Why Engineering Education Fails to Protect the Public Interest and What Could Be Done About It

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Abstract
Twenty-five years ago, our comprehensive study of undergraduate engineering education asked the following two questions: How well do we teach future engineers to understand the influence of technology on human life, society and the biosphere? and: To what extent do we teach them to use this understanding in a negative feedback mode to achieve the desired results and, at the same time, prevent or greatly minimize harmful effects? These two questions were converted into extensively tested research instruments to permit the quantitative scoring of the components of all the courses in the curriculum. The results showed that the answer to both questions was: almost nothing.

Since this study, its findings have been confirmed by a number of economists who have estimated net wealth production by subtracting from the Gross Domestic Product (GDP) the costs incurred in producing it. They found that net wealth has been declining for decades. These and other data point to the inevitable conclusion that the undesired consequences of technological and economic growth are undermining the desired ones.

This brings us to a crossroads in engineering education. Either we continue to deal with the undesired consequences of design and decision-making in an end-of-pipe fashion, or we do so preventively. However, preventive approaches require a new knowledge system that links the disciplines examining the consequences of technology with those in the technical core of the curriculum in order to create negative feedback loops. This paper will describe some of the features of such a knowledge system, and how it supports preventive approaches in a new curriculum developed by the Centre for Technology and Social Development at the University of Toronto. This approach would permit engineering education to help society address the ever more pressing challenges of our time.

Scoping Our Failure
Some 25 years ago, our comprehensive study of engineering education asked the following two questions: How well do we teach future engineers to understand the influence technology has on human life, society and the biosphere? and: To what extent do we teach them to use this understanding in a negative feedback mode to adjust design and decision-making to achieve the desired results and at the same time prevent or greatly minimize harmful effects? These two questions were converted into extensively tested research instruments to permit the quantitative scoring of an undergraduate engineering curriculum at one of the leading Canadian schools. The results showed that the answer to both questions was: almost nothing [1].The results were widely

circulated to the deans of most Canadian and US engineering schools, given the similarity of the requirements of the Canadian Engineering Accreditation Board and the Accreditation Board for Engineering and Technology. The results were also forwarded to these boards and the Canadian Engineering Academy. Despite some polite gestures, the seriousness of the implications of the findings were ignored. Our profession cannot claim to protect the public interest except in the narrowest technical sense of the term, which could raise questions regarding its ability to regulate itself.

Outside the profession, the response was much more positive. In 1995, the former Premier's Council of Ontario appointed the lead author of the study to co-chair a roundtable to advise on how best to restructure professional education on the conviction of the possibility of a new kind of technological and economic development, which would produce the desired goods and services while preventing or significantly reducing harmful social and environmental effects. In 2002, the Canada Foundation for Innovation recognized preventive approaches as one of 25 leading recent Canadian innovations [2]. In 2003, the Natural Science and Engineering Research Council of Canada (NSERC) together with the Social Sciences and Humanities Research Council of Canada (SSHRC), under the leadership of their former presidents, developed a joint initiative (STS21) to explore the possibility of transforming research and teaching in the Canadian universities, in part to develop the potential of preventive approaches. There were other attempts as well, but largely because of the shifting political spectrum, nothing concrete was accomplished.

However, there is a growing body of research showing that the undesired consequences of technological and economic growth are undermining the desired ones. This brings us to a crossroads in engineering education. Either we continue to deal with the undesired consequences of design and decision-making in an end-of-pipe fashion, or we do so preventively. The latter approach requires a new knowledge system that links the disciplines examining the consequences of technology with those in the technical core of the curriculum in order to create negative feedback loops. Following a diagnostic assessment of the present situation, this paper will describe some of the features of such a knowledge system and how it supports preventive approaches in a new curriculum developed at the Centre for Technology and Social Development at the University of Toronto. Eventually this approach could help society address the ever-more pressing challenges of this century.

Our Current Knowledge Infrastructures

The evolution of contemporary ways of life is deeply affected by the decisions of countless specialists based on an established intellectual and professional division of labour. These specialists belong to groups responsible for advancing and applying a body of knowledge. Jointly, these bodies of knowledge constitute knowledge infrastructures that support the many decisions that evolve these ways of life. The following three characteristics of these knowledge infrastructures are of concern. First, on the macro level they institutionalize an end-of-pipe approach to dealing with the undesired consequences of any decision. Second, on the micro level, they trap individual specialists in a triple abstraction, which leads to a steady decline in the ratio of desired to undesired effects of their decisions. Finally, on an intermediate level, they bar the road toward genuine solutions to the many difficulties faced by contemporary societies because they lie outside of the domains of specialization of the practitioners that would normally deal with them[3]. These characteristics will now be discussed in detail.

