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THE GOLDEN AGE OF THE SCIENTIFIC TECHNOLOGICAL RESEARCH UNIVERSITY

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1 UNIVERSITY EDUCATION AND HUMAN RESOURCES

The Golden Age of the Scientific Technological Research University

by

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Abstract

The current crisis in the classical research university scene, the on-going fusion of science and technology which is driving a new scientific-technological revolution, the changing rationale of research funding, and the need of advanced nations to develop competitive, knowledge-based economies, have set the stage for a potential 'golden age" for *Scientific Technological Research Universities (S&TRU)*. The historical roots of this university model go back to the medieval university on the one hand and the European technological institutes on the other. In order to meet and transcend the challenges facing it, the *S&TRU* must contend with a series of issues relating to the content, mission, structure and governance of this future institution. These issues are addressed and discussed in this paper.

The Crisis of the Research University

On the threshold of the 21st century, the Research University (RU) is embroiled in controversy and crisis (1). Some of the reasons for this crisis include:

- The escalating cost of university education
- The preoccupation of faculty with research rather than teaching
- The high overhead costs of research
- The increasing level of fragmentation and specialization
- The reduction of governmental funding
- The claim for administrative waste and even fraud and corruption in academia
- The risk of conflict of interest of faculty involved with technology transfer
- The slow response of universities to technological innovations in teaching
- The erosion of public trust and disenchantment with science and technological progress
- Conflicts between academic freedom, freedom of speech and 'political correctness'
- Novel postmodernist views questioning the very validity of rational scientific thinking

Consequently universities and the scientific community in general are increasingly viewed by society as yet another special interest group in search of public funding, and are being asked to demonstrate greater efficiency and accountability to society.

In spite of this multi-dimensional crisis, and the rapid pace of change in today's world, universities with their centuries old, guild-like tradition, decentralized organization and multiplicity of purpose seem unable to respond in a timely manner to the many challenges and hard decisions facing them. Yet in re-examining the RU scene thirty years after his Godkin lectures (3), Clark Kerr(2) again expresses guarded optimism, which stems from the increase in the productivity of the economy through advances in knowledge generated at the RU, " *particularly in the areas of usable energy, new materials, biotechnology, and further exportation of the possibilities of electronic technology.* One thing is almost certain, he adds, " *and that is that the RU, with its combination of knowledge and higher skills, will become increasingly important to the maintenance, and possible improvements in society.*"

Many share this notion. Indeed, the most compelling arguments that are put forward on behalf of the RU are related to their contribution to new discoveries and highly skilled education, as suggested by Derek Bok (4): "*Through these developments, we have come to recognize that all advanced nations depend increasingly on three critical elements: new discoveries, highly trained personnel, and expert knowledge. In America, universities are primarily responsible for supplying two of these ingredients and are a major source for the third*". That is why different observers "*have described the modern university as the central institution in postindustrial society.*" Indeed, R.R. Nelson (5) stresses the role of the universities in technological advance and innovation: "*And it is more on the mark to say that with the rise of modern science-based technologies, much of science and much of technology have become intertwined. This is the principle reason why, in the present era, technology is largely advanced through the work of men and women who have university training in science and engineering. This intertwining, rather than serendipity, is the principal reason why, in many fields, university research is an important contributor to technical advance, and universities as well as corporate labs are essential parts of the innovation system*". F. Narin et al. (6) demonstrated the significant contribution of public science to industrial technology by tracing the rapidly growing citation linkage between U.S. patents and scientific research papers. Finally, H. Brooks and L. P. Randazesse (7) point out that, while federal funding in the United States per full-time academic scientist active in R&D fell in the 1980s, there was a parallel rise of industry funding, which demonstrates industry's conviction regarding the relevance of academic research to innovation.

Of course, technology (defined mistakenly by most dictionaries as the scientific study of industrial arts or the application of science to industrial arts (8); when the correct definition is the accumulated human knowledge for making artifacts) has always been *the* dominant factor in human evolution. This becomes evident when examining, for example, the growth of human population over the past 1,000,000 years, which is characterized by three major surges. Each surge is attributed to a technological revolution (9): the invention of hand tools, agriculture, and industrial technology, respectively. Indeed, Paul Kennedy (10) proposed that the rise and fall of the great powers is related to the sum-total of a nation's economic resources, which in turn are determined and driven by technology, rather than social, cultural or other factors. And more recently, Lester Thurow (11) predicted that the rise of brainpower-based high-tech industries is among the underlying forces that will restructure world economics. Finally, David Landes(12) in his recent book "The Wealth and Poverty of Nations", which attempts to "trace and understand the main economic advance and modernization", clearly outlines the dominant role technology has on economic development and the complex interplay between culture and technological progress.

It seems, therefore, that the scientific technological research universities (*S&TRU*), which focus primarily on the sciences, engineering disciplines, biology and medicine[1], and have become the main venue for promoting technological innovation and progress, will gain prominence among all other university models and assume a leading role in the 21st century. The *S&TRU* can play a crucial role in overcoming the crisis of the research university and renewing public trust and support, and if the challenges it faces are successfully contended with, the *S&TRU* stands to enter a new, ***golden age***. For this to take place, however, a series of questions relating to the content, missions, structure and organization of the future *S&TRU* must be addressed, which are discussed below.

