Rails and Snails and the Debate over Goals for Science

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Summary: Should society run on rails like a train or pant over its spit like a snail, exploring the slopes? The successful evolution of both the biosphere and science suggests that the setting of goals, even if a posteriori correct, may forbid the system the exploration of potentially fruitful routes and thus constitutes an inferior form of strategy. Yet human society, its technology and science do move along discernible evolutionary tracks; these can be mapped, and goals set within the envelopes of possibility suggested by the trajectories. The current anxiety associated with the end of one historical era and the birth of a new one whose features we do not yet clearly perceive intensifies the debate over goal-oriented strategies. In this time of conjunctural change, participants in the scientific enterprise should reaffirm the need to balance action and permission, rail journeys and random walks.

Introduction

MY SUBJECT is the debate over long-term goals for society and for science. Long-term means decades and generations. In the United States, a chorus has called for closer links between science and societal goals and for institutional and procedural changes to fasten them.[1] In this paper I seek to clarify the positions in the debate, explain its present urgency, and achieve a reconciliation.

The plan of the paper is as follows. First, I approach the question of goals at an abstract level in terms of evolutionary strategy. Then, I turn to the question of whether science has failed to deliver for society by examining changes in technical performance in several sectors of the economy. Next, I discuss the implications of the existence of stable, discernible technological trajectories. Then, I evaluate what is peculiar to the present historical moment, when many developments culminate simultaneously, and the risks in such times of conjunctural change. Finally, I return to the question of goal-oriented strategies and institutions for the scientific and technical enterprise.

Goals for society and science

Does society in fact have general goals? In the Middle Ages in Europe, the response was neat. Christians believed that society evolved toward a grand design, the Kingdom of Heaven, the final cause of evolution itself. Within Judaism, a comparable concept prevailed.

Is the concept of a grand design still valid? If so, should the scientific community help strive to unveil the design of Providence and indeed establish it? In the Middle Ages the answer to this question would have been fully affirmative. Today, the answer is not clearcut.

Ironically for the current debate about long-term goals, the doubts originate in what science has learned about life and in the method and success of science itself.

Consider first our current understanding of the evolution of the biosphere. Darwin provides the basic theory of biological evolution. Perhaps the most important, and controversial, point in the Darwinian theory is that it deprives the system of a grand design into or toward which the system evolves, as was quite firmly thought before Darwin. Instead, mutation and selection make evolution. According to the Darwinian paradigm, the system has no goals at all. Rather, it explores stochastically (that is, by mutation) the realm of contiguous possibilities, moving in the direction of certain gradients in an optimization space (that is, selection). Humanity is a naturally evolving branch of the biosphere. We may extrapolate to our own species the trends detected in the three billion years of history of the full biological system.

Consider now science. Recall the origins of modern science in the observations of Galileo. The great discovery of the Italian astronomer was not factual but methodological. Galileo, like Darwin, took the final cause out of the system. Instead, he imposed the very strict rule that the invention (that is, the mutation) must survive the trial of confrontation with the external world through experiment (selection).

This strengthening of the rules, and elimination of objectives, gave an immense impulse to the scientific enterprise.

What do we make of the great success and sophistication of these two systems, the biosphere and science, developed on the basis of very strong rules but no objectives? It appears that the setting of goals, even if *a posteriori* correct, may forbid the system the exploration of potentially fruitful routes and thus constitutes an inferior form of strategy.

Physicist Cesare Marchetti offers the metaphors of rails and snails to describe the puzzle over evolutionary strategies.[2] Should society run on rails like a train, or should it pant over its spit like a snail, exploring the slopes?

Rails are the present political fashion, more specifically super-efficient cars and *trains à grand vitesse.* In defense of those who want to set the schedule for specific mileposts and terminals, it may be said that their design is not as grand as those of Medieval Catholicism or Judaism. In fact, the long-term societal goals mentioned by political and scientific leaders – cleaner environment, better health, more efficient energy – appear bland and imprecise compared to the visions offered in a fourteenth-century Italian altarpiece, or in the books of Maimonides.

Vague goals provide freedom for enterprising individuals, but they are problematic for the large governmental and industrial organizations that fund most of science. The price of their endeavors in a world of scarce resources presses for complete and organized plans, close match between what is anticipated and performed, and detailed and documented procedures.

