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A few beeps reshape engineering

In which the memory of a few beeps gets me thinking more about the cadence of engineering's relationship with its foundation

Friday evening, 4 October 1957. I'm in my mother's '51 maroon Plymouth, listening to the radio, looking out over Lake Ontario, trying to keep my girlfriend warm, hoping for the best. I no longer remember my girlfriend's name. Wish I did. But I surely remember the beep ... beep ... beep ... from the car radio. It was Sputnik. Sputnik telling the world: I'm up here. I'm up here, first!

From childhood I had often daydreamed of space travel.[1] Later, as a teenager reading Arthur C. Clark's *The Exploration of Space*, I realized there were straightforward possibilities for escaping Earth's gravitational field to glide towards the stars. That evening the Plymouth's radio told me it had started. Although childhood daydreaming meant I wasn't immune to the significance of those beeps for civilization, I certainly didn't realize how much they would shape engineering. And therefore, in turn, shape me.

Memories of that long ago evening in the Plymouth flooded back while writing about the relationship between classical physics and engineering — because Sputnik's beeps signaled a sudden change in that relationship. The links between physics and engineering are sometimes clearly visible, right at the surface of engineering advances. But sometimes these connections recede. They are always the bedrock that underpins everything engineers do, yet are sometimes remote, forgotten, and far beneath the surface. So I decided we should pause before continuing our odyssey — leave the anchor down for a while — pause to reflect on the cadence of these physics–engineering linkages.

Perceptions are shaped by the experiences of the perceiver. So it seems appropriate that I first touch on the path that brought me to my view of engineering. The path probably starts when, at age five, my dad first took me through the paper mills in northern Quebec where he was responsible for maintenance. I have vivid images of walking up ladders and along catwalks watching huge slapping belts driving enormous wheels. Later, like many teenagers of the era, I lay on the garage floor under my Model A Ford tightening the rod brake linkages, replacing crankcase bearings (with my dad's help), and often just lying there, gazing up at the under-car workings. Soon after I went to Queen's University in Canada for a degree in mechanical engineering. After graduation and about three years working in the steel and fiberglass industries, I entered Northwestern University in the United States to study for a doctorate in mechanical engineering and astronautical sciences. At Northwestern our research group was caught up in the study of plasma flows — flows of ionized (electrically conducting) gases. We thought the research had applications to magnetohydrodynamic (MHD) power generation (which came to naught), MHD drag for decelerating space vehicles during re-entry (which came to naught), controlled fusion (which so far has come to naught) and understanding what makes the aurora so beautiful (which can never come to naught).

Leaving Northwestern I followed a conventional academic path, from assistant professor to chair of mechanical engineering at the University of Toronto, with some time out to start a research institute. It was a wonderful opportunity to think about our discipline, where it came from and where it was leading. No doubt all this has influenced the way I see the relationships between physics and various disciplines of engineering — such as, electrical, civil, chemical, industrial, materials, aerospace and, of course, mechanical.

[1] My memories of childhood, especially during summers spent in the beautiful village of Kamouraska on the south shore of the St. Lawrence river in Quebec, were filled with aunts, uncles and sometimes parents who, it seemed to me, felt a need to continually bring me back from one daydream or another.

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Starting from antiquity, it seems to me that the relationship has had four phases — so far. Beeps triggered the transition between the second and third. The remarkable thing about the 'beep' transition is that it happened so quickly and is now so conspicuous.

Today we are in a transition between the third to fourth phases. It seems a gradual transition. But perhaps that's because we're living it today. It is often difficult to see today's significance, today. Still I doubt any transition will be as fast as the 'beep' transition.

The first phase of engineering took place over those centuries when engineers built pyramids, Chinese walls, castles, castle moats and lift bridges to cross the moats — and windmills, sailing ships, roads, viaducts, plows and cathedrals, printing presses and cannons, indeed, the totality of civilization's infrastructures from pre-history through medieval times and up to the mid-18th century. While building and manufacturing, engineers were also learning how the physical world worked — although none of the crisp insights we now call classical physics were uncovered during those centuries. Still, these early engineering endeavors showed the *practical* value of learning more about how nature ticked. For example, the simple relationship that governs how levers work helped people know how levers could be used to lift monstrous stones to build fortress walls (if you pushed on the lever's long arm), or could be used to catapult a victim's head over those walls (if you pushed quickly on the short arm).