As noted, the evolution of contemporary ways of life depends on the decisions of countless specialists. Most of the consequences of these decisions fall beyond their domains of expertise, where they cannot “see” them. As a result, the undesired or illegal ones must be dealt with by other specialists in whose domains they fall. Consequently, the “system” institutionalizes an end-of-pipe approach to undesired effects. Instead of getting to the root of any problem, the “system” adds technologies or services. There is a great deal of evidence to suggest that the “system” now produces undesired results at a greater rate than desired results, because the costs incurred in the production of wealth are growing more rapidly than the increases in gross wealth production, as measured by the Gross Domestic Product (GDP); and a number of economists have calculated that, as a result, net wealth has been declining for decades[4]. Similarly, we are now producing pollutants (products that we produce but cannot sell) at a greater rate than desired goods and services. A study by the American Academy of Engineering estimates that of what we extract from the biosphere, 93% is turned into undesired products (pollutants) and only 7% into goods and services[5]. Our materials and production systems may well turn out to be the most uneconomic and environmentally destructive ones created by humanity. Some time ago, Blue Cross was the largest supplier of the largest corporation in the world. Apparently, physically and mentally ill workers were the company’s most valuable undesired output[6]. To deal with these and other health problems, it was necessary to expand our “disease care” system. Rapidly growing health care budgets would suggest that the rate at which contemporary ways of life produce illnesses outstrips their ability to deal with them. If the costs externalized into society by many corporations are subtracted from their profits, they should be making losses amounting to several times their current profits[7]. It is not difficult to multiply these kinds of examples, but the deep structural economic crisis is obvious. We have created a “system” whose “signal-to-noise” ratio of desired to undesired effects is steadily declining because of our increasingly global knowledge infrastructure.

Second, this knowledge infrastructure traps specialists in a triple abstraction that makes them unable to do anything about the present situation. In separating a domain of expertise from the remainder of the world, the latter is represented in any specialty by the desired outputs it hopes to contribute to that world and the requisite inputs received from that world to produce these outputs. In a second abstraction, only those aspects of the process converting requisite inputs into desired outputs that are coterminous with a specialist’s domain of expertise are retained. For example, everyone working at a hospital knows different aspects of the process that transforms ill people (admitted from the world) into people on the mend (discharged back into it). A third abstraction flows from the way a domain of specialization seeks to make improvements. It begins by creating a model of the process that converts requisite inputs into desired outputs, followed by varying its form and correlating such variations to performance in order to select the “best” one. Since no specialist has the knowledge of which form is best for human life, society or the biosphere, the “best” one is reduced to the one that obtains the highest desired outputs from the requisite inputs as measured by output/input ratios like efficiency, productivity, profitability, cost-benefit comparisons and GDP (obtained from a society interacting with the biosphere). As a result, a specialist has no idea whether any gains in desired outputs are realized, in part or in whole, at the expense of human life, society or the biosphere. There is therefore a significant tendency for such decisions to obtain the desired results, but at the same time to undermine the integrality and context-compatibility of what has been made “better”. As a civilization we succeed brilliantly in the domain of improving performance, and fail equally spectacularly to prevent performance from undermining human life, society and the biosphere.

A third characteristic of the knowledge infrastructures follows directly from the second. What if a genuine solution to a particular set of difficulties cannot be achieved by optimizing one or more aspects of the process of obtaining the desired results from requisite inputs? In such cases, practitioners may be unable to arrive at genuine solutions, trapped as they are in this triple abstraction. For example, is it reasonable to expect that the solution to our traffic congestion in most cities lies in the optimization of the present transportation system? It may well be that the real solution lies in reducing the need for mobility. In that case, the urban form would have to be rethought; and this is clearly beyond the traditional domain of traffic engineering. Similarly, it is highly unlikely that in the long term the energy crisis can be dealt with by improving the efficiency of power generation and distribution and the building of more power stations. The exponential growth in energy demands will have to be reshaped; and this is clearly beyond the domain of power engineering. Consequently, the present intellectual and professional division of labour, and the knowledge infrastructures built up with it, together prevent genuine solutions from emerging when these represent a non-cumulative development. All this manifests the fundamental shift that our civilization has undergone during the last half century. We no longer ask how this or that can improve human life, but how this can be made to yield the greatest power by converting requisite inputs into desired outputs.

