MATH, POLICY AND RESPONSIBLE ACTION

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THIS ARTICLE ATTEMPTS to reposition engineering mathematics, and engineering mathematical education, into a sphere of influence different from the one in which it is traditionally envisioned (or assumed) to occupy. More significantly, the modelling comments we make embed engineering mathematics firmly into a "responsible decision making" or "public policy" context, and thus move the study of engineering mathematics from a largely individualist pursuit to a more collective undertaking. As a secondary effect, this argument leads naturally into a brief consideration of some of the biggest challenges facing both humanity and engineering in the 21st century.

It is sensible to start by saying a few things that are likely obvious (though implicit) to almost all who work within applied sciences. We, the practitioners of science, almost universally believe a number of key things about reality. We believe (i) that a physical world exists (the world is not entirely imaginary), and (ii) that we willingly influence this world (sometimes significantly) by our actions and choices. We also believe (iii) that the physical world responds to these actions in ways that are real, but not always obvious. Yet we believe (iv) that the consequences of our actions usually include some combination of beneficial/desirable and detrimental/undesirable outcomes. With a bit more reflection, most of us also would believe (v) that even though the consequences of our choices and actions may have wide influence both on human and natural systems, the evaluation (or weighing) of the positive and negative outcomes takes place largely within a human system of values, beliefs and expectations.

Since a statement like this is a little abstract, it is helpful to provide a simple illustration. So imagine that we clear a piece of land beside a river, cultivate a field, plant seeds and eventually harvest a crop. Each action is taken in anticipation of how both people and nature respond to our unfolding actions, but each outcome is latent with possibilities of other outcomes, some of which we don't intend and might not anticipate. For instance, the river could flood and our crops drown or wash away before harvest. In anticipation of the flood, or in response to some observed historical one, we might seek to divert river water away from the field, an action that might have other consequences to other places and other people. The evaluation of the desirability of the outcome–a settled piece of cultivated land–will depend not only on who does the evaluation, but likely also on such issues as over what time, and from what perspective, such an evaluation is made. A politician, an historian, an ecologist, a hydrologist and an economist might all have quite a different verdict on the value, significance and success of the whole set of human interventions.

ANTICIPATING CONSEQUENCES

As long as the consequences of our action are predominately personal–that is, as long as they matter supremely to those who act and less to those who observe and experience–we might be prepared simply to take the actions that seem best to us. However, if there is at least a possibility of larger-scale or longer-term consequences, simply taking action might not be reasonable, responsible or even possible. Our neighbours might object to our planned actions and even be prepared to block them; or our plans might effectively require their co-operation, since without some collective action individual actions might be of much less value. Indeed, this is essentially the definition of public policy as the process for decision making involving collective actions and consequences. In a profound way, public policy analysis often explicitly or implicitly invokes mathematical reasoning and an anticipated chain of consequences with the expressed goal of making public decisions that have outcomes that the collective prefers. Put another way, we ask: What is the sequence of actions and incentives that delivers the most benefits to the most people? But this is not an easy task. If individual preferences vary along some kind of spectrum, we must assume there will be individuals whose preferences will run counter to those of others and hence to the "collective."

We see evidence of these tensions all the time. Almost any public policy along the lines of "the needs of the many outweigh the needs of the few" will almost inevitably come into conflict with the deeply felt but contradictory interests of the few. The current tension between provincial policy to promote wind power overall can create perceived risks and impose costs for those citizens in whose communities the pylons and turbines are to be installed. A related and long-standing tension lies between the need for urban societies to dispose of waste, and the reluctance of other communities to serve as the depository. The relevant question for policy is whether the collective good is the sum of individual goods, or its average.

But what precise role does mathematics play in such cases? It is at least this: when collective action is desired or likely to be rewarded or punished, there are huge potential benefits or incentives to formally and consciously anticipate both human and natural responses prior to our proposed actions. Such a "formal method of anticipation" has a more common name, and it is simply modelling. Our models act as stand-ins or substitutes for the reality of direct action and, in the 21st century, such models are almost invariably hybrid mathematical and conceptual constructs showing through symbols an association between actions (decision variables) and consequences (output or design variables). Voinov et al. (2010) make the strong point that even the construction of such models, in complex fields like the earth sciences, largely takes place in the context of community.

Although this description positions mathematical modelling as a practitioner of science would understand it, it is not necessarily the way mathematicians describe mathematics to themselves. But we will let the mathematicians worry about the thorny problem of the essence of mathematics. What is more relevant in the current context is this: as obvious as the statement "math as purposeful modelling" is for many, this approach is seldom the explicit motivation or preoccupation of engineering mathematics courses. The average engineering student–and the authors have polled many over the years–tends to view mathematics as an exercise or aptitude test, a necessary and rather unpleasant initiation into the world of engineering through a strange and alien wasteland. Mathematics (particularly as taught in explicitly mathematics classes) tends to be seen as an abstract system of symbol manipulation, not as a way of collective and responsible decision making. From the perspective argued here, engineering mathematics should instead be viewed as a direct extension of what it means to make (and document) better collective decisions. Thus, the need to couple the mathematic model to the decision should be the overwhelming priority.

A CHANGED PERCEPTION

It is perhaps dangerous to invoke a stereotype, but since in this case it makes our point efficiently, we cautiously run that risk. So, in this vein, we sketch the caricature of the mathematically gifted student–someone who is, in our popular imagination, socially inept, head in the clouds, cut off from the normal interplay of society, certainly at home with numbers but seldom with people. This is precisely the student who historically might be most likely to be encouraged to enter engineering. By contrast, the person who cares about collective actions, who is seen as socially oriented, is often imagined as (or self-consciously chooses to be) technologically inept, unskilled with gadgets and inept with numbers, but surrounded by a crowd of well-connected and influential people, would rarely be pushed into engineering.

