My brilliant career

Gordon Thompson

Where can a mathematics education lead you? In this series, mathematics and statistics graduates from Australian universities write about their careers, proving that the world is their oyster. Gordon Thompson, graduate of the University of New South Wales and Oxford University, currently is the executive director of the Institute for Resource and Security Studies in Cambridge, Massachussetts. Over the past three decades he has acquired wide experience with natural resource and international security issues. One of his major interests has been the environmental and security impacts of nuclear technologies.

Plasma, policy and progress

I was pleased to be invited to write for the Gazette, but then wondered what I could say that would interest students and practitioners of mathematics. More than three decades ago I was trained in mathematics, but have not practiced it as a profession. Instead, I have done technical and policy studies on issues of energy, environment, international security, and sustainable development. Some of this work has been controversial, and much of it has been done in association with citizen-based groups. I describe this experience here, to illustrate the diverse career paths that can be followed after a mathematical training. Also, from my experience I distil a few lessons about the roles of mathematical logic and scientific principles in policy debates.

On 24 October 1945, the Charter of the United Nations entered into force, symbolizing widely shared hopes for lasting peace after the tragedy of two World Wars in close succession. Far from the centers of world power, I was born in Sydney on that day, to loving parents. Memories of the World Wars permeated the culture I encountered during early childhood. Artillery pieces and other items of military equipment were placed in many public parks, providing play structures for children and a reminder of Australia's contribution to the titanic struggles between nations.

Becoming educated

At Sydney Technical High School our education was rigorous and traditional. We studied Latin, wore blazers embroidered with the school crest, and at assemblies sang the school song in Latin while the teachers entered in their academic robes. Physics, chemistry and mathematics were heavily emphasized. I was, like many, an ungrateful teenager but, in retrospect, see the teachers as a committed group who did their best for their unruly students. My fondest memories are of English and history teachers who tried to give us a sense of our place in the flow of civilization.

From an early age I aspired to be a designer of machines. This led me to study mechanical engineering at the University of New South Wales. While completing that degree, I also acquired a science degree involving study of physics and mathematics. During university vacations I worked for the New South Wales Electricity Commission as a trainee, learning about the design, construction and operation of electricity generating stations. After graduation I worked for the Commission as a design engineer. Then, as now, coal was the dominant source of Australia's electricity. In the 1960s the Commission was hard at work building electricity generating stations on the New South

Wales coalfields. Conveyor belts were constructed to carry continuous streams of coal out of the mines, across the landscape, and into the generating stations.

Environmental consciousness was less well developed in the 1960s than it is at present. Yet, a reader of the engineering literature at that time could find discussions of environmental and resource issues — such as human-induced climate change that have entered public discourse more recently. I wrote an undergraduate thesis in 1967, on magnetohydrodynamic (MHD) generation of electric power. In a MHD generator, a flow of electrically-conducting fluid — typically, an ionized gas — traverses a magnetic field, generating an electric potential. This device could, in principle, be used to generate electricity from the heat released by nuclear fission or the combustion of fossil fuel. In practice, MHD generators have not yet been used for commercial power generation.

The introduction to my thesis argued that nuclear fission or nuclear fusion would be preferred energy sources in the future, for two reasons. First, these sources would not emit carbon dioxide to the atmosphere. Second, their use would reduce the depletion of the Earth's limited reserves of fossil fuel, allowing this material to be used for purposes such as chemical feedstock. Recognition of the need to reduce emissions of carbon dioxide, thereby limiting human-induced climate change, did not indicate significant foresight on my part. Instead, it simply reflected then-current engineering literature on energy systems and strategies.

My interest in nuclear fusion power led me to graduate studies at Oxford University, and to a few years of modest competence in mathematics. At the Mathematics Institute at Oxford, I studied the theory of the behaviour of high-temperature plasma — fully ionized gas. This was a subject of interest to the Culham Laboratory of the UK Atomic Energy Authority, which gave me an associate appointment. The Culham site is a few miles from Oxford. It was, and remains, the primary site in the UK for investigating the potential of nuclear fusion as a commercial energy source. While at Oxford I was a member of Balliol College.