Yet most researchers, I among them, lack confidence in the ability, especially the collective ability, of the leaders of America or the European Union, the main supporters of science, to specify goals conducive to the laying of rails. As emphasized by the Carnegie Commission on Science, Technology, and Government, the United States has no regular and influential forum on scientific research where discussions begin and end with long-term goals. The Commission accordingly proposed the formation of a National Forum on Science and Technology Goals, to be hosted by the U.S. National Academies of Sciences and Engineering.

Notwithstanding the paucity of reference points, the proposed formula for a successful research enterprise, increasingly, is: move directly along a linear path, allowing for some fluctuations. Otherwise, the argument runs, it is doubtful science will ever get where society wants to go.

The guidance is difficult to follow, for reasons suggested by the cases above. First, the target location is frequently unknown. Second, research is an activity endowed with a random component.[3] As Elliott Montroll and Kurt Shuler pointed out, the proper description of research must characterize the stochastic process that generates the random component.[4] Montroll and Shuler observed that exploration of a region occasionally exposes a bright spot of special significance. Then, many researchers concentrate in the neighborhood of that spot. The sphere of understanding around it expands until some natural boundary impedes progress in the conceptual space. Or, perhaps someone discovers a new bright spot that distracts attention.

Management that insists upon the direct achievement of a preconceived complex goal may suffer from underestimating the number of ways progress can be arrested ("the tyranny of many dimensionless constants," in the technical terms of Montroll and Shuler), and it may also miss opportunities embedded in regions near bright spots. Of course, a management that allows researchers to admire the bright spots indefinitely may never develop products. As Montroll and Shuler noted, subtle interplay between action and permissiveness characterizes progressive management.

The scientific community seems to be losing its permission and permissiveness.[4] Why?

Have science and technology failed?

I do not think the principal reason for the apparent shortening of the leash on science in the United States is that science, or technology, has performed badly. In fact, they have not. Examples from computing, communications, transport, agriculture, and energy demonstrate astonishing success.

Modern computing began in the late 1940s with the ENIAC machine, operating on vacuum tubes. One of the first customers for the most advanced machines has always been the U.S. military, in particular the national laboratories such as Los Alamos, which designs nuclear weapons. The top computer speed at Los Alamos, shown in Figure 1, increased one billion times in 43 years.

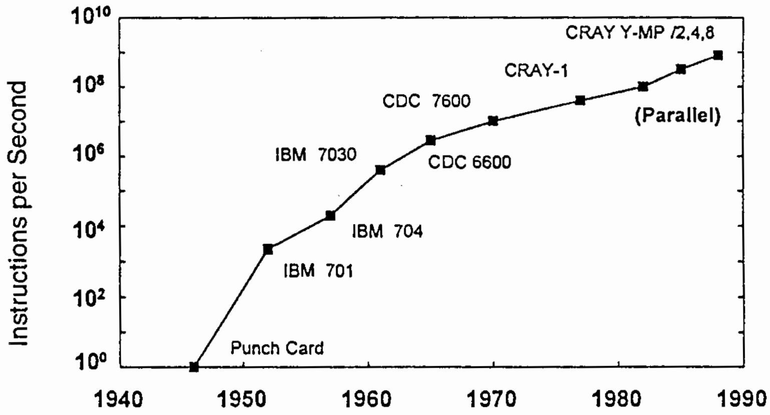

Figure 1: Computer speed, Los Alamos National Laboratory
Source of data: Worlton (1988), see Additional Sources of Data

Telephones excited talkers a century ago by the speed and distance a message could travel, but they were frustrated by the capacity of the available lines. Long-distance calls had to be booked in advance until quite recently. In the days of the telegraph it was one line, one message. In one hundred years, as Figure 2 shows, engineers have upped relative channel capacity by one hundred million times. In fact, fiber optics appear to initiate a new trajectory, above the line that described best performance from 1890 to 1980.

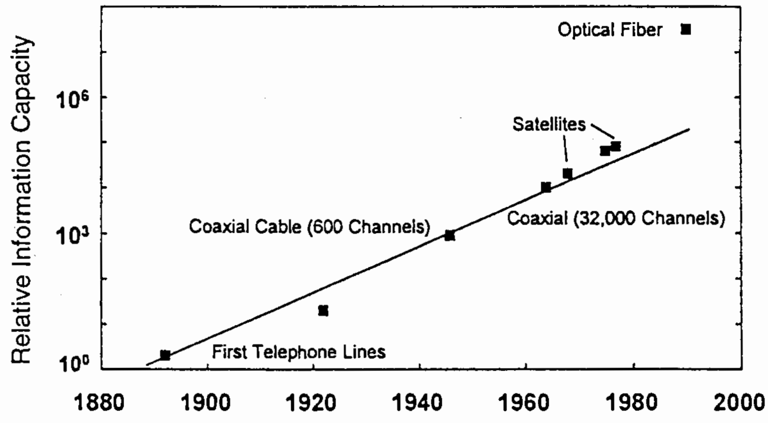

Figure 2: Communication channel capacity
Source: Patel (1987), see Additional Sources of Data