Considering the fact that historically, the engineering disciplines that were traditionally associated with technology were considered somewhat inferior to the humanities, arts and sciences within the comprehensive research university culture (although the permeation of exact sciences and mathematics into engineering gave them some 'academic respectability' (13)), the current perception of technology and engineering together with science as the "raison d'être" of the research university, is an event in the history of universities worth noting.

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[1] And, those RUs which have strong programs in these disciplines

Historical Roots of the *S&TRU* and the Technological and Scientific Revolutions

All modern universities, in all their rich diversity, including the *S&TRU*, are the lineal descendents of the archetypal medieval university that coalesced in the 11th century in Bologna and Paris (14,15). These seminal institutions became the wellspring of the '*idea of the university*' that crystallized over the centuries and still governs current thinking on the role and mission of the university (3,16-19).

The historical roots of the *S&TRU*, however, can also be traced back to the technical institutes created in the 18th century to train 'military engineers'[2] initially, and later 'civil engineers'. The industrial revolution, which began at about the same time and was characterized by(12) (a) the substitution of machines for human skills, (b) the substitution of inanimate for animate sources of power, and (c) the use of new and far more abundant materials, was the main driving force for the proliferation of the technical institute model, based on the École Polytechnique [3], and the establishment of a host of *polytechniques* in France and all over Europe, the *Technische Hochshule* in Germany, and *institutes of technology* in the US and elsewhere. These early institutes closely cooperated with the growing industrial sector and provided the trained manpower and technological developments to meet its needs.

The paramount symbol of the industrial revolution, it is interesting to note, was not conceived in industry, but rather at a university, with a broken-down, rather inefficient Newcomen steam engine used for research and demonstration at the University of Glasgow in 1780. The machine was sent to Mr. James Watt, the chief instrument designer of the university, for repair. Watt not only fixed the machine, but also immensely improved it by applying steam pressure to drive the piston rather than atmospheric pressure, and by introducing a separate condenser. In doing so he dramatically catalyzed the burgeoning industrial revolution that restructured the world!

This revolution, which was natural resource- and cheap labor-dependent, took place within the context of an already on-going, centuries-long scientific revolution. But it was to take another 200 years and several

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[2] The Encyclopedia Britannica of 1779 defines an engineer as: *"one in the military art, an able expert man who by perfect knowledge in mathematics, delineates upon paper or makes upon the ground all sorts of facts and other works for offense and defense."*

[3] The École Polytechnique was established by the 1794 Convention, inspired by the French Revolution, and the *Siècle de Lumière* (G.Bugliarello, "The University-And Particularly the Technological University, Pragmatism and Beyond", in D. Zindberg ed., The Changing University, Kluwer Academic Publishing, Boston, 1991)

stages of evolution before these two revolutions fully merged into one sweeping scientific-technological revolution at the close of the 20th century.

The industrial revolution started by James Watt expanded in waves generated by the expanding railroad steel and electricity industries, the new internal combustion machine and chemicals extracted from coal and later oil[4]. Each wave reinforced the others, and were driven by the genius of the great inventors, from James Watt himself, to Eli Whitney, William Henry Perkins, Samuel Morse, Alexander Graham Bell, Thomas Alva Edison, Gugliemo Marconi, George Eastman, Charles Goodyear, Nicola Tesla and many others.

During the industrial revolution, science initially played a very small role, if any[5]. It did, of course, provide new knowledge that in some indirect way eventually led to new technology. But it took many more years for science and technology to merge.

Indeed, many of the great, early inventors came from very different professions. Watt, for example, was an instrument maker (though in the end he did receive an "honorary doctorate" from his university), Whitney was a cotton grower, Morse was an artist, Bell was a vocal physiologist and Edison was a professional inventor without formal education.

This initial lack of contact between science and technology is not surprising, because historically, they originated in very different places. Technology derives from the arts and crafts practiced by humble artisans, whereas science stems from philosophical, theological and speculative inquiries about nature. Indeed the study of nature in the Middle Ages was regarded as adjunct to understanding God. Science was a branch of theology – which was referred to as the "Queen of Sciences".

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[4] This hectic, invention-intensive period was captured by the American poet Walt Whitman who described the industrial landscape of the time (1871) as: "*Leather-dressing, coach-making, boiler-making, rope-twisting, distilling, sign-painting, lime-burning, cotton-picking, electro-plating, electro-typing, stereo-typing, stave-machining, planting machines, reaping machines, thrashing machines, steam wagons*".

[5] This, in spite of Francis Bacon's claim that science leads directly to invention and application, a statement that anticipated events by two centuries, although not in the linear fashion he conceived. A well-documented case in point demonstrating the initial lack of connection between science and technology is Watt's steam engine. Watt was a friend of Professor Black at the University of Glasgow, whose main interest was the study of latent heat. What could be more relevant to Watt's invention of a separate condenser? And although some have tried to prove the crucial role played by Black's science in forwarding James Watt's invention, repeated studies showed that it had none!