However fitting or accurate such characterizations might once have been, such images do great harm to the kind of reconciliation that is urgently needed in engineering between having both a head and a heart. Or perhaps stated more concretely, there is a great need for engineers to understand better the relationship between the world of technology, in which engineering actions are generally taken, the complex "real world," where the consequences of actions take place, and the often mysterious world of public policy, in which the consequence and meaning of those actions are evaluated and sometimes either constrained or encouraged. We assert with many that the large collective problems we will progressively face in this century–whether of food or employment, energy for comfort and health, wealth and water for the largest human population in history, resources from progressively more diffuse sources but in progressively larger quantities–mean that we must learn to do better than we have in the past even as we learn to live more gently on the planet.

Within engineering degrees, mathematics is clearly a fundamental skill that must be developed. However, it is all too often taught with the above mathematically gifted student in mind. Although real-world examples and connections may be examined in passing, the subject is taught in very much the same way as it would be to a student pursuing pure mathematics, or perhaps to a scientist wishing to describe, but not necessarily change, the world. Emphasis is placed on formal manipulation; less emphasis is placed on achieving reasonable results within the decision-making context that motivated the need for the mathematical abstraction in the first place. What is needed–and increasingly so, given the global issues we are facing–is a distinct approach, an approach to mathematical education that is designed to give engineers the particular skills and perspectives they will need in their careers, to make, evaluate, troubleshoot, and document responsible decisions. And this will require great physical intuition, as well as the formal skills of abstraction and symbol manipulation. Mathematics, as used and applied by all engineers and by almost all practitioners of science, should primarily be an exercise in embedded and responsible decision making.

ALTERNATIVES

For a subject that is perceived as having straightforward, objective answers, math gives rise to much discussion and debate. When students ask from an early age why they need to study math, answers vary from simplistic ("So you can understand money") to practical ("So you can get a job") to philosophical ("So you can better understand the nature of the world"). There is not even agreement on the nature of math itself. On the one hand, some point to the inherent beauty in mathematics and its internal consistency. Math can be considered to pre-exist humanity and to have been only discovered by us; it is thus independent of us. On the other hand, some point to a more pragmatic character of math and focus on its utility in the real world. Math can be considered to be something that is not discovered by us, but invented or developed by the human mind. We employ mathematical methods to help us make sense of the world around us. Math is created by us and so dependent on us. Indeed, the ability of math to accurately describe or predict something about the world has often engendered a sense of wonder; Eugene Wigner's 1960 classic paper, "The Unreasonable Effectiveness of Mathematics in the Natural Sciences," is still very much worth reading.

It is an interesting question whether this debate is one that can, or even should, be settled. However, what is perhaps more interesting is the divisive effect of this debate on students of math. For some–perhaps the mathematically-gifted student described above–math keeps them apart from the real world, an escape from ever making a real decision with real consequences. The rules and patterns in math are so compelling because they are constant and unfailing, because of their internal consistency, in stark contrast to the variable and fickle nature of the world and humanity. It could even be argued that the real world itself does not exist, or exists only insofar as it is perceived by the human brain. Math, by contrast, is outside of us and is not encumbered by physicality or the semblance of it. For others, though, math drives them to the real world and vice versa. Math is compelling because it helps to explain and predict physical phenomena, from planetary orbits to resource availability to human behaviour. It provides a logical method by which to study our observations of the real world.

Engineers frequently fall into the second group. As asserted above, the real world is considered to exist, and our actions have consequences within it. Whatever the nature of math itself, its power lies in the fact that it allows us to make predictions about these consequences. Through mathematics, we can create models based on our observations and then use these models to predict at least some outcomes of multiple scenarios. One of the key developments in human history has been the realization that nature need not always be experimented on directly, but that models can be created to gather the possible consequences of proposed actions, in order that those actions can be modified to more preferentially select desired outcomes over unintended ones. The internal consistency of the models–while perhaps compelling and beautiful in and of itself–gives us the provisional confidence to foresee some of what could happen without necessarily having to observe consequences first-hand. Mathematics is at its most useful to engineers when it is employed to explore and predict–and then adjust and hopefully improve–potential future outcomes.

To the practitioner of science, what is perhaps most significant–the concept decisions, units and measurements that bind any symbol within the model to the world around it–is to the mathematician sometimes most insignificant or distracting. Thus, the approach to the practice of engineering, and indeed to teaching mathematics to engineering students, must reflect this distinction, and this might come about by a direct, conscious and creative framing of mathematics by both individual decisions and by collective, public, significant and complex ones. All engineering courses should prepare students to be informed, critical and responsible decision makers. Mathematics in particular can be taught in such a way that students understand the utility and the power, as well as the limitations, of the models they use. Standard optimization problems, for example, can address city planning issues and incorporate local data, such as material costs and wages; graphs can be used to examine both short- and much

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longer-term consequences (not just intercepts, asymptotes and end behaviour) and can be coupled with discussions on the value of the resulting predictions. Students should be exposed to questions in such a way that they are challenged to give not simply a "correct" answer but a thoughtful one.

The whole point is to appreciate that the sometimes dramatic consequences of our human behaviour can be formally anticipated and then adjusted in a mathematical model, and that this approach is not as an escape from reality, and is not taken with the presumption that our models are perfect, but rather embeds the conviction that responsible collective action is not only possible, but ethically expected and, potentially at least, both rewarding and rewarded.

Of course, how all this is fleshed out in university courses and in the minds and hearts of engineering interns is a huge and relevant problem. It will take careful thought and engagement to improve on what we have done. But what else is new? This challenge of continuous improvement is the essence of what it means not only to be an engineer, but also to be human. Σ

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