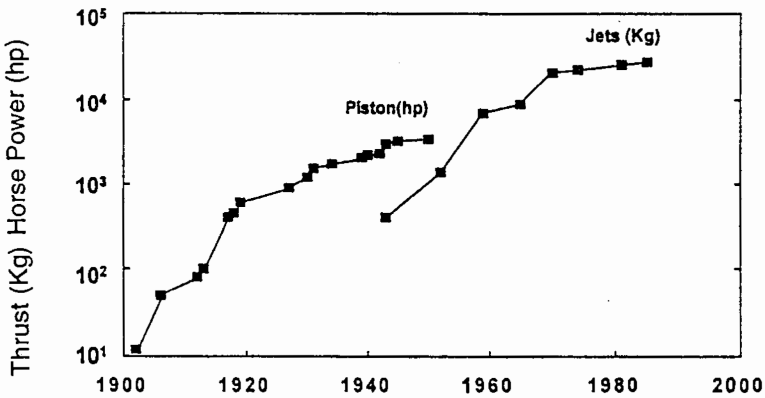

Figure 3: Performance of aircraft engines. After Grübler (1990), see note 8
Sources of data: Angelucci and Matricardi (1977), Grey (1969), Taylor (1984), see Additional Sources of Data

Propulsion for aircraft, shown in Figure 3, has improved by one hundred thousand in 90 years. We can see clearly that the aeronauts have exploited two trajectories, one for pistons, ending about 1940, and one for jets, culminating in the present.

It is commonly believed that the revolution in agricultural productivity preceded the revolution in industrial productivity. In the United States, this was not the case. Thomas Jefferson's Virginia fields yielded roughly the same number of bushels of wheat in 1800 as the average American field yielded until about 1940. Americans harvested more by bringing in more land. Productivity per hectare

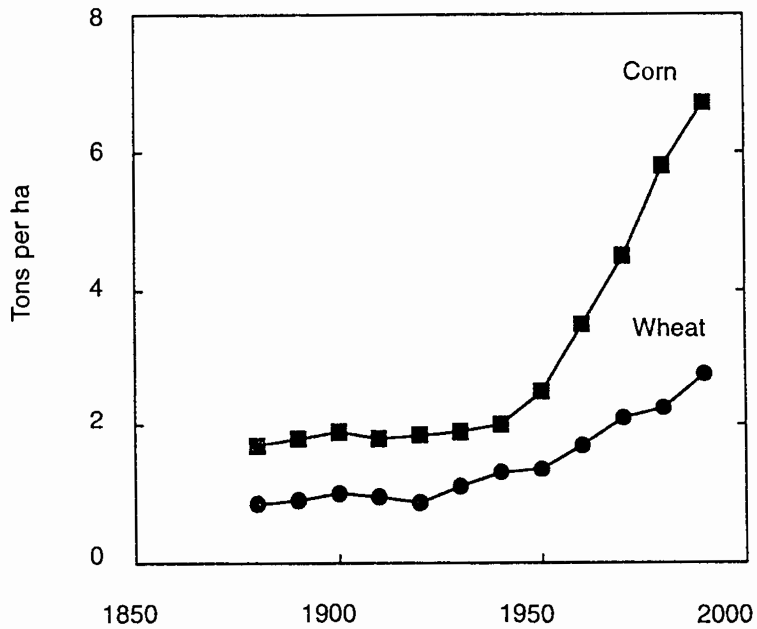

Figure 4: Yields of wheat and corn per hectare in the United States, 1880–1990
After Waggoner (1994), see Additional Sources of Data

took off in the United States in the 1940s, just like jet engines and computers, as is evident from Figure 4. U.S. wheat yields have tripled since 1940, and corn yields have quintupled. Other crops show similar trajectories. Yields in agriculture synthesize a cluster of innovations, including tractors, seeds, chemicals, and irrigation, joined through timely information flows and better organized markets.