The scientific revolution -- that complex set of changes that took place between 1500 to 1700 -- claims Bronowski (20) *"was just as radical as the invention of agriculture, the invention of writing, the invention of poetry and art, or the invention of urban life. All those are things which we now take for granted in our civilization, but all were irreversible steps, and from the moment that they took place human life changed and nothing could turn it back.... Science is a world view based on the notion that we can plan by understanding ... that there is only one form of truth in it (and that), there is no distinction between man and nature."*

Indeed, the scientific method was so potent, and it facilitated the discovery of so many satisfactory answers about nature, that it could not be stopped. In Bronowsky's words: *"The transition in human evolution with the advent of science was irreversible"*. Moreover, science gradually began to open doors for technology, making it profitable for many, which, of course, greatly reinforced its standing.

The fusion of science and technology (S&T), however, was a slow and gradual process that lasted over a century and, as suggested by Henderson's aphorism that *"Science owes more to the steam engine than the steam engine to science"*, exerted its force in both directions. Nevertheless, the essence of the process was threefold: science was used to analyze and improve technology, scientific discoveries provided new opportunities for technology, and technological tools facilitated scientific progress[6].

Much of the interaction between S&T took place in industrial laboratories, whose beginnings can be traced to the German chemical and pharmaceutical industries of the latter half of the 19th century. Still, historians regard the General Electric laboratory established in 1900 in the United States, as the first true R&D laboratory. In these laboratories, the distinction between science and technology was blurred because, in the process of developing useful products, many 'basic science' discoveries were also made.

This gradual convergence of S&T continued throughout the 20th century and was greatly accelerated during WWII, when the application of science to technology proved to be immensely useful to the war effort

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[6] Indeed, Freeman Dyson in his book "Imagined Worlds" (Harvard University Press, 1997), based on his Jerusalem Lectures of 1995, stresses that the Kuhn type scientific paradigm shifts or revolutions are not exclusively concept-driven, as Kuhn claimed (e.g. associated with Copernicus, Newton, Darwin, Maxwell, Einstein and the quantum-mechanical revolution that served as his model), but that during the same time there were some 20 tool-driven revolutions such as the Galilean revolution resulting from the invention of the telescope, the Crick-Watson revolution resulting from x-ray diffraction, those driven by the computer technologies and others.

and, backed by the economic power of the United States, was instrumental in determining its outcome. The 'atomic bomb' project, radar, and the synthetic rubber projects are cases in point. Finally, the two explosively developing tracks merged into each other, igniting a new on-going *scientific-technological revolution,* which will undoubtedly continue well into the 21st century.

In this new revolution, science is no longer applied *to* technology, but rather science *and* technology are so intertwined that they are almost indistinguishable. It is hard to say which leads and which follows, and this is the first characteristic of the S&T revolution. The distinction is more in the mind and the intention of the researcher, than the kind of work he/she is doing. Evidence for this merging of science and technology became overwhelming in the closing decades of the 20th Century with breakthroughs in electronics, microelectronics, computing and computer technology, lasers, communication technologies, new materials, robotics, genetic engineering and biotechnology, molecular engineering, and nanotechnology among many others. Though science is still concerned with knowing "why" and technology with knowing "how", the difference between them was no longer so clear.

A second characteristic of this revolution is that it is not raw material- or cheap labor-dependent, but *knowledge-dependent.* Grazing land for sheep, cheap labor, iron ore, oil and coal were replaced by highly qualified brainpower as the crucial strategic national resource (11). In fact, this revolution is the 'alma mater' of the 'high-tech' industry, which has become the dominant global economic force.

A third characteristic of this revolution is that S&T, as well as the means of production were no longer site specific, and began to flow freely around the globe. Thus, S&T were not only critical for laying the technological infrastructure for globalization, but they also swept the process of globalization forward at its revolutionary pace, changing the world in its wake.

A fourth characteristic of this revolution is that, in general, the time lag between invention and application has contracted. Finally, a fifth characteristic, discussed below, is a blurring of the classical division between 'basic' and 'applied' research, which has even rendered the distinction rather obsolete.

A major implication of the S&T revolution is the growing significance of the RU models mentioned above as primary sources of new S&T knowledge and of qualified human resources. Thus, the cardinal role of the RU as a means for guaranteeing the technological superiority and economic success of nations, as observed by Kerr (2) and Bok (4), is not a coincidence or a passing phenomenon, but rather the result of the preceding and profound historic developments. Furthermore, of all university models, the *S&TRU*, which amalgamates the key elements of the classical university models with those of the technical institutes, has the disciplinary breadth and authority of tradition which makes it best suited to fill this state-supporting role. However, in order to succeed in ushering in a *'golden age'*, the *S&TRU* will have to undergo important structural changes, academic adjustments, and expansion of its scope and missions.

Finally, the corollary that emerges from all these developments is that national economic success in the future mandates leadership and creativity in *both* science *and* technology *as well as* the capacity to convert them into high quality products through expert managerial capabilities. Thus, government, industry and academia (GIA) must develop a new alliance to provide the necessary infrastructure where this type of multifaceted leadership can be cultivated.

Engineering Education

The increasing interaction between S&T throughout the 20th century also had a profound effect on engineering education (EE) and the culture of engineering schools, and led to the foundation of the modern engineering educational philosophy.

