

MAJOR CHALLENGES TO ENGINEERING EDUCATION FOR SUSTAINABLE DEVELOPMENT: WHAT HAS TO CHANGE TO MAKE IT CREATIVE, EFFECTIVE, AND ACCEPTABLE TO THE ESTABLISHED DISCIPLINES*

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Introduction

Scholars and professionals committed to fostering sustainable development have urged a re-examination of the curriculum and the restructuring of research in engineering-focused institutions of higher learning. The focus is on engineering, more than on the natural and physical sciences or on social science, because the activities that drive the industrial state – the activities that implement scientific advance – are generally rooted in engineering. Moreover, engineers are known as ‘problem solvers’ and if economies are becoming unsustainable because of engineering, it is natural to ask whether engineering as an activity and as a profession can be re-directed toward achieving sustainable transformations. Of course, engineering can not do it alone; scientific as well as social and legal changes must occur as well. This paper addresses the challenges ahead, if this optimistic vision is to be more than wishful thinking.

Following a treatment of the philosophical and intellectual foundations of technological, organizational, social, and pedagogical innovation necessary for sustainable transformations of existing institutions and mindsets, this paper ends by addressing the following themes and questions: (1) How can multi- and trans-disciplinary research and teaching coexist in a meaningful way in today’s university structures? (2) Does education relevant to sustainable development require its own protected incubating environment to survive, or will it otherwise be gobbled up and marginalized by attempting to instill it throughout the traditional curriculum and traditional disciplines? (3) Even if there exist technical options to do so, how can it be made safe for courageous students to take educational paths different from traditional tracks? (4) What can we learn from comparative analysis of universities in different nations and environments? and (5) What roles can national and EU governments have in accelerating the needed changes?

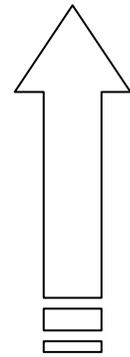
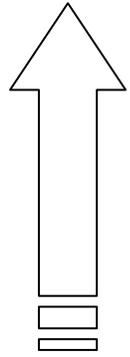
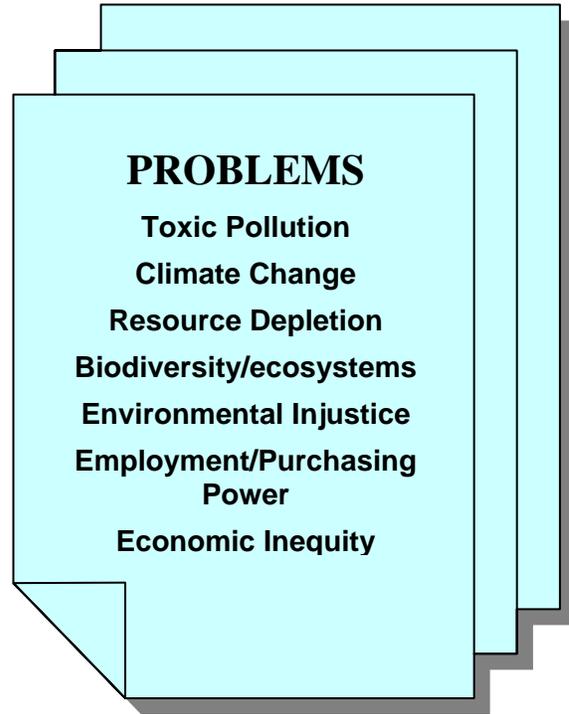
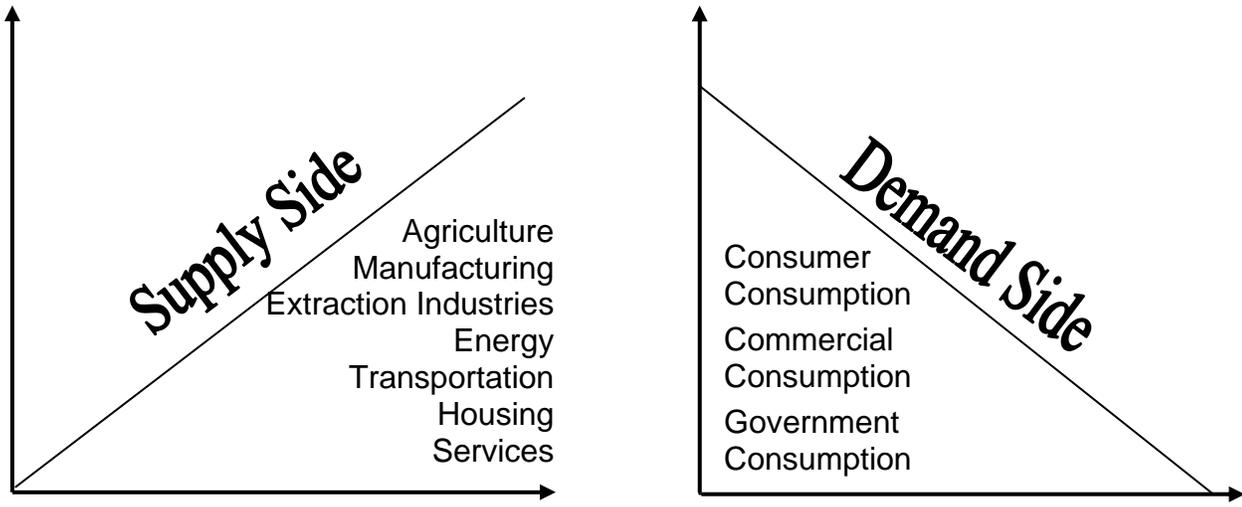
The Unsustainable Industrial State