One of the technical quests that began about 1700 was to build efficient steam engines. As shown in Figure 5, engineers have taken about 300 years to increase the efficiency of the generators to about 50 percent. Alternately, we are midway in a 600-year quest for perfectly efficient generating machines. The struggle for energy efficiency is not something new to the 1980s, just the widespread recognition of it. Figure 5 also explains why we have been changing many light bulbs recently. We have been zooming up a one-hundred year trajectory of increase in the efficiency of lamps.

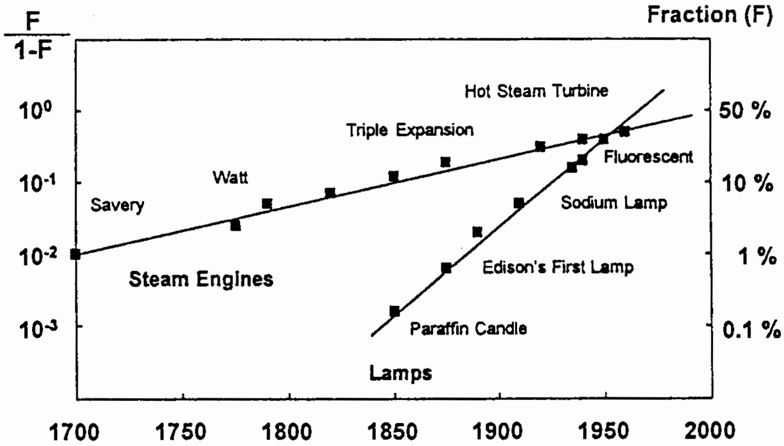

Figure 5: Efficiency of energy technologies
Sources: Starr and Rudman (1973), see note 5; Marchetti (1979), see Additional Sources of Data

Snails on rails

Now you will feel that I have confused matters. I have suggested that we should not ride on rails, and then I have shown you a series of elegant trajectories, the dream of every government or business strategist. Let me try to reconcile the apparent contradiction by disclosing myself as a neo-fatalist.

In fact, human society, its technology, and, more subtly, science itself move along evolutionary tracks. These can be mapped,[5] and goals can be set within the envelopes of possibility suggested by the trajectories, which simply represent the progressive realization of innovative opportunities. Foresight, to use the term increasingly popular in the United Kingdom and the Netherlands, is possible in both science and, especially, technology. In technology the performance axis – horsepower, bandwidth – is readily identified. Science is often more abstract, but it follows the same rules. Figure 6 shows the entirely regular behavior exhibited by chemists in discovering the first 50 or so stable elements of the periodic table.

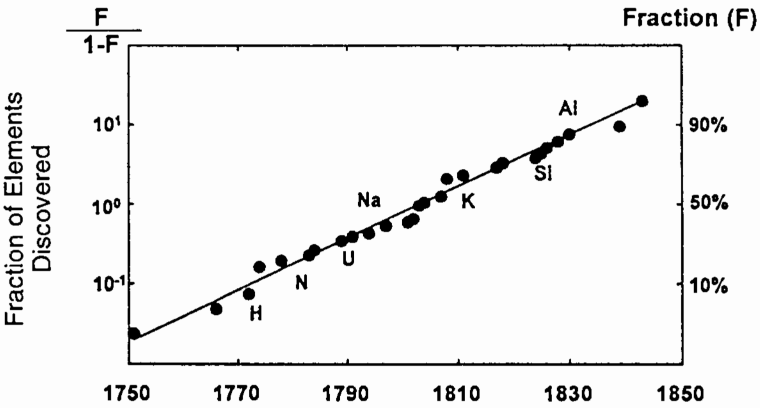

Figure 6: The fraction of the set of about 50 stable elements discovered 1750–1850

Source: Wetterau (1990), see Additional Sources of Data

The system itself may know where it is going and systems analysts can occasionally make a trajectory explicit; nevertheless, the efficient strategy for progress remains the apparently sloppy and inefficient evolutionary exploration of the snail. The technical community can, for example, set 70 percent efficiency for power-generating machinery as a goal realistically to be achieved over the next 50 years, but we cannot write a plan that will achieve it.