The perception of EE as being firmly rooted in the sciences was part of a new educational philosophy that evolved during the first quarter of the 20th century. One of its prominent leaders was Karl Taylor Compton (21), President of MIT, who made this the theme of his inaugural address in 1930: *"I hope"* he said *"that increasing attention in the Institute may be given to the fundamental sciences; that all courses of instruction may be examined carefully to see where training in details has been unduly emphasized at the expense of the more powerful training in all-embracing fundamental principles. "*

The movement toward fundamental principles became the dominant trend in EE throughout the century. It was triggered by the phenomenal progress being made at that time in the natural sciences, which was expanding mankind's understanding and horizons beyond all expectations, and created a desire to apply the scientific method to engineering in the hope of achieving similar success. This process gained momentum particularly after WWII, when engineering curricula were purged of vocationalism, which was replaced by fundamental sciences. It also led to the formulation of the engineering sciences, which form the core curricula of modern EE, and provided the engineering professoriate with 'tough quantitative and mathematical' challenges, which, as pointed out above, also imparted 'academic respectability' to the profession. Yet, at the same time, it distanced the engineering schools from the industrial scene and focused the educational process on analysis -- which is the basic tool of the scientific method -- at the expense of design or synthesis -- which in many respects is the essence of engineering (22). Moreover, it also focused the attention of the faculty on research at the expense of teaching.

Funding Rationale, the New Government-Industry-Academia Alliance, and Basic and Applied Research

The on-going, critical re-evaluation of the rationale and policies of academic research funding by government and industry (23) is another catalyzing factor for the emergence of the 'golden age' of the *S&TRU*.

Until recently, governments, industry and the public accepted the notion that basic scientific research is an 'endless frontier'; that scientific progress hinges on free, undirected investigator initiative rather than programmatic support; that it leads in a straightforward linear process to technological innovation and economic progress; and, that scientific leadership is a prerequisite to economic prowess. This notion was eloquently formulated by Vannevar Bush(24) in his 1945 report to the U.S. Government, which as is well-known, led to the establishment of the US National Science Foundation[7].

However, this notion of the limitless boundaries of scientific potential by itself would have not been sufficient to justify the massive financial investments into basic research that ensued. In fact, it was the great success of scientific applications to the war effort in WWII which caused a shift in the public consciousness. During the Cold War era, national awareness of the country's reliance on scientific predominance for its security, which was

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[7] For a broader historical perspective on the role of V.Bush and others on the formulation of S&T policies in the US see: D.Hart " Forged Consensus: Science, Technology & Economic Policy in the US 1921-1953" Princeton U. Press, 1998.

further reinforced by the shock created in the wake of the "Sputnik" launching by the Soviet Union, created the "defense rationale" which dominated scientific research funding policies for decades.

An additional and no less powerful rationale for investing in basic research came from the subsequent, revolutionary breakthroughs in both military and civilian technologies. At an amazing pace, the public watched as groundbreaking developments in electronics, microelectronics, computer technology, materials, aerospace technologies, medicine and later molecular biology and biotechnology, changed their lives.

As a result of these massive investments in research, the scientific enterprise greatly expanded, which led to an unprecedented flourishing of the RU, which David Goodstein (25) coined as its *golden age.* Indeed, the current perception and vision of the professoriate on the character of the ideal RU, is strongly rooted in that *golden age.*

Yet, for many reasons, the foregoing funding policy is undergoing a critical reevaluation. First, with the collapse of the Soviet Union and the end of the 'Cold War', the military rationale vanished. Second, science turned out to be not only an '*endless frontier*' for new discoveries and ideas, but also an enterprise consuming no-longer available *endless resources.* Science, observed Derek de Sola Price (26), has been growing faster than the GNP of nations for close to 300 years, and no enterprise that requires financial resources can do so indefinitely. The scientific enterprise has now reached such a significant size that even the richest among nations cannot afford to sustain its further growth at the rate that we have become accustomed to, doubling in size every 10 to 15 years. Third, science became the victim of its own success. Both the public and the policy makers accepted the notion, promoted somewhat carelessly by the scientific community, that if only sufficient financial resources were allocated, science could resolve any problem facing humanity. The 'failure' of science in this regard has repeatedly precipitated disappointment, with cures for cancer and AIDS being cases in point. Moreover, a growing number of social problems plaguing modern human society such as crime, violence, urban decay, and the population explosion, to name a few, seem impervious to solutions through science and the scientific research, although perhaps increasing international cooperation will in due time lead to solutions (27). And, finally, the global environmental issues which are by-products of modern human society, are perceived to be the evil other face of technological and scientific progress, a position which creates anti-scientific sentiments among the population and policy makers.