Harnessing nuclear fusion as an energy source requires the presence of a number of the appropriate light nuclei, and a collision velocity between the nuclei, that are sufficient to produce a useful amount of energy from fusion of nuclei. The energy input to achieve reaction conditions must be smaller than the energy output, so that the device is a net producer of energy. The most accessible fusion reaction is that between deuterium and tritium, the heavier isotopes of hydrogen, but even this reaction requires the attainment of temperatures of tens of millions of degrees Kelvin. Achieving such temperatures, and confining the resulting plasma, clearly poses a major technical challenge.

In a star such as our sun, gravity provides the necessary confinement mechanism. This mechanism is not available for human use, but two other confinement options are potentially within our grasp. One option is inertial confinement, in which the nuclei experience a brief period of compression and heating, followed by a rapid expansion driven by the release of fusion energy. The fusion burn occurs over a period of nanoseconds. This option is used in a thermonuclear (i.e., fission-ignited fusion) weapon, but in that case the energy release cannot be harnessed for a useful purpose. Efforts have been under way for several decades to employ inertial confinement at a small scale inside a closed chamber, so that the energy release can be harnessed. These efforts have not yet yielded a workable fusion reactor. Moreover, it is now understood that promotion of this line of research could facilitate the building of thermonuclear weapons by countries that would otherwise lack the necessary knowledge.

The second option for confining a superhot plasma is to construct a virtual bottle made of magnetic fields. At Culham and other sites around the world, theorists, experimentalists and engineers have struggled for decades to make magnetic confinement a useful option. Over time, they have increased the density, temperature and confinement time of the plasma, moving slowly toward a combination of these parameters that can yield a net output of energy. During the same period, they have sought to solve the practical problems of harnessing the energy release. For the most accessible fusion reaction — that between deuterium and tritium — a daunting technical problem is that 80 percent of the energy release is in fast neutrons.

A basic problem in improving the confinement parameters of a magnetically-confined plasma is to understand, and compensate for, the many instabilities that can occur. My graduate research made a minor contribution to theory in this area. I considered a model in which a homogeneous plasma in a uniform magnetic field has two components with sub-relativistic energy. One component is a thermalized plasma (i.e., with a Maxwellian velocity distribution) of fully separated ions (i.e., nuclei) and electrons. The second component is a comparatively small number of fast ions with a velocity distribution corresponding to either the charged product of a fusion reaction (e.g., the helium nucleus resulting from fusion of deuterium and tritium) or ions injected into the plasma to provide heating. My task was to determine the region of parameter space in which the fast ions initiated plasma instabilities (i.e., growing perturbations of the initial electric field, magnetic field, spatial distribution, or velocity distribution of the system).

Completing this task required the solution of the Vlasov equation, a well-known plasma physics equation developed by A.A. Vlasov in Moscow during World War II. The solution also had to satisfy Maxwell's electromagnetic equations. By linearizing these governing equations, which assumed an initially small perturbation of the system, and by employing a variety of analytic approximations, I identified the unstable regions of the applicable parameter space. This work, together with some analysis of other plasma phenomena, was sufficient for me to earn an Oxford D. Phil in 1973. I then turned to other interests.

Becoming an independent analyst

Oxford was for me a place that stimulated a variety of interests. I arrived with a rather naïve and parochial mentality, and an excessive interest in technology as a solution to the world's problems. Through the Oxford college system, especially through living in a graduate-student residence, I became exposed to people from all corners of the world, with a wide range of interests and perspectives. Accompanying this exposure was my burgeoning interest in the environment and its protection, an interest that I fed by climbing rock and ice faces in remote parts of the UK, and mountains in the Alps. These influences left me skeptical about the then-prevailing paradigm of science, technology and progress, but without a clear vision of a career path that challenged that paradigm.

The 1970s was a period of rapidly growing awareness of environmental issues, especially in the USA. New laws were passed, government departments for environmental protection were created, and citizen-based groups blossomed. Yet, the old paradigm of economic expansion and growth in material consumption remained dominant. In the UK, where I chose to stay after completing my graduate studies, the government conducted a major program of road building during the 1970s, overriding strong opposition by citizen-based groups. The rail network that was replaced by roads at that time would, if it had been preserved, be an asset to the present UK government as it seeks to reduce the nation's emissions of greenhouse gases.