These three characteristics are clearly manifested in undergraduate engineering education. For example, the creation of environmental engineering is, for the most part, an end-of-pipe solution to the problem that all the other branches of engineering do not internalize environmental considerations. If all the other branches could be made to take on a preventive orientation with respect to the environmental consequences of design and decision-making, only those consequences that could not be prevented would have to be dealt with by mitigation[8].The currently fashionable focus on energy also has an end-of-pipe orientation. Each and every branch of engineering should internalize energy considerations into its design and decision-making, including the consequences energy use has for human life, society and the biosphere. In sum, since we teach future engineers almost nothing about the influence technology has on human life, society and the biosphere and even less about how to use this understanding in a negative feedback mode to obtain the desired results with a better ratio of desired to undesired effects, our profession educates future engineers who will continue to aggravate the above problems. These result in ways of life that are uneconomic, socially non-viable, and environmentally unsustainable. Like other specialists, engineers are obliged to delegate responsibility for the consequences of their actions to other specialists, thereby leading to a corresponding end-of-pipe professional ethics. Similarly, the protection of the public interest has been reduced to ensuring reliable and relatively safe performance while delegating the responsibility for the consequences to others.

Preventively-Oriented Engineering Education

From the above diagnosis flows a prescription of how the engineering profession could give leadership in beginning to turn the present situation around. An iterative curriculum development process must be set in motion that will teach future engineers how technology influences human life, society and the biosphere and how this knowledge can be used to steadily improve the ratio of desired to undesired effects of design and decision-making. In other words, they must learn to guide technical processes by means of negative feedback, like other daily life activities. They must learn to verify that any new technology is not a compensation for problems created by earlier technologies. Responsible design and decision-making involves going to the root of a problem, hence a distinction must be made between compensatory technologies and services and genuinely new ones corresponding to real needs and aspirations. They must learn to distinguish between situations in which a technological response is appropriate and those where this would create a "techno-fix" because these situations are not amenable to a technical solution. They must understand that any critical evaluation of a technology depends on a frame of reference and a vantage point; and what one group may deem to be a good technological solution may not be seen as such by others. This is inevitable in any society in which groups are differentially affected in terms of who pays, who benefits and who bears the negative consequences. They must also learn that none of us are detached observers of technology. Our lives are so unthinkable without it that it is next to impossible to imagine who we would be and what our world would be like without modern technology. As a result, we all approach technology-related issues and problems with certain pre-judgments that come from living a life in a technology-permeated society and world[9].

The development of a preventive orientation in undergraduate engineering education depends on the creation of a synergistic relationship between the technical core and the complementary studies components of the curriculum. At present, the intellectual "worlds" of the disciplines and specialties of the one are full of technology and little else, while the "worlds" of the others are full of everything else and little technology. This situation was also quantitatively measured in the above study of undergraduate engineering education. This dualism blocks all preventive approaches because it makes it impossible for students to understand how their technical design and decision-making contributes to the functioning technology of a society, and how this in turn influences all aspects of that society, from its economy to its art[10].

To overcome the above difficulties, the transformation of undergraduate engineering education could begin with the creation of several "bridge" courses that mediate between the technical core and complementary studies. What the students learn in these courses could then be built on in their technical and complementary subjects to guide technological design and decision-making by negative feedback, based on an understanding of the likely consequences for human life, society and the biosphere. Such developments could also have a major impact on introductory design courses, as well as a capstone design course in the final year.

