems will form possibly the most important technologies of the 21st Century. They will require the input of researchers from solid state and organic chemistry, biology and medicine, physics and mathematics, informatics, and engineering if their potential is to be fully realized.

In Universities, inter-departmental barriers are often very high, particularly in "traditional" institutions based on small Departments of 10-20 academics focused on a single narrow discipline. A modern approach, that has been shown to be more useful, flexible, and efficient, is to have teaching activity based in larger Schools, of up to 100 academics, that can be broadly based and allows for the development and delivery of curriculum from a range of discipline specialists. Research can then be focused either within the School around particular themes, or linked to cross-cutting University Research Centres that can span Schools and Faculties and further exploit the opportunities for cross-disciplinary collaboration.

The primary functions of universities are to educate students, perform innovative and horizon-broadening research, and transfer new knowledge for the benefit of society. Universities need to be flexible enough in their structures, management and culture to establish new interdisciplinary, interdepartmental Centres for working on the scientific fields of tomorrow.

D. The roadmap for the Inter-Trans disciplinary Universities of the Future

There is a need for a change in approach, and a revisitation of recent trends, in fully enabling Universities to become incubators of successful inter/trans-disciplinary research.

For University Leaders, there needs to be:

- Recognition that teaching is primarily for students who will not become future academics, and who will be pursuing careers that do not exist yet;
- Recognition that research and teaching must be closely linked, so that students will benefit from the new ideas of knowledge that research will provide;
- Recognition that research changes very rapidly. It is therefore good practice to develop teaching within large Departments with strong vision for curriculum and continuity, and have research institutes into which it is easy to bring people from various departments for the span of a project.

For Funding Agencies, there needs to be:

- A diversity in approach to funding at all levels, since the challenges of interdisciplinary science are so diverse.
- Better integration between funders and those who conduct the research, so that funding decisions are informed by current challenges.
- Successful models that reward and encourage success, and have a low management burden.
- Active encouragement of interdisciplinary approaches in the solution of research challenges.

E. Global University Mobility

In ensuring the move towards globalisation is meaningful and successful, University education plays a vital role. To facilitate collaboration between universities worldwide, it is important that the curriculum and degrees of the various universities is unified. Europe, with its 30 countries and multiple University systems with different curricula succeeded in realising a uniform University education system called the "BOLOGNA Minister's declaration". The United States have a system quite similar to Europe, and other continents as South America and Asia should move towards a global unified system in the future.

An intercontinental University education system demands great efforts from Universities and governments. A global, uniform education system which facilitates contact between students and academics from universities and nations on a global scale will result in multiple benefits in education quality, mobility, and cultural understanding. The mobility of young students and scientists demands knowledge of foreign languages and cultures and this should form part of the curriculum.

F. Mobility of Students and Scientists

It is important to encourage greater exchange of students and scientists between disciplines and countries. This would be aided by standardised qualification recognition procedures, world-wide training courses, and official exchange programmes. An interdisciplinary culture must be implanted through educational and funding initiatives. It must also be realised that the heterogeneity of world cultures is an asset, not a hindrance, with the potential to provide imaginative ideas and diverse skills. As an example, in the European Union the ERASMUS programme was developed in which possibilities were offered to students and scientists from all countries throughout Europe to study at the faculties of universities of their choice with recognition of their obtained degrees all over Europe.

Employers in the future will be looking for candidates with broad experience and flexibility of thinking. Employers often bemoan that the graduates they recruit are unprepared for the jobs that they are asked to do. The modern economy places an enormous premium on brainpower, and there is not enough to go around. The best evidence of "talent shortage" can be seen in high tech firms: companies such as Yahoo! And Microsoft are battling for the world's best computer scientists. Many firms now have some form of talent-management.

G. Global University Curricula

The criteria for a high-level education could be formulated as follows:

- Multi-disciplinary skills
- Literacy in complementary fields
- Exposure to advanced research projects
- Literacy in key technological aspects: exposure to real technological problems
- Basic knowledge in social science, management, ethics, foreign languages
- Literacy in neighbouring disciplines: international business, law, etc.
- Interlinkages between education, research and industrial innovation
- Sharing of post-docs, Masters and PhD students to foster the mobility of permanent researchers and academics between different institutions to create extended, global teams.

III. TECHNOLOGY TRANSFER: ACADEMIA TO INDUSTRY BASED ON INTER-TRANS/DISCIPLINARY PRINCIPLES

Technology transfer has become a new buzzword in the academic world. Everywhere in the world, research institutions within universities look at their American counterparts with envy and respect. The goals of research are to explore new frontiers, and creators of industrial innovations that lead to globally-successful initiatives rank alongside Nobel Prize winners in their universities. The academic entrepreneur is, however, a very rare species and likely to remain so. It is, therefore, essential to promote collaborative research between universities and industry.

The inter/trans-disciplinarity aspects, together with the exchange of ideas and inspiration to innovate, will form the building blocks for the successes of the university-industry research. The synergy between university-based and industry-based research teams has been an important factor in the success of US research, exemplified by the excellent "Industry-University" laboratories established by DuPont, IBM, AT&T, and Corning. These laboratories have in themselves produced several Nobel Prize winners.

The conflict of curiosity-driven science and the current needs of society are as old as science itself. One needs only recall the famous encounter between Faraday and King William IV, who once asked the celebrated scientist what his "electricity" was actual good for. Faraday answered, "One day you will tax it"[2].

This is not to say that University research should be an extension of industrial development programmes. Allowing scientists at universities to pursue curiosity-driven research free from commercial constraints is the only way to ensure a truly innovative research environment. In the long term, private industry and the economy will benefit from the new ideas and discoveries that will be made.

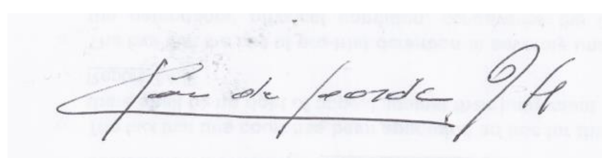
IV. SUMMARY

Universities have historically focussed their education and research towards specific academic disciplines. It is often overlooked that most of the problems that research and education are supposed to help us solve are not defined in terms of disciplines, and these problems are precisely the ones that are particularly urgent: examples are the environment, energy, and health.

In ensuring a broad-based education, that is globally-recognised and allows for global mobility of students, there is a need to develop a World University System that promotes networks of universities with shared qualifications and close research collaborations.

A. Acknowledgments

MEF is grateful for funding from the Lloyd's Register Foundation, a charitable foundation helping to protect life and property by supporting engineering-related education, public engagement and the application of research.



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[2] Faraday was right.