Those that argue that the industrialized state – whether developed or developing – is currently unsustainable emphasize a number of problems. These are depicted schematically in the figure on the next page. The ‘environmental problems’ include toxic pollution, climate change, resource depletion, and problems related to the loss of biodiversity and ecosystem integrity. The environmental burdens are felt unequally within nations, between nations, and between generations, giving rise to inter-national, intra-national, and intergenerational equity concerns that are often expressed as ‘environmental injustice’. The Brundtland formulation of sustainability seems to focus concern on intergenerational equity, but all three kinds of mal-distributions are important.

The environmental problems stem from the activities concerned with agriculture, manufacturing, extraction, transportation, housing, energy, and services -- all driven by the demand of consumers, commercial entities, and government. But in addition, there are effects of these activities on the amount, security, and skill of employment, the nature and conditions of work, and purchasing power associated with wages. An increasing concern is economic inequity stemming from inadequate and unequal purchasing power within and between nations – and for the workers and citizens of the future.

Whether solutions involving industry initiatives, government intervention, stakeholder involvement, and financing can resolve these unsustainability problems depends on correcting a number of fundamental faults in the characteristics of the industrial state: (1) fragmentation of the knowledge base leading to myopic understanding of fundamental problems and the resulting fashioning of single-

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SOLUTIONS



purpose or narrowly-fashioned solutions by technical and political decision-makers, (2) the inequality of access to economic and political power, (3) the tendency towards ‘gerontocracy’ – governance of industrial systems by old ideas, (4) the failure of markets both to correctly price the adverse consequences of industrial activity and (5) to deal sensibly with effects which span long time horizons for which pricing and markets are inherently incapable of solving. It is to the first failure that this essay is directed.

Conceptualizations of Sustainable Development

It makes quite a difference whether you look at sustainable development as just an environmental issue, or alternatively as a multidimensional challenge in the three dimensions: economic, environmental, and social. We argue that competitiveness, environment, and employment are the operationally-important dimensions of sustainability – and these three dimensions together drive sustainable development along different pathways and go to different places than environmentally-driven concerns alone, which may otherwise require tradeoffs, for example, between environmental improvements and jobs. The inter-relatedness of competitiveness, environment, and employment is depicted in the next figure.