Then, in 1687, approaching the end of this first phase of engineering history, Newton published his *Mathematical Principles of Natural Philosophy*. Newton was a scientist, not an engineer. Yet by writing down the laws of motion, his insights about light and his advances in mathematics (the language of both science and engineering), he provided tools essential to the second phase of engineering that would begin a century later.

The second phase of engineering began with a stroll. "It was on the Green of Glasgow. I had gone for a walk upon a Sabbath afternoon. I was thinking upon the engine..." Thus James Watt spoke of how he came to his concept of external condensation for steam engines in 1765. Steam engines had lived before. But they had been bulky, slow and inefficient. Watt's concept for external condensation — previously steam engines had used internal condensation — allowed steam engines to colonize application after application. Watt's walk upon the Green marks the beginning of the second phase of engineering history. So I must explain why that Sabbath afternoon in 1765 was so significant.

To do that we must briefly return to the ideas of energy conservation. We talked about the many ways that energy can be stored. And even more important, we've talked about the three ways that it can be moved from one place to another: it can be carried within material that is moving, it can be transported as *heat* and it can be moved by *work*.

Work transactions are what today's energy system *really* provides. The work of mining, of flying airplanes, of pulling trains or pushing ships... and (with electricity) of running computers, TV sets and CAT-scan machines.

Before the invention of the steam engine *every drop* of civilization's work was done by wind, falling water or muscle. But after the steam engine, civilization could change heat into work. This meant the energy in *any* fuel — wood, or coal and so on — could first be converted to heat (usually by burning) and then converted to work by steam engines. Steam engines were the first technology that could achieve heat-to-work conversion. They were then followed by better steam engines, and then by internal combustion engines, jet engines, and later nuclear power plants. All these are 'heat engines'. All have genealogies going back to Watt's walk upon the Green. Watt's steam engine is the 'Lucy' of today's energy system.

Heat-to-work conversion pushed aside more and more drudgery from human lives — and begot evermore occupations that created wealth and enriched life. More people could become poets and artists, scientists, composers, writers and musicians, traders, merchants and investors, aircraft pilots rather than oxen drovers, backhoe operators rather than pick-and-shovel laborers. Among the plethora of lifestyle riches, average human life spans doubled — from about 40 years to now about 80 years. Fools who lecture about how technology has brought only misery have little idea what it was like to live in earlier centuries.

Culture selects from what technology allows.

For example, it is fashionable to attribute the decline and ultimate outlawing of slavery to evolving mores — mores that grew out from being more 'civilized', more sensitive to the suffering of fellow humans, nothing to with technology. And of course the 'evolving mores' part is true. But what eased the path to changing mores? Let's smell some land. Let's ask: with the arrival of heat engines, what tasks[2] were left for slaves to do? From antiquity, the Egyptians, Etruscans, Greeks, Romans ... had built their empires on the sweat and misery of slaves. America

[2] Particularly back straining tasks, like hoeing fields, lifting stones for castle walls and pyramids, and rowing ships.

started that way too. But then Watt walked upon the Green in 1765 and Emancipation came in 1863. Methinks there could be a connection.

Trying to imagine a world where work can only be delivered by wind, water or muscle, the Green of Glasgow becomes a holy place.

During the 18th and 19th centuries heat engines powered the economic and cultural maturing of civilization. And while working to improve heat engine performance engineers uncovered several more rules about how nature ticks. Watt made steam engines work. But they still didn't work very well. That's because people didn't yet understand those few of nature's fundamental laws that could be used as principles to guide better design. To acquire these principles, they needed to uncover the first and second laws of thermodynamics — or, what is the same thing, the third and fourth laws of mechanics.

In 1753 Benjamin Thompson was born in New Hampshire. He soon moved to Europe to escape the American Revolution — a revolution of which he did not approve. He became a military engineer and was responsible for drilling out the bore of cannons for the Bavarian army. While boring cannons he noticed that the amount of heat generated during drilling was proportional to the work put into the drilling machinery. He realized that there must be some kind of equivalence between heat and work. He also realized that heat was related to (molecular) motion within the material rather than (as had been previously thought) a separate material itself. He presented his ideas to a skeptical Royal Society of London in 1798.[3] They were a first step in uncovering nature's law of energy conservation. Later, between 1885 and 1887, an Englishman, James Joule, tightened up these concepts. So civilization had learned that energy was conserved, and 'named' this knowledge the first law of thermodynamics.[4]