All of these factors have brought about a re-evaluation of funding policies, characterized by stagnation in the allocation of funds, and the replacement of the *military rationale*, which drove investments into science since WWII, with one promoting *economic competitiveness.*

Indeed, F. Press (28) in a study of the National Academy of Sciences (29), recommends a complete reevaluation of research funding policies. Specifically, he suggests a new budget category: *Federal Science & Technology*, for producing new knowledge and new enabling technologies. This is a sharp departure from the *linear model* of funding basic science as the logical predecessor to technological development. As he points out in the report: *"In most instances, the sequential view of innovation implied by the terms 'research' and 'development' - is simplistic and misleading".* The *Economist* (30) similarly points out that *"analysts have at last noticed that innovations meander into economy along a much more circuitous path"*, that *"innovation tends to drive basic science, not the other way around"* and that *"this sort of thinking is blurring the distinction that government used to make between basic and applied science".*

Clearly, this is yet another consequence of the previously discussed fusion of science and technology. And, in view of this 'fusion', it no longer makes sense to categorize research into 'basic' and 'applied', because either *may* or *may not* lead to application. Indeed, Harvey Brooks defined *'pure technology research'*, as worthy of public funding, and Branscomb (31-33) coined the term *'basic technology research'* as incorporating much of the research in engineering sciences, and in fields such as high temperature superconductivity, parallel computing, biologically based computing systems, and the like.

Other characteristics of the new funding policies are systematic attempts to define 'thematic goals' and 'directed programs', to pay increased attention to structural elements of research (e.g., creating larger, frequently multi-disciplinary groups), to allocate block grants and to support the research effort for longer periods of time, recognizing that the time constant for demonstrable success is longer than that of the current year grant system(23). Of course, undirected, curiosity-driven, investigator-initiated research still remains the main source for novel ideas and new breakthroughs. Sound national funding policies, therefore, must find a productive balance between 'curiosity driven research' and 'strategic research'.

Parallel to this reevaluation of academic research funding, corporate research funding practices have also changed. Unlike in the past, when significant basic research was conducted in their own research laboratories, corporate attention and resources are now focused on "just-in-time" research (23,34). In parallel, industry's inherent demand for a steady stream of new technologies has led it to acquire entrepreneurial start-ups and make increased investments into university research.

Clearly, the restructuring of both public and corporate funding and the increasing significance of S&T to the economic competitiveness equation of nations has set the stage for a new GIA alliance to promote the development of new, enabling technologies. In this new environment, the RUs with strong science and engineering programs and in particular the *S&TRUs*, are becoming critical components of the national scientific-technological-economical infrastructure.

The Scientific & Technological Research University at the Crossroads

This new role of the *S&TRU*, against the backdrop of the foregoing historic changes, not only ushers in its 'golden age', but also, as suggested, mandates certain academic and structural changes. A new 'mindset' is required for both faculty and management, and a host of dilemmas are placed at the door of the *S&TRU*. The *S&TRU* will need to find the appropriate, and delicately balanced organizational structure that will support:

- a fruitful coexistence of pursuit of knowledge for its own sake, with the utilitarian role of becoming the wellspring of technological progress
- cooperation with industry without becoming subservient to it
- acceptance of increasing support of the government while retaining academic independence
- growth in size and scope while retaining the individual creativity of faculty and students
- responsiveness to society while retaining autonomy.

Some of these issues are discussed below.

Multidisciplinarity, Disciplinary Distribution, Critical Mass & Research Practices

Knowledge is one, but human limitations have inevitably led to its subdivision into many well-defined, manageable segments or disciplines. This segmentation was a profoundly important step, because it eliminated dilettante scientific research and enabled the exploration of nature and technology in depth by professional scientists that resulted in an enormous growth of knowledge. Each discipline in science and engineering developed its own specialized approach, jargon, and interconnected global network, which are essential elements to evaluate, maintain and promote scientific excellence.

But now, at the dawn of the 21st century, multidisciplinary research has become almost mandatory for tackling the increasingly complex problems which characterize frontier research in both science and technology. Moreover, it is the interaction of different disciplines that is expected to bring the most innovative and creative, new scientific and technological breakthroughs. These developments require, first of all, an institutional culture which encourages the individual faculty member to cross disciplinary boundaries in both research and teaching, and to overcome the currently prevailing academic culture of isolated academic departments, which behave as tiny 'nation states'. Secondly, they have two important consequences, one related to the structure and organization of the *S&TRU* and the other to its sheer size.

Regarding structure, the 'obvious' solution to these developments on the university scene is the formation of new 'interdisciplinary entities'. These are often disappointing, however, because they tend to disregard both the need of faculty members to be rooted in their own discipline, and the fact that research subjects shift frequently, requiring a new and different mix of disciplines. One possible academic model that resolves these difficulties is the formation of *virtual* multidisciplinary centers. Such a model was successfully developed at the Technion. Faculty members belonging to a *virtual center* remain in their home department with their labs, and cooperate around a well-defined central research theme. Management allocates the significant resources needed for the infrastructure, and the faculty raises the operating funds from regular, competitive sources. Such *virtual centers* were successfully established at the Technion in optoelectronics, high temperature superconductivity, space technology, protein engineering, biotechnology, water technology, interfaces, complex fluids & macromolecules among others. One can conceive of a future *S&TRU* which is dynamic enough to respond to shifting research needs, consisting of an array of stable, permanent, classical disciplinary units in sciences and engineering, interconnected through a host of transient, virtual multidisciplinary centers.