We can, however, check ideas and proposals for their consistency against the trajectories. Those far away are unlikely to succeed. Let me give one scientific example. In 1988, Wolfgang Panofsky updated a chart showing energy attainable by high energy colliders (Figure 7).[6] Clearly, the designers of the Superconducting Super Collider (SSC) were off the rails when they proposed to operate in 1995. In practice, all the SSC delays and redesigns might have led to operation closer to 2005, and by then the system, so it seems, would have been ready for it. In any case, the attempt to forcefeed the machine to the society brought a predictable revulsion. The message is: remember the system, it will remember you.

The season of saturation

Deviation from the trajectory was not the only reason the SSC died. The project sought to grow at the wrong time. In examining many hundreds of technological trajectories, and quantified social processes generally, the striking fact is that every 50 years or so, a whole bunch of them culminate together.[7] Historical eras end in seasons of saturation, so to speak.[8] The Austrian economist Joseph Schumpeter called these seasons conjunctures, when economics and politics as well as technology all change significantly.[9] Many technologies, such as pistons and jet engines, strengthen and spread rather continuously within the Schumpeterian time boxes. Upon reaching the wintry discontinuity, they reorganize to begin a new branch of development, or wither.

I believe that the current crisis about goals and objectives for science is largely an artifact of conjuncture, part of the generalized crisis of confidence associated with the end of one era and the onset of a new

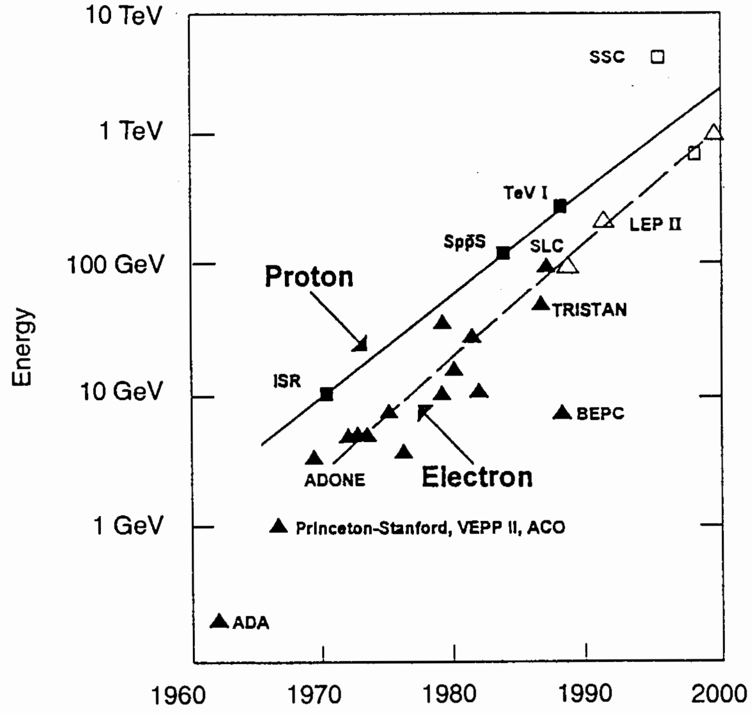

Figure 7: Energy attainable by high energy colliders. The squares are proton–proton (or proton–antiproton) devices, the triangles electron–electron (or electron–positron) devices. Those not filled in were not yet in operation at the time the figure was prepared.
After Panofsky (1989), see note 6

one whose features we do not yet perceive clearly. When times are tight, the tendency is to talk of goals, even if we do not know what they are. Spenders, especially of large amounts of funds, are forced to detail their rationales. When the niches are full, the competition for resources is stiff and bloody.

And the niches, at least in American academia, are full. Figure 8 shows the growth of the population of universities in the United States, the leading performers of basic scientific research in the world. America created universities in two pulses, a long, large one culminating about 1940, and a short, smaller one ending recently. The supplemental pulse involved the creation of about 75 universities, mostly daughter campuses of the state universities. The actual data conform perfectly to logistic curves, the function normally used to describe the growth of organisms and populations in constrained environments. The inset in Figure 8 presents the data in a linear transform convenient for showing the secular trend and – that the growth process has reached its limit.