A *sustainable development* agenda is, almost by definition, one of systems change. This is not to be confused with an *environmental policy* agenda, which is – or should be – explicitly effect-based, and derived from that, a program of policies and legislation directed towards environmental improvements, relying on specific goals and conditions. The sustainable development policy agenda focuses at least on processes (e.g., related to manufacturing, transport, energy, construction, etc.), and may extend to more cross cutting technological and social systems changes.

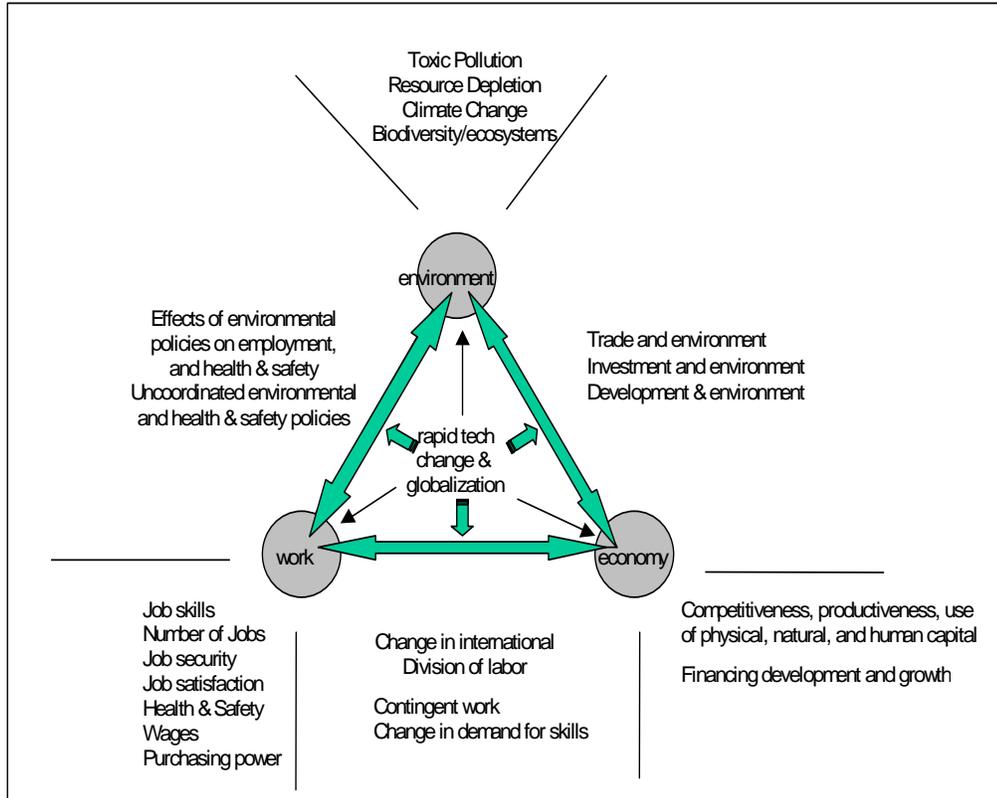
<u>AGENDA</u>	<u>Competitiveness</u>	<u>Environment</u>	<u>Employment</u>
Current	Improve Performance/Cut Costs	Control pollution/make simple substitutions or changes Conserve energy and resources	Ensure supply of adequately trained people; dialogue with workers Provide safe workplaces
Sustainable	Change nature of meeting market needs through radical or disrupting innovation (a systems change)	Prevent pollution through system changes Change resource and energy dependence	Radical improvement in human-technology interfaces (a systems change)

Note that *current strategy agendas*, even those that go beyond environmental goals, are defined as those that are focused on those policies that (1) improve profit and market share by improving performance in current technologies or cutting costs, (2) controlling pollution/making simple substitutions and changes, and conserving energy and resources, and (3) ensuring an adequate supply of appropriately skilled labour, and safe and healthy workplaces. We would describe these strategies as ‘reactive’ vis-à-vis technological change, rather than proactive. They are usually pursued separately and by different sets of government ministries and private-sector stakeholders. At best, policies affecting competitiveness, environment, and employment are *coordinated*, but not integrated.