Regarding size, in the past, when much of the research conducted was disciplinary research, there was no inherent need to maintain a broad disciplinary distribution within an *S&TRU*, and even small-specialized technological institutes could achieve excellence in specific disciplines. But now, when multidisciplinary research has become so important, and since it is unpredictable how disciplines will interact with each other, small, narrowly focused institutes have less chance to excel and break new ground. Therefore, the future *S&TRU* will need to maintain a *critical mass* in *all* relevant disciplines: natural sciences, mathematics, engineering disciplines, and life sciences including medicine.

Moreover, management related disciplines must be added to this core group as well. These disciplines fall well within the realm and mission of the *S&TRU* not only because the *S&TRU* will closely cooperate with industry -- and management research and education are natural links to industry -- but because industrial success depends equally on technological as well as management capabilities. Thus, the future *S&TRU* will stand on four legs: natural sciences & mathematics, engineering disciplines, life sciences & medicine, and management & economics. The need for a critical mass in all these disciplines makes it necessary for the future *S&TRU* to maintain a sizable faculty, and for supporting such a large faculty, a sizable undergraduate and graduate student body is necessary. Hence the new *S&TRU*s will probably be larger entities than in the past.

These conclusions are also relevant to the comprehensive RU wishing to take advantage of the '*golden age*'. Not only will it have to secure a critical mass of faculty in the relevant disciplines of the science-technology complex, but it will also have to break down barriers now existing between the various segments of this complex, and adopt a new institutional culture whereby technology and science assume a central role and mission.

Finally, the advances in S&T, coupled with the increasing role of scientists and engineers in society, raise difficult ethical questions related to the impact and consequences of technological progress, questions that the *S&TRU* will have to address. Hence, the *S&TRU* will also need faculty in the relevant subjects of humanity and social sciences. It appears, therefore, that the technological university of the future will be somewhat more 'comprehensive' than that of today, and the comprehensive university of today may become more 'technological'.

The character of the research at these future institutions will most likely be a blend of 'curiosity driven' research and 'programmatic research', with the latter in particular being carried out within larger multidisciplinary groups. Consequently, teams of faculty members and graduate students may replace the classical apprentice-mentor team. Moreover, in programmatic research and within the framework of the unfolding GIA alliance, more research will most likely be carried out within university-industry research centers, which are most suitable for generic pre-competitive type research. Harvey Brooks observed (7) that there are already over 1000 such centers in 200 colleges and universities in the US. They may be virtual or real, and could play an important role in the future *S&TRU*.

Teaching, Engineering Curricula & Novel Technologies

A common thread in the criticism leveled against the modern RU is the faculty's neglect of teaching in favor of research. Consequently, the RU culture is gradually changing and more attention is being focused on teaching, so that faculty members are now expected to devote equal attention to teaching and research. Quality teaching, however, requires faculty members who can not only delve into a narrow specialty[8], but who can also see the broader picture. Such faculty members are also better suited for multidisciplinary research because they can better communicate with neighboring disciplines.

In addition to increasing attention to teaching, the engineering curriculum itself must undergo reevaluation in view of the on-going, exponential growth of scientific and technological knowledge. The tiny percentage of existing knowledge that can be taught within the traditional, four-year university curriculum is shrinking. At the same time, industry continues to become more S&T intensive and demands increasing levels of knowledge from engineering graduates. Moreover, there is a growing need to incorporate elements of management, marketing and finance, and to reintroduce modern design methodology into the engineering

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[8] Jose Ortega Y Gasset refers to them as *learned ignoramuses* (The Barbarism of Specialization in "The Revolution of the Masses" 1930).

curriculum (22). In fact it has become increasingly difficult to educate a professional engineer in four years, as eloquently stated by Norman Augustine the former COB of the American Academy of Engineering (35): "*It takes eight years to educate a medical doctor, but only four years to anoint an engineer...one needs more formal training to give my neighbor's basset hound a vaccination than one needs to design an aircraft in which millions of people fly... it is time for the four-year engineering degree to join the slide rule, log tables, the French curve and ammonia reeking blueprints as artifacts of the past".*

However, because it is not practical to extend undergraduate B.Sc. curricula, the solution may be to create a double degree, five year education program which leads to combined B.Sc. and ME (21) degrees. The ME would then become the entry-level degree for positions in advanced industry.

Changes may also occur in the character of the doctoral degree. Today this is strictly a research degree for students opting for an academic career. High-tech industry, however, needs very highly trained employees with doctoral degrees which are not purely research-oriented. The *S&TRU* would be ideally positioned to develop such a program.

Finally, universities have been rather reluctant to adopt advanced teaching technologies. Intensive use of computers, interactive visual aids, distance teaching, Internet and other methods are penetrating the RU rather slowly. This, however, may change as younger faculty, who grew up with these tools, replace the older faculty.

New technologies have enabled the 'virtual university' to become a reality, yet, it is unlikely that the virtual university will replace the current campus-centered university model. Ultimately, the *S&TRU*, with its dominant lab-dependent teaching and research components and growing interaction with industry, will probably incorporate the 'virtual university' within its framework. Still, the personal interaction between faculty and students and among students must and will surely remain an essential and dominant component of engineering and science education, and therefore, the physical campus of a university should and will remain its focal point.