The message is that the species "U.S. university" has exhausted its environment for growth, at least temporarily. In fact, it did so a

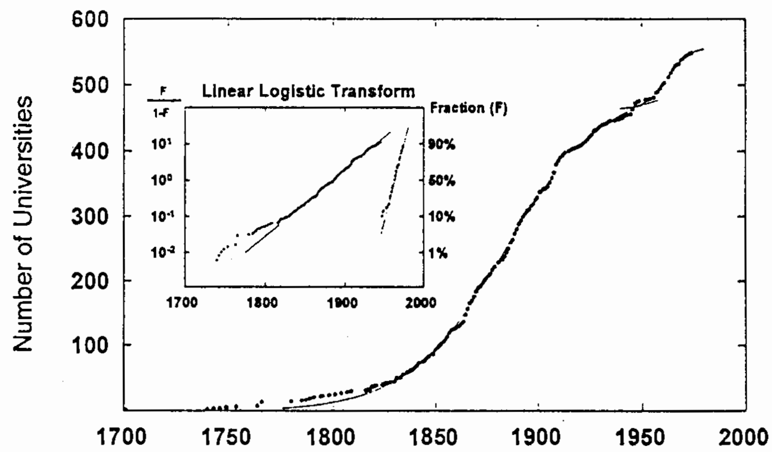

Figure 8: The population of U.S. universities plotted as a logistic growth function. In the inset panel, the linear transform of the identical data are presented as two pulses.
Source of data: *Webster's Collegiate Dictionary* (1985), Springfield, MA: Merriam-Webster

decade ago. It is not surprising that the United States has been sucking up students and faculty from around the world. The exploitation of larger markets by the export of education and research may be the only strategy for survival for a system with so much capacity. The United States system of higher education and research can be compared to the Japanese auto industry.

Regeneration without war

The problem for the scientific enterprise is not only that it is at peak size while the world economy is in a trough. Some traditional niches for research threaten to shrink drastically. I will play a somber, penultimate note in this regard. At present much attention in the United States, Russia, and other countries focuses on conversion of the defense technology base for civilian purposes. The Carnegie Commission aggressively recommended means for such conversion.[10]

The world was in a conjunctural crisis 55 years ago, too. The ripening of a new cluster of technologies helped thrust us out of it. Industries surged around antibiotics, aircraft, synthetic chemicals, electronics, nuclear energy, telecommunications, and new materials such as aluminum and plastics. The U.S. and world economies restarted in 1940, not 1946 or 1950, as many would prefer to believe. The data are unequivocal. Unfortunately, it took a World War to achieve an industrial restructuring and to fully invigorate science and technology for the new pulse of long-term growth.

The usual economic view of war emphasizes that it increases public debt. But in the trough of economic cycles, the availability of loose money stimulates the growth of state debt even without a war, as is happening now. The State absorbs cheap funds and looks for ways to spend the money, to occupy the unemployed and to regenerate the economic cycle that feeds the state over the long run. Are the availability of money and spare productive capacity in fact a stimulant for war? If so, the preferred interpretation of cause-and-effect capsizes.

And the selection of goals for science and for society, peaceful goals, becomes truly urgent.

Kicking goals

I will close on the question of goal-oriented strategies and institutions for the scientific and technical enterprise. I have argued that societal development is fundamentally evolutionary and thus to a high degree without purpose though with strict rules of choice at every stage. However, society does have directions in which it is driven. It moves in these directions largely without intent, particularly of the kind that characterizes political discourse.

Now, America and other societies sense that they have come to the end of one set of rails, as is true in a time of conjuncture, and large organizations, in particular, seek the security of new ones, with expressed goals. And surely it helps to affirm such broad goals as low-cost speed in travel, agriculture that both feeds and spares land for nature, a zero-emission system of industrial production, and global economic development and security. The balancing of such goals, at least, has implications for the number of workers in the various fields of science and technology.

Yet we should not overestimate our capacity for coordinated, creative design in the economy. The King of England did not declare a 300-year project to improve energy efficiency when Thomas Savery developed the first practical machine powered by steam in 1698. Neither is it clear that anything would have changed had he done so.

At the same time, as scientists and engineers, we can foresee that certain technical developments are logical, perhaps inevitable. For example, fuel cells would neatly continue society on the upward trajectory of efficient energy generators that Savery began. But the scientific progress that may enable the development of fuel cells – for example, advances in electrochemistry – is best assured by a process that is more like a random walk than a rail journey. Heterogeneity of preferences and expectations are required for evolution. Few types of institutions, few nations, have been comfortable with such heterogeneity. It takes a more mature individual to live with ambiguity.

Here academies of sciences and engineering may have a special role to play, as suggested by the Carnegie Commission. Academies concentrate society's best judges about the evolutionary tracks of the system and yet embody the questioning, entrepreneurial spirits needed for evolutionary success. Functioning at their best, these institutions may be the ones most likely to influence public discourse to balance action and permission, the rail and the snail.

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