In contrast, *sustainable agendas* are those policies that are focused on technological changes that alter the ways goods and services are provided, the prevention of pollution and the decreased use of energy and resources through more far-reaching system changes, and the development of novel socio-technical systems -- involving both technological and organizational elements -- that enhance

The Dimensions of Sustainability

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SYSTEMIC PROBLEMS:

- o Inadequate response & adaptation times
- o Insufficiency of domestic policy options
- o Uncoordinated industrial, environmental, employment, and trade policies

the many dimensions of ‘meaningful employment’ through the *integration*, rather than coordination, of policy design and implementation.

The kind of innovation likely to be managed successfully by industrial corporations is relevant to the differences between current and sustainable technology agendas. We argue that the needed major product, process, and system transformations may be beyond those that the dominant industries and firms are capable of developing easily, at least by themselves. Further, industry and other sectors may not have the intellectual capacity and trained human resources to do what is necessary.

This argument is centered on the idea of ‘the winds of creative destruction’ developed by Joseph Schumpeter¹ in explaining technological advance. The distinction between incremental and radical innovations – be they technological, organizational, institutional, or social – is not simply line drawing along points on a continuum. Incremental innovation generally involves continuous improvements, while radical innovations are discontinuous² possibly involving *displacement* of dominant firms, institutions, *and ideas*, rather than evolutionary transformations. In semantic contrast, Christensen³ distinguishes continuous improvements as ‘sustaining innovation’ and uses the term ‘disrupting innovation’ rather than radical innovation, arguing that both sustaining and disrupting innovations can be either incremental or radical, where the term ‘radical’ is reserved for the rapid or significant performance changes *within* a particular technological trajectory.

Thus, in Christensen’s terminology, radical sustaining innovation is a major change in technology *along the lines that technology has been changing historically*, for example a much more efficient air pollution scrubber -- and is often pioneered by incumbent firms. Major innovation that represents an entirely new approach, even if it synthesizes previously invented artifacts, is termed ‘disrupting;’ and in product markets, it almost always is developed by firms not in the prior markets or business. This is consistent with the important role of ‘outsiders’ – both to existing firms and as new competitors -- in bringing forth new concepts and ideas⁴.

Counting only or mainly on existing industries, or on traditionally-trained technical expertise, for a sustainable transformation ignores increasing evidence that it is not just willingness and opportunity/motivation that is required for needed change, but that a third crucial condition -- the ability or capacity of firms and people to change -- is essential.⁵ In some situations they may do so because society or market demand sends a strong signal, but not in all or even in most of the cases.

We argue here that the same holds true for government and societal institutions faced by the triple challenge emanating from new demands in the areas of competitiveness, environment and employment. Intelligent government policy is an essential part of encouraging appropriate responses of the system under challenge, and of assisting in educational transformations as well.

¹ Schumpeter, Joseph. (1939). Business Cycles: A Theoretical, Historical and Statistical Analysis of the Capitalist Process. New York, McGraw-Hill, as discussed in Niehans, Jurg, “Joseph Schumpeter” in A History of Economic Theory: Classic Contributions 1720-1980. Baltimore: Johns Hopkins University Press, 1990, p. 448.

² Freeman, Chris (1992) The Economics of Hope, Pinter, London.

³ Christensen, Clayton (2000). The Innovator’s Dilemma: When New Technologies Cause Great Firms to Fail. Second edition. Harvard Business School Press

⁴ de Poel, Ibo. “On the Role of Outsiders in Technical Development” Technology Analysis & Strategic Management, Vol. 12, No. 3, 2000, pp 383-397.

⁵ Ashford, Nicholas (2000). “An Innovation-Based Strategy for a Sustainable Environment”, in Innovation-Oriented Environmental Regulation: Theoretical Approach and Empirical Analysis, J. Hemmelskamp, K. Rennings, F. Leone (Eds.) ZEW Economic Studies. Springer Verlag, Heidelberg, New York, pp 67-107.