The Library

For centuries the library has been the heart of the university, serving as the central repository of knowledge accumulated from generation to generation. Indeed, one quantitative measure of the quality of a university has always been the number of books and scientific journals in its library. The library is also a focal point for services provided by the university to society and generally accessible to the public at large. However, the combination of communication and computer technologies has created a timeless and interconnected network supporting the global research enterprise, which has profoundly changed the role of the library. Already key scientific developments are globally shared through the Internet, and by the time a paper is published in a journal, let alone in a book, it is already well disseminated.

On a personal level, the Internet enables a direct link between individual researchers reminiscent of the personal correspondences scientists used to have with each other in the past. On the institutional level, it has launched a revolution that is restructuring the entire global scientific enterprise and bringing about a complete redefinition of the university library. The library will no longer exclusively define and codify existing knowledge; this role will be increasingly assumed by new 'shared research groups' on the electronic media. Librarians will be dispersed throughout the university community as members of research groups, and papers will become 'live' on the Internet with constant additions and changes by 'others'. "*In the fluid, electronic world of the future*" suggests Chodorow (36) "*the body of scholarship in a field may become a continuous stream, the later work modifying the older and all of it available to the reader in a single database or a series of linked data bases. In such a world, scholarship would progress in a perennial electronic conference or bulletin board. Contributions and databases would occur on the Internet and be continuous.*"

There are many difficult questions that these changes entail, regarding copyright, ownership, validity of data, preservation of knowledge, and funding for the resources. But, the dispersion of the library and its functions throughout the university down to the individual level has already begun. Consequently, instead of making massive investments in physical libraries in a futile effort to keep them up-to-date, future funding will have to be redirected into computer communication systems and shared database services.

These radical changes that universities will have to integrate into their culture are perhaps somewhat easier to assimilate by the research community dealing with S&T than by other segments of the university, because the main interest of the former is already sharply focused on current knowledge, rather than its historical evolution, data and documents.

Technology Transfer

Traditionally, faculty in the RUs transferred their knowledge to society at large only via their scientific publications and graduates. Direct commercial implementation of the new knowledge was rare. This situation has changed due to several factors:

- the immediate, commercial applicability of research results is increasing
- there is greater emphasis on advancing the country's economic competitiveness through commercial application of university research funded by national resources
- there is increasing industry-university cooperation driving commercial application
- universities struggling with financial difficulties consider technology transfer as a promising source of income
- faculty are more aware of the personal opportunities offered by the commercialization of their research findings
- society views technology transfer, and the consequent creation of jobs, as a return on the public investment into the university system.

There are both benefits and risks to technology transfer. The benefits include: the opportunity to promote technology in practice, which is consistent with the mission of a *S&TRU*; the ability of faculty to acquire practical experience, which helps teaching and research and offers a role model to the students, and a change in faculty image in society as being remote from reality and living in an 'ivory tower'. The disadvantages entail the risks of conflict of interest with academic research activities; the exploitation of graduate students for the advancement of business interests, and the creation of tension and a new type of inequality between members of the faculty unrelated to traditional academic excellence.

These and other ethical and pragmatic questions such as the rights of students to the benefits of their research results, the manner in which the benefits are divided between university and faculty (and students), and the role of such activities on academic promotion will have to be addressed, since technology transfer has become a permanent and increasingly dominant feature of the future *S&TRU.*

Technological universities are also getting involved in establishing 'technology-parks' for outside entrepreneurs, inventors, and start-up companies, offering them access to useful university resources. Such parks enhance technological-economic development, provide important financial resources to the universities, and encourage university-industry cooperation, and therefore they too will certainly be a part of the future *S&TRU* scene.

Continuing Education

The need for continuing education or life-long learning for engineers, scientists, and managers in industry throughout their professional career is a universally accepted concept. These studies offer participants updated information on the latest technological progress, as well as the option of periodically undergoing in-depth retraining.

Since the need for continuing education exists in all fields, adult education has become the fastest growing segment of university education. Most of these studies in S&T, however, take place outside the universities. This development occurred because universities failed to recognize the demand for such programs and respond in time, the faculties were too remote from industry and its practical requirements, and the larger companies were able to conduct in-house programs and even formal studies. This trend may change, however, with the downsizing of corporate research.

The *S&TRU,* with its increasing involvement with technological breakthroughs, cooperation with industry, and technology transfer, is also well-suited to answering the challenges of continuing education, and becoming a *center for life long learning,* with continuing education incorporated into the academic culture and recognized as an integral part of academic scholarship.

Outreach

The quality of a university depends very much on the quality of the students. Because of the deterioration of science education in high schools, compounded by a decline in science literacy and the status of science in society, the *S&TRU* will need to pursue a proactive enrollment policy. This can be accomplished through outreach programs for high-school students such as advanced classes, summer science camps, science competitions etc. Therefore, the future *S&TRU* campus must also have significant youth related enrollment activity.

International Relations

At the dawn of the 21st century, extensive international relationships and increasing global competition characterize the industrial scene. Companies conduct global research, manufacturing, development, marketing and management activities linked via new and efficient communication networks. Consequently, universities have started to emphasize the international aspects of engineering and management education. Many have initiated international student exchange programs to widen the students' horizons and better prepare them for the challenges of modern society. In fact the trend in undergraduate engineering education is to incorporate studies at another university in a different country.