Three such bridge courses have been developed, based on extensive research into the way industrialization has established new methods of connecting people to one another, to society and to the biosphere. This research led to an intellectual "map" of the "ecology of technology" and how this map may be used to find our way to more preventively-oriented design and decision-making. The function of these bridge courses in the undergraduate curriculum is to establish a bridgehead from which economic, social and environmental considerations can be internalized into all engineering disciplines and specialties to create a preventive orientation. This is not a daunting or impossible task. We have successfully accomplished two such major internalizations. In the not too distant past, mathematics was taught as a separate subject by mathematics professors. During a transition phase, these professors worked with their engineering colleagues, who could contribute the applications for which this mathematics was required. Eventually, mathematics was internalized into the curriculum and into engineering practice, to the point that most of us would have no idea how to teach our courses and practice our specialties without it. Similarly, numerical methods and computers were first taught in separate courses, but gradually they permeated the entire curriculum. With the establishment of these bridge courses, social and environmental considerations could follow the same pathway. The development could be quite incremental. There is no need for every instructor to come on board from the beginning. Interested colleagues could be invited to teach these bridge courses as a first step to internalizing into their courses and specialties the important social and environmental implications on the road toward a more preventive orientation. Of course, this would require leadership from the top to ensure that those faculty members who move in this direction are not penalized by the current administrative regime, which thrives on depth and penalizes breadth. Understanding one's discipline or specialty in a broader context of how, through technology as a whole, it influences human life, society and the biosphere, must be recognized as an achievement on a higher professional level and must be awarded as such, in the consideration of tenure and promotion, as critically important contributions to the profession and to the public interest. Some measures have already been developed[11]. Finally, an effort has to be made to confront the hidden curriculum as well as the attitudes of potential employers. Many practicing engineers and their employers believe that operating to high social and environmental standards is expensive and therefore non-competitive. This is true if these higher standards are achieved by adding end-of-pipe compensatory technologies or services, but not if this is accomplished by preventive approaches. We all remember the spectacular gains some companies made when they began to practice pollution prevention. However, this was short-lived. Pollution prevention has to become an integral part of a new "intellectual culture" that displaces the old "end-of-pipe intellectual culture".

The First Bridge Course

The first bridge course has evolved over two decades, for much of which it was a compulsory course in first year engineering. It has two primary components. The first examines how through the process of industrialization, technology was woven into the fabric of relationships that constitutes human life, society and the biosphere. Two constraints on this process are considered. The first stems from the fact that no human activity can create or destroy the matter and energy on which it depends. This matter and energy must be exchanged either directly with the biosphere or via chains of human activities. Consequently, all activities of a contemporary society are connected by a network of flows of matter and a network of flows of energy, in turn suspended within corresponding networks that represent these flows within the biosphere. The introduction of a technical division of labour, followed by mechanization and industrialization, disturbs the dynamic equilibrium in each of these networks, with the result that the activities by which people change technology become increasingly interdependent as the process of industrialization advances. Today this interdependence can be captured in input-output models of the economy. Consequently, industrialization cannot be done in a piecemeal fashion. It requires a transformation of both technology and society. Obvious as this may seem when industrialization is examined from the perspective of thermodynamics, the consequences have been all but completely overlooked in the usual history of technology, economic history, sociology of technology, and sociology of industrial civilization.

The fact that human activities in general, and technological activities in particular, are integral to the biosphere in a metabolic aspect also reveals their being integral to human life and society. People engaged in industrialization do not think or act in terms of disturbing the local dynamic equilibrium of a network of flows of matter or energy, restoring this equilibrium, dealing with the next disturbances, and so on. They think of their involvement in terms of the meaning and value, of these activities for themselves and others. Satisfying the thermodynamic constraints must therefore take on a meaning and value, and this can only be done by substantial economic, social, political and legal adjustments to a way of life. Since few creative responses have succeeded in doing this, the thermodynamic constraints translate into economic, social, political and legal constraints on the ways of life of industrializing societies.

All this can readily be examined, beginning with the recognition that no mechanized activity mimics its craft-based precursor. The technical division of labour shatters these craft-based activities into rational sequences of production steps that can be assigned either to machines or human beings. As such it does far more than simply disturb the local equilibrium in the networks of flows of matter or energy associated with a way of life. Mechanization and industrialization transform the human activities connected by these networks, and this also must have some meaning and value. It must make sense to some people, who then have to compel others to follow suit.

The second constraint on the process of industrialization is related to the necessity of people to make sense of their lives and their world. This recognition requires a brief exploration of what we know about the way human beings make sense of their experiences and the way they organize their relationships with each other and the world into a coherent way of life[12].A culture accomplishes all this by symbolizing everything in human life and the world (I am using the word *culture* in the sense of cultural anthropology). In other words, unlike animals, human beings do not take reality at face value. A fallen branch on the forest floor must first be symbolized as some tool or weapon before it can become so. A tree trunk floating by in the river with some birds perching on it must first be symbolized as a potential canoe before work on it can begin. Death was never taken at face value, as ritual burial indicates. All relationships are symbolized by a culture to reveal their meaning and value in a unique culture-based connectedness that incorporates the technology-based connectedness resulting from thermodynamic constraints. The presence and importance of this culture-based connectedness becomes painfully obvious in people with short-term memory loss or during a certain stage in the development of Alzheimer's, where each experience is no longer symbolized and connected to all others, making it impossible to live one's life. Each moment of that life becomes a separate micro-world as it were, connected only by the life lived before the onset of the disease. On the level of a society, the loss of this culture-based connectedness can cause it to collapse because its culture can no longer give meaning, direction and purpose to the lives of its members, with the result that such a society cannot evolve and make history. The rise and fall of civilizations are inseparable from those of the cultural systems on which they are based.