Environmentalist thinkers of that period made some mistakes in predicting future trends, but the overall thrust of their predictions has been borne out by experience. For example, the Limits to Growth study, published in 1972, was not accurate in all of its projections. Yet, by applying a systems-dynamics approach to resource and environmental issues, the study broadened our understanding of the inter-connectedness of these issues, and made us face the challenge of meeting human needs and desires within the constraints of a finite biosphere. Those constraints are becoming ever more obvious, most notably through rising concentrations of greenhouse gases in the atmosphere. There are limits to reserves of readily-accessible resources, as illustrated by present concern that world oil production will reach a peak soon, perhaps within a decade.

My role in this evolution of our collective consciousness was to become an independent analyst on issues of energy, environment, international security, and sustainable development. The desire for independence arose from my sense of discomfort with established institutions. During the first few years of this career path I was heavily engaged in self-education, trying to develop something useful to say. Sustenance came from a variety of jobs including teaching and technical consulting. One consulting assignment was to help the government of Libya to establish a technical college.

In 1976 I was one of the founders of the Political Ecology Research Group, which operated for a decade from its base in Oxford. Since 1979 I have been based in the USA, working initially at Princeton University and then at an organization called the Union of Concerned Scientists. In 1984 I founded the Institute for Resource and Security Studies, located in Cambridge, Massachusetts, where I continue to work. I am also associated with Clark University through its George Perkins Marsh Institute, which was established to conduct interdisciplinary studies. In 1989 I was a visiting fellow at the Peace Research Centre, Australian National University. These various associations illustrate an important principle that I have learned. Independence has its satisfactions, but collaboration with colleagues is essential.

Over the three decades since becoming a lapsed mathematician, I have done a variety of technical and policy studies, organized conferences, presented testimony to official bodies, and been an expert witness in legal proceedings. This work has been sponsored by local, state and national governments, international agencies, citizen-based groups, and foundations. Subjects that I have addressed include arms control and disarmament, renewable energy supply, sustainability policy, energy economics, the safety and security of nuclear facilities, conflict management and postwar social reconstruction, and human security. There are common threads linking these diverse subjects, which I discuss below. As would be expected given the interdisciplinary nature of these subjects, much of my work has been done with partners. I first worked in an international team in the late 1970s, when the logistics of international collaboration were cumbersome. Now, information and communications technology has made such collaboration easy. In recent years I have worked with people whom I never met or talked with by telephone, which may take email collaboration further than it should go. Videoconferencing might correct this trend toward depersonified interactions.

Nuclear debates

Policy debates about nuclear power and nuclear weapons have been a prominent feature of society's struggle to develop a paradigm for a sustainable civilization. This is not surprising, because nuclear technology can provide, to the people who control it, immense power over nature and other people. Discussion about the application of nuclear technology is often framed in terms of technical issues — such as the safety of a particular nuclear reactor, or the strategic stability of a particular deployment of nuclear weapons — but there is always an underlying awareness of the physical and political power associated with nuclear fission and fusion. Some people believe that this power can be a force for good. Others look at human history and conclude that our species is not ready for nuclear technology.

My first role in an intense debate on nuclear policy was to be a participant in the Windscale Public Inquiry of 1977. The UK government held this inquiry to discuss its plan to build a nuclear fuel reprocessing plant — the THORP facility — at the Windscale site. That site was established to produce plutonium for UK nuclear weapons, but the focus of activity at the site gradually shifted toward nominally civilian applications of nuclear technology.

The THORP facility exemplified a technical vision that was formed early in the development of nuclear technology. Nuclear pioneers quickly recognized that only 0.7 percent of natural uranium — namely, the U-235 isotope — is fissile. Yet, in a fission reactor, some of the majority, non-fissile isotope — U-238 — is converted to plutonium, which is fissile. Thus, uranium fuel can be removed from a reactor after a period of use, and the plutonium can be separated from the fuel by chemical processes. This activity is called reprocessing. The separated plutonium can be used in nuclear weapons, or as reactor fuel. If used as reactor fuel, the plutonium could be used in a breeder reactor, a device that can produce more plutonium than it consumes, by converting U-238 that would otherwise have no application.

In the 1970s, many scientists, engineers and public officials were convinced that the world needed a large number of nuclear power plants. The underlying assumption was that electricity consumption would, and should, follow a trend of exponential growth. Given the known quantity of uranium reserves worldwide, it followed that reprocessing plants and breeder reactors would be needed, thereby allowing U-238 to be converted to plutonium that would be used as fuel. The THORP project emerged from this paradigm, as did the UK program to develop breeder reactors. Similar visions were pursued in the USA, USSR, West Germany, France, Japan and elsewhere. In each country, the vision of a plutonium-based electricity sector was backed by influential people, including prestigious scientists. Numerous technical and economic studies supported their arguments.