An essential concept in fostering innovative technical responses is that of 'design space.' As originally introduced by Tom Allen et al. of MIT, design space is a cognitive concept that refers to the dimensions along which the designers of technical systems concern themselves⁶. Especially in industrial organizations that limit themselves to current or traditional strategies or agendas, there is a one-sided utilization of the available design space. Solutions to design problems are only sought along traditional engineering lines. In many cases unconventional solutions – which may or may not be hi-tech -- are ignored. For that reason radical, disrupting innovations are often produced by industry mavericks, or as a result of some disruptive outside influence (such as significantly new or more stringent environmental regulation and foreign competition, or influence of an outsider to the organization).

What has all this to do with engineering education? For an answer, we need to delve into the disciplinary focus of research and education.

Inter-, Multi- and Trans-disciplinary Research and Education

Appreciating the distinctions between these three terms is essential to understanding why well-meaning efforts at solving complex problems by assembling professionals from different disciplines or expanding a traditional education in a particular direction often leads to disappointing results.

Inter-disciplinary research (and teaching) – literally 'between disciplines' -- often precedes the creation of a new well-defined field. Thus, biochemistry begins with a focus of traditional chemistry principles and knowledge applied to biological systems; it adapts and grows; and the intellectual boundaries are refocused and redrawn. Finally, biochemistry becomes a field unto its own, different, but not necessarily broader or narrower than the parent disciplines that spawned it.

Multi-disciplinary research (and teaching) – literally 'several or many disciplines' – brings together several disciplinary focuses, and thus deals with more than one traditional concern. For example, costing out different energy options necessarily involves knowledge of both energy technology and economics. Multi-disciplinary research and teaching can be carried out by multi-disciplinary teams or by one individual who has been trained in more than one discipline.

Trans-disciplinary research (and teaching) – literally 'across disciplines' – transcends the narrow focus of one or more disciplines and is not constrained to adopt pre-existing models for problem definition or solution. Boundaries might necessarily have to be drawn as a practical matter, but they are not dictated by limitations of the analyst or designer. Where broad system changes are desirable, trans-disciplinary approaches are essential. Trans-disciplinary approaches really 'open up the problem space of the engineer'. By their nature, trans-disciplinary approaches synthesize and integrate concepts whose origins are found in different disciplines, and system innovation requires synthesis.

Addressing the many facets of sustainability requires an extremely broad list of possible enquiries related to policy analysis and design. In the annex to this paper is the author's trans-disciplinary approach to addressing a 'technology and policy' problem' that contemplates system changes.

The Dimensions of Policy Analysis and Design

On the next page is found a conceptualization of the many activities that constitute policy analysis and design. They are used in both multi-disciplinary and transdisciplinary policy research, but in different ways. There are both 'policy sciences' and 'policy engineering'. The policy sciences are grounded in the disciplines of science and mathematics and include both inter-disciplinary studies, such as biostatistics – and multidisciplinary studies, such as life-cycle analysis or cost-benefit analysis. Policy engineering focuses on changing, rather than merely assessing science and technology, e.g., the design of environmentally sound materials, which requires knowledge of physical properties, toxicity, economics, and industrial processes. Policy engineering makes use of the policy sciences, but

⁶ Allen, Tom J., et al., "Government Influence on the Process of Innovation in Europe and Japan," *Research Policy*, Volume 7, Number 2, April 1978, pp. 124-149.

design and assessment are different endeavors. For one thing, 'art,' as well as knowledge, is involved in both defining what needs to be changed and how it is to be changed. If the policy engineer is narrowly focused, he/she may come up with a single purpose design with unanticipated problems down the road. For example, in an effort to design energy-efficient buildings during the various energy crises, buildings were constructed that created serious indoor air quality problems.

Multi-disciplinary approaches may borrow many tools from the policy sciences, but full conceptual integration and cooptimization of sustainability goals are usually not achieved. These approaches, though well-motivated, give the appearance of inclusiveness in analysis and design options, but they fail to identify multiple win options necessary for sustainable industrial transformations. This author regards undue reliance on, and satisfaction with, multidisciplinary approaches to be a serious impediment to more transdisciplinary creative problem solving⁷.