The technical division of labour severed the close ties between the technology-based and the culture-based connectedness of a society. Mechanization and industrialization intensified this separation, leading to a strengthening of the former at the expense of the latter. It is in this way that students learn how the process of industrialization makes, breaks and transforms connections between technology and human life and society on the one hand and with the biosphere on the other. They learn to see industrialization as the constant adjustment of the web of connections of our world, and it is in this context that every technological activity must be understood if its full implications are to be taken into account. This "people changing technology" is indissociably linked to "technology changing people" because the experiences of the new emerging world affect the organization of the brain-mind through neural and synaptic changes. In the course of generations, this results in substantial cultural changes, which in turn affect how people make sense of their lives and their world and the way they are engaged in that world. In approximately two thirds of a semester, students learn to understand the process of industrialization with its two interacting components of "people changing technology" and "technology changing people".

The second part of this first bridge course introduces the concept of preventive engineering. It utilizes the intellectual map developed in the first part to identify the consequences of engineering design and decision-making in order to improve the ratio of desired to undesired effects. It contrasts preventive engineering with its conventional counterpart, explores the potential advantages, but also the barriers that block the path to realizing its potential. Several approaches for guiding contemporary technology are explored, including positive and negative feedback showing how presently we rely primarily on the former. The course then turns to the development of the intellectual tools for map-making and the kinds of values required for assessing the success, or lack thereof, of preventive approaches. It concludes with an overview of preventive approaches in four areas of application (materials and production, energy, work and cities) and formulates preventive design approaches in these areas. For engineering students this constitutes a one-semester course, but for social science students it constitutes the first half of a full-year sociology course, of which the second bridge course makes up the second half. Students in environmental studies can take these two bridge courses as one-semester courses. Further details, including texts and other resources are provided elsewhere[13].

The Second Bridge Course

The second bridge course continues where the first component of the above course left off. It begins by tracing the developments in technology and its uses as a result of the so-called computer and information revolution. Again, this sets off a chain-reaction-like process which transforms technology and its connections to everything else. It extensively builds on prior developments, including what is referred to as the separation of knowing and doing from experience and culture, as was examined by Max Weber as rationalization and by Jacques Ellul as technicization[14]. These transformations increasingly affect every sphere of human activities and lead to the displacement of the cultural approach by the technical approach. Both science and technology break their bonds with their host societies to become universal, which leads to the kinds of knowledge infrastructures described earlier. The consequences are examined in great detail. This development necessitated the creation of concepts such as appropriate technology and sustainable development because these characteristics of traditional technologies and ways of life, which were generally context compatible, could no longer be taken for granted. Consequently, the computer and information revolution is merely a symptom of a much deeper and larger transformation. It marks the transition from a primary reliance on experience and culture to a primary reliance on the technical approach found in contemporary societies. The course also discusses the implications of these transformations of technology and society for the development of preventive approaches. Full details are provided elsewhere[15].

The Third Bridge Course

The third bridge course picks up the development of preventive approaches in the four areas of application introduced in the second component of the first bridge course. Students gain a working knowledge as to what can be done in the areas of materials and production, energy, work and cities by means of further theoretical development backed by case studies. The course concludes with a discussion of the limitations of preventive approaches when the primary undesired consequences of technological and economic development flow from a great many undesired consequences produced by many decisions in various disciplines and specialties. The need for macro-level preventive approaches is explained, which gradually must transform the technological and economic "system" to be more compatible with human life, society and the biosphere.

Conclusion

Preventive approaches are a necessary but not sufficient development to begin to address the roots of our deep economic, social and environmental crises. The three bridge courses, developed at the Centre for Technology and Social Development at the University of Toronto, are a bridgehead from which engineering education can be reformed to get the profession back on the road toward strengthening its ability to protect the public interest in a more meaningful and comprehensive fashion. Without this kind of development, the status of a self-regulating profession will be increasingly weakened. If, on the contrary, our profession recognizes how we have become trapped in the labyrinth of technology, a process has been developed that points to an opportunity to provide our profession with a more decisive role in transforming our present situation and to help create ways of life that are more economic, socially viable and environmentally sustainable.

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