University research, which was always international in character, is also growing more cooperative, as bibliometric studies on joint authorship show. It has become a routine matter for research groups based in different countries to share daily results through the electronic communication system.

These trends are likely to grow, and the future *S&TRU* is likely to become a *node* in a global network of universities, exchanging information in research and teaching. The only hindrances to this trend are the thorny issues of intellectual property rights, and the expected pressure of national funding agencies to prevent 'leaks' of commercially useful research results.

Structure, Institutional Culture & Governance

The current structure, institutional culture, and governance of the RU as well as that of the *S&TRU* have long-established and deeply entrenched roots. Clearly, some of these will have to change.

The centrality and national role of the *S&TRU*, the high cost of its maintenance, its accountability to society and its sheer size will make it necessary to find a new equilibrium between faculty-dominated, dispersed academic governance, and central leadership, direction and control. Faculty should continue to play a central and positive role in any future governance structure, and thus secure and guard the academic freedom which is the soul of any research university and an essential element for scientific progress and for the pursuit of excellence. But, the current institutional culture, that has been referred to as '*collective irresponsibility*', will have to be replaced by a new culture of '*shared responsibility*'. Faculty must view themselves as stakeholders in the new, emerging entity of the *S&TRU.*

Strong, central leadership implies that there must be one CEO who heads the university (President, Chancellor or Rector), not just as a manager or mediator of diverse interests, but as a strong academic and administrative *leader* of the university as a whole, who via a coherent, structured top management of mostly academics, *leads* the university. This, however, should not imply a large, burdensome academic or administrative bureaucracy on the shoulders of the faculty; rather it must secure and efficiently employ the huge resources such a university needs.

The disciplinary departments, which are the 'home base' or 'core units' of the *S&TRU,* should remain and continue to be the basic academic 'building blocks'. They are also the entity that can best evaluate academic accomplishments and deal with the promotion of faculty members. An excessive number of such 'building blocks', however, leads to duplicity and inefficiency, and makes the crossing of disciplinary boundaries more difficult. Therefore, these 'building blocks' should agglomerate into larger units while retaining the individual character of the components. For example, in many universities, electrical engineering and computer science are separate departments, yet scientific and technological developments indicate that they should merge.

In most universities these core and larger units are assembled within even larger supra-structures (e.g., 'colleges' and 'schools'). Although such structural units have a long tradition and may simplify management, they may also create barriers between disciplines that happen to fall in different supra-structural units. However, scientific progress is unpredictable and it is impossible to foresee which combination of units is best within the supra-structures. Hence a reasonable organizational compromise might be to create *virtual*, transient supra-structures, which should be permeable to cross-disciplinary activities. Such, virtual 'schools' may jointly enroll students, share teaching loads, and cooperate in research, but retain separate identities in management responsibility and hiring of new faculty.

Conclusion

Clearly, the university, which has evolved over the course of almost a millennium, has been flexible and responsive to the needs of society for centuries. The scientific revolution gradually converted it from being just a center for *maintaining and transmitting* knowledge to becoming a center for *creating* knowledge. The industrial revolution expanded its mission to include engineering education and technology, and the current ongoing scientific-technological revolution singles out the *S&TRU* as uniquely fitted to deal with both science and technology and their interaction, and to become a central and crucially important tool for the advancement of mankind. The *S&TRU*, therefore, in its unfolding '*golden age*', will not just be a large university campus, where students learn, engineers and managers train, and research is carried out, but rather it will become a major ***national-technology-science-complex;*** or rather a ***science-technology-city*** with the *university* at its core, surrounded by a large array of buffer institutions, industrial parks, technological incubators, science related cultural activities, science oriented youth camps, and international meeting places.

In spite of the growing national significance of the *S&TRU* (or perhaps because of it), and in view of the current crisis of the research university in general, the *S&TRU* must conduct a thorough reexamination of its mission, function and organizational structure along the lines discussed above. And, unless the *S&TRU* succeeds in continuing the millennium long tradition of adapting to society's needs, while remaining conscious of the shrinking time span available to carry out this task, it may fail its mission and miss its *golden age*.

We live on the threshold of the most technological scientific era ever, not only because of economic imperatives, but also because only science and technology can offer *real* solutions to the great problems mankind is and will be facing. Not the revival of fundamentalism and religions, not radical environmentalist 'green' movements, nor any other political, social, or fashionable intellectual movement, can show the way, offer the solutions and produce the hardware to resolve the most crucial problems threatening the survival of mankind on this planet. Only science and technology can suggest solutions how to feed, heal, provide shelter, supply the essential needs, and offer the hope for a better quality of life to the ten to eleven billion human beings expected to inhabit this planet during the lifetime of the next generation. The daunting challenge facing mankind is to find the way to do so in harmony with nature without destroying our fragile planet, and to do so without sliding back into the dark ages, and losing our civil rights, freedom, or the hope offered to mankind by modernity and enlightenment. The *S&TRU* should play a key role in meeting this challenge.

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