Note especially, that under policy engineering, policies necessarily include creating *both* the appropriate technology and market-based economic incentives for persons and institutions to change, *and* appropriate legal approaches and instruments. Knowledge of both market economics and the law are necessary for comprehensive policy design. Many policy programs do not give adequate attention to use of legal instruments, and multidisciplinary teams addressing technology policy problems rarely include persons knowledgeable in legal policy analysis and design⁸.

Note also, the value-laden assumptions in policy assessment (such as cost-benefit analysis) and policy design. A trans-disciplinary approach necessarily requires *valuation*, as well as evaluation, of outcomes and alternatives. Thus, the distributional consequences of a policy are critical to include. Effects of a policy on competitiveness, environment, and employment – and the distributions of costs and benefits – all must be considered. Is traditional engineering education transformable to meet this challenge?

Returning to the Questions

How can multi- and trans-disciplinary research and teaching coexist in a meaningful way in today's university structures?

Most faculty are neither multi-disciplinary, nor trans-disciplinary. The creation of separate divisions or departments within a university to house, tenure, and promote multi-disciplinary faculty may succeed, especially if there is a two-key system – i.e., they hold joint appointments in traditional departments. However, trans-disciplinary faculty are unlikely to receive initial or final approval from the traditional departments, and these separate entities may not hire them. (An engineer that works on less-polluting car may be welcome, but a person who used to be an engineer and is now working on policies to change consumer demand for energy may not be so well-received by traditionally-focused engineering faculty.) A two-key system may not be conducive to attracting or retaining trans-disciplinary faculty. Traditional departments want their faculty to do what the others do, at least some of the time. And what about teaching? If the separate division or department is degree-granting, trans-disciplinary teaching might survive, but other things are necessary.

Does education relevant to sustainable development require its own protected incubating environment to survive, or will it otherwise be gobbled up and marginalized by attempting to instill it throughout the traditional curriculum and traditional disciplines?

Given that much needed research for sustainable development needs to focus on larger system changes, and the fact that government and industrial support, is likely to be traditional -

⁷ The distinction is akin to the difference between making a Hungarian goulash and a fine French puree. The ingredients are the same, but the final result looks and tastes differently.

⁸ Indeed, the considerable writing on science and technology issues found in law review articles, the mainstay of legal scholarship, is rarely accessed by most economically- or technically-trained policy analysts.

DIMENSIONS OF POLICY ANALYSIS AND DESIGN

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POLICY SCIENCES

RISK ASSESSMENT

- ¥ BIOSTATISTICS, EPIDEMIOLOGY
- ¥ TOXICOLOGY
- ¥ MODELING FOR POLLUTANT TRANSPORT
- ¥ FAULT TREE ANALYSIS
- ¥ EXPOSURE MODELING
- ¥ LIFE CYCLE ANALYSIS

TECHNOLOGY ASSESSMENT

- ¥ THEORY OF THE FIRM
- ¥ PREDICTING INNOVATION
- ¥ OPERATIONS RESEARCH
- ¥ THEORY FOR REGULATION'S EFFECT ON INNOVATION
- ¥ EFFECTS ON JOB CONTENT AND EMPLOYMENT

ECONOMICS AND MATHEMATICAL MODELING

- ¥ STATISTICS
- ¥ ECOMETRICS
- ¥ SYSTEMS ANALYSIS
- ¥ PORTFOLIO AND INVESTMENT ANALYSIS
- ¥ ORGANIZATIONAL THEORY

DECISION-MAKING

- ¥ C/B ANALYSIS
- ¥ RISK-BENEFIT ANALYSIS
- ¥ TRADE-OFF ANALYSIS
- ¥ COMPUTER-BASED DECISION SYSTEMS

VALUES RESEARCH

- ¥ BENEFITS EVALUATION
- ¥ ETHICS IN SCIENCE AND TECHNOLOGY

LAW AND JURISPRUDENCE

- ¥ LAW AND SCIENCE AS PARADIGMS FOR ESTABLISHING TRUTH AND FACT
- ¥ PROPERTY RIGHTS AND JUSTICE
- ¥ ANALYSIS OF EXISTING LAW AND ITS INSTITUTIONS
- ¥ LAW AND ECONOMICS AS COMPETING PARADIGMS FOR PUBLIC POLICY