Independent analysts questioned this vision. Most fundamentally, they questioned the assumption that electricity consumption would continue to grow exponentially. Anyone familiar with biology or ecology knows that continued exponential growth is not consistent with the survival of living systems. Many other concerns about plutonium-based electricity were also raised. For example, it was pointed out that the promotion of plutonium as a fuel could facilitate the proliferation of nuclear weapons.

At the Windscale Public Inquiry, the pro-plutonium position was backed by the UK establishment, including senior scientists. The questioners and challengers were local governments or citizen-based groups. Their experts were academics or independent analysts, none of whom had substantial funding for their investigations. Unsurprisingly, the Inquiry found in favour of THORP, which was ultimately constructed. Today, THORP sits idle due to a serious design flaw, and the UK government is contemplating its closure. Breeder reactor programs have collapsed everywhere, and reprocessing is recognized as an uneconomic activity. In short, events have shown that the critics had a much better grasp of the situation than did the establishment.

Since 1977, I have been involved in a range of debates about the use of nuclear technology for civil and military purposes, and have observed other debates. The outcomes of these debates have varied, and have sometimes corresponded to a position that I argued. I draw a number of lessons from this experience. First, secrecy is fatal to good decisionmaking. Second, competent scientists can fall into the trap of using arguments that are superficially scientific but are actually based on ideological positions or questionable assumptions. Third, large, established institutions can be extremely reluctant to change their position, even when faced with compelling evidence that such a change is indicated. Fourth, it is difficult, but possible, to separate technical issues from the emotions and political factors that are associated with nuclear technology. Fifth, the most productive debates are those that employ long-established scientific principles — provide open access to information, respect evidence, provide a level playing field for experts with differing positions, refrain from rigging the debate by restricting its scope, and allow all interested parties to observe and comment.

Common threads

The world is a complex place, and determining the best position on a public-policy issue is rarely simple. Yet, from working in diverse subject areas, I have identified common threads that link many policy issues. Most importantly, we are stretching the limits of the biosphere. We must, as a species, adjust our behaviour to conform with those limits. If we fail in that task, our descendants will experience growing conflict, reduced opportunities and, eventually, the collapse of modern civilization. In facing up to the task, we will need to challenge some prevailing habits and arrangements. Three challenges stand out. First, technology should be our servant, not our master. We can already do more with technology than is wise, and we need to be more sophisticated in choosing what we do. Second, large disparities in living conditions and opportunities around the world should be eliminated. This is an ethical issue, because persistent poverty should not coexist with wealth. It is also a practical issue. The rich cannot expect the angry poor to cooperate with them in preserving the biosphere or controlling infectious disease. The rich cannot shield themselves if the poor become angry enough to wreak havoc with nuclear, chemical or biological weapons, or other destructive means. Third, an effort to maintain control of a turbulent world by seeking to dominate people and nature will work, if at all, only in the short term.

The value of mathematics

Science and mathematics can be misused. Too often, entrenched power or ideology is defended by a mathematical model whose function is to create a false impression of objectivity. I have encountered such models repeatedly. In many cases, the model's bias reflects the unquestioned assumptions of its creators, but deliberate bias is not unknown. Critics of mathematical economics have argued that this field is riddled with unconscious ideology.

An unfortunate result of the misuse of science and mathematics is that young people may turn away from these disciplines. Given the difficulty of mastering these disciplines, a young person may say, why bother if they offer a truth that is no better than politics or advertising? My response to such a question is that mathematical skill is an essential attribute of an educated person. Mathematics fosters clear thinking and mental discipline. From other areas of study and life experience, a person can learn critical thinking and healthy skepticism. With those skills, the person can judge when a mathematical model is an honest attempt to represent reality, and when it is a device to manipulate opinion. Similarly, the principles of science provide our most reliable foundation for understanding and improving the world. Part of becoming educated is to understand when those principles are being followed, and when they are being abused.

The policy issues that I have studied provide grounds for worry about our children's futures. Our species has a propensity for greed and aggression, and a great capacity to rationalize these behaviours. Yet, over the millennia we have developed moral principles and mental skills that are sufficient to address the problems of the modern world. I am optimistic that this inheritance will carry our civilization forward. Mathematics is one of our key mental skills.

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