POLICY ENGINEERING

DESIGN AND EVALUATION OF TECHNOLOGY AND MARKET-BASED POLICIES FOR INDUSTRY, AGRICULTURE, ENERGY, TRANSPORT and HEALTH, SAFETY & ENVIRONMENT:

- ¥ MATERIALS AND RESOURCES
- ¥ TRANSPORTATION
- ¥ TECHNOLOGICAL INNOVATION
 - MANUFACTURING
 - BIOTECHNOLOGY
 - INFORMATION SYSTEMS AND TELECOMMUNICATIONS
 - SERVICES
- ¥ DIFFUSION OF TECHNOLOGY AND TECHNOLOGY TRANSFER
- ¥ IMPROVING ENVIRONMENT, HEALTH AND SAFETY
- ¥ HEALTH CARE DELIVERY AND TECHNOLOGY
- ¥ LAND USE AND URBAN DEVELOPMENT
- ¥ MANAGERIAL AND TECHNICAL MANPOWER DEVELOPMENT
- ¥ REDUCING BARRIERS FOR INNOVATION, EMPLOYMENT AND INTERNATIONAL TRADE
- ¥ INDUSTRIAL & OFFICE AUTOMATION
- ¥ UNEMPLOYMENT & TECHNOLOGICAL CHANGE
- ¥ SUSTAINABLE ECONOMIC DEVELOPMENT
- ¥ ENERGY EXPLORATION, GENERATION, TRANSMISSION, USE & ALTERNATIVES
- ¥ ARMS CONTROL, MILITARY TECHNOLOGY & DEFENSE
- ¥ REGIONAL/STATE PROGRAMS
- ¥ DEVELOPING COUNTRIES

THE USE OF LAW AS AN INSTRUMENT FOR CHANGE

- ¥ LEGISLATION
- ¥ REGULATION & DE-REGULATION
- ¥ ESTABLISHMENT OF INDIVIDUAL RIGHTS & CONSTITUTIONAL ISSUES; COURT REFORM; ACCESS TO INFORMATION
- ¥ PRODUCTS LIABILITY, TORT LAW & VICTIMS' COMPENSATION
- ¥ DISPUTE RESOLUTION
- ¥ PATENT POLICY
- ¥ INTERNATIONAL ENVIRONMENTAL ACCORDS
- ¥ INTERNATIONAL TRADE REGIMES
- ¥ INTERNATIONAL LABOUR ISSUES

- or at most multidisciplinary -- the needed research for sustainability needs to be incubated and protected, and with a long-term focus. Instilling sustainability concepts into traditional areas may be useful, but more is required.

Even if there exist technical options to do so, how can it be made safe for courageous students to take educational paths different from traditional tracks?

This is a major problem, especially if the majority of faculty are traditional and unsympathetic to even multi-disciplinary work. It is no secret that faculty like to create 'vest-pocket editions' of themselves. The insecurity of future employment also makes this a high-risk venture for them.

What can we learn from comparative analysis of universities in different nations and environments?

Certainly, successes and failures from other institutions and countries would be instructive in the design of both research and teaching arrangements.

What roles can national and EU governments have in accelerating the needed changes?

The establishment of government programs – both national and in Europe at the EU level -- for sustainability research where the evaluators/'peer reviewers' of the research proposals are themselves trans-disciplinary is essential. Otherwise, innovative, cross-cutting research will not be encouraged or funded. In addition, government should commit to hiring early graduates of the programs – and providing incentives to the private sector to hire graduates of multi- and trans-disciplinary programs. There is a need for government to 'make a market' to lead this educational innovation.

Conclusion

The increasing universal concern for advancing more sustainable development presents considerable challenges to both education and research. The established disciplines continue to provide some useful advances, but the portfolio of needed approaches is under-represented in multi-disciplinary and trans-disciplinary scholarship and pedagogy. Trans-disciplinary thinking is often confused with multi-disciplinary thinking, and significant institutional and intellectual barriers for the emergence of integrated systems thinking -- in government, firms, and educational institutions alike -- remain major problems in both research and education. Beyond lip-service, without clear, vocal, and strong continuous leadership and rewards for a 'second track' of problem solving in these institutions, progress will continue to be slow.

ANNEX
TECHNOLOGY AND POLICY: Problems and Analytical Approaches
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1. Introduction to the Technology and Policy Problem

- Statement of the problem: public/societal/technical problem(s) in need of attention (unmet needs, technical & institutional failure)
 - Description
 - Problem type (see matrix at the end)
 - Historical context (e.g., why this arose as a problem)
 - Issues (e.g., why intervention is needed)
 - Stakeholders

- Description of any prior attempts to resolve/improve the problem(s), and analysis of their inadequacy/failures in terms of:
 - economics and markets (inadequate and/or perverse incentives, prices, markets, institutional/organizational structure and behavior, -- and inappropriability of benefits/free-rider problems, and unrecognized/unmet needs and demands)
 - law and political process (inadequacy of existing legislation/regulations; lack of knowledge/enforcement thereof; inadequate stakeholder involvement)
 - private sector management (lack of adequate incentives or perverse incentives for, or commitment to, management of the problem)
 - technical system failures or inadequacies

- Description of prior tools, models, techniques, approaches (e.g., c/b, lca, risk assessment, institutional/organizational behavior theory, innovation theory, system dynamics, etc.) used to inform the decision-making process working through:
 - economics and markets
 - law and political process
 - private sector management

2. Goals/Targets of a Desired Transformation

- technological/scientific changes (options for R&D, innovation , and diffusion)
- system changes related to organizational/institutional structure
- changes in prices, markets, and industry structure
- changes in demand
- changes in law and political process (legislation, regulation, negotiation, stakeholder participation)
- changes in private sector activity
- other

3. Tools, models, techniques, and approaches that could affect the willingness, opportunity/motivation, and capacity for the stakeholders (industry, consumers, workers, citizens, government at all levels) to change

- willingness
 - towards change in general (rigidity)
 - influenced by an understanding of the problem
 - influenced by knowledge of options or solutions
 - influenced by the ability to evaluate alternative courses of action
 - other

- opportunity/motivation
 - presented by gaps in technological/scientific capacity
 - possibility of economic cost savings or new/expanded market potential (competitiveness)
 - consumer/worker/societal demands
 - regulatory/legal requirements
 - other

- capacity
 - influenced by an understanding of the problem
 - influenced by knowledge of options or solutions
 - influenced by the ability to evaluate alternative courses of action
 - resident/available skills and capabilities
 - other

4. Formulation of specific strategies (economic, legal, institutional, firm-based, societal-based, etc.) affecting willingness, opportunity, and capacity to bring about desired changes.

5. Identification of Barriers and Strategies for Surmounting/Circumventing Them (including evaluation of likelihood or ease of implementation and political coalition-building).

PROBLEM TYPES (types and examples)
Resolving (for policy action purposes) contradictory or uncertain scientific & technological Information, e.g., <i>breast implants; star wars</i>
Technology development in a socially beneficial way/direction, e.g., <i>genetically engineered crops</i>
Controlling the Adverse Effects of Technology, e.g., <i>climate change, toxic chemicals</i>
Promoting Technology to Meet Unmet Human Needs, e.g., <i>rapid rail systems, new cancer therapies</i>
Responsibility of Scientists & Engineers in Industry & Government, e.g., <i>Challenger accidents</i>
Uneven distributions of the benefits and costs of a technology, e.g., <i>Health care technology</i>
Etc.