Destined to find the second law, Sadie Carnot was born in Limoges in 1796.[5] He studied engineering at École Polytechnique in Paris and then, encouraged by his father, became interested in heat engines. Sadie wanted to understand how an *ideal* heat engine would operate. This led to his concept for a perfect heat engine cycle: four processes sequenced in a cycle that would convert the maximum fraction (allowed by nature) of input heat into output work. Sadie wasn't thinking about how to assemble bits of sheet metal, connecting rods and wheels. He was thinking about fundamental thermodynamics — asking what an ideal heat engine cycle would be like, not whether people could practically build such an engine. It was a milestone because, although no one has ever been able to build (what came to be called) a 'Carnot' engine, having such an *idealized* engine exposed the key principles for improving *real* engines — principles that were used to improve efficiencies more than 10-fold. Proving, once again, that nothing is more practical than a good theory.

A characteristic of good theories is that they are usually destined to have much wider relevance than originally expected. So it was with Carnot's principles for heat engines. They led to nature's law of entropy, the second law of thermodynamics — the law some consider the most profound of nature's laws. Sadie Carnot wrote down his ideas in 1824, 44 years after Ben Thompson began to realize energy was conserved and 59 years after James Watt walked upon the Green.

By the mid-19th century, engineers boring canons and setting out the principles for ideal engines had uncovered the energy and entropy laws of classical physics. Many other people would subsequently refine our understanding of these laws, enabling them to be applied to the design of new technologies *and* to further illuminate the truths of modern physics that would come in the 20th century. With the energy and entropy laws to supplement the mass and momentum laws discovered during Newton's time, civilization now had the complete set if four laws that define classical mechanics.

[3] The Elector of Bavaria made Thompson his Minister of War. Then, just plain Ben was elevated to become a Count of the Holy Roman Empire when he chose, for his name, 'Count Rumford' — after the New England village in which he had been married. Like so many achievers of that era, he was much more than an engineer and Minister of War. His canon boring adventures led him into more scientific adventures, he studied domestic economy and cooking and, it is said, was a friend of the 'lower ranks' (perhaps a legacy of his youth spent within the intellectual ferment then stirring in the North American colonies.)

[4] It is preposterous, using a single paragraph, to attempt a history of how the first law of thermodynamics was revealed. For those wanting a better review, I can't do better than recommend the excellent book, *Advanced Engineering Thermodynamics* (2nd Edition), by Adrian Bejan. This may be the best book on the advanced concepts of engineering thermodynamics available today. Remarkably, Bejan also takes 'time out' to describe the people, and the cultural setting in which they were embedded, who delivered these epoch-making ideas to civilization.

[5] Sadie Carnot's father, Lazare, began contributing to heat engine development before Sadie was born. Both were intellectual giants. Both were revolutionaries — in technical as well as political thinking.

The four laws of electromagnetics came slipstreaming along behind the laws of mechanics. Michael Faraday, born of a poor English family in 1791, was a scientist rather than an engineer. His experiments showed relationships between electricity and magnetism. (Remember that the second law of electromagnetics is named in his honor.) He also found that when polarized light is shined through a magnetic field, the field altered the polarization. This discovery held profound implications, because it was the first hint that there might be links between light and magnetism. Next came James Maxwell — a Scot like Watt, but from Edinburgh rather than Glasgow. He wrapped together civilization's understanding of electromagnetics with the famous set of equations presented in his *Treatise on Electricity and Magnetism* in 1873.[6]

Faraday, Maxwell and their colleagues-of-the-day also formulated the electromagnetic force law. The acceleration and gravitational force laws had already been discovered earlier in Newton's time. Now with this third-force law added to the four laws of electromagnetics and the four laws of mechanics, the complete menu of classical physics was laid out before us.

Both engineers and scientists uncovered classical physics. Does it matter who contributed more? I think not. In those days engineers and scientists were much of a sameness. If there was a difference, I suppose it lay in the fact that as their highest objective, scientists were more interested in uncovering nature's rules than in building things, while engineers were seeking nature's rules to help them build more useful things.

After Maxwell, the distinction between engineers and scientists became more visible. Physicists (and chemists) had little more to do in uncovering classical physics. That was complete. But new surprises and paradoxes were popping up, showing that the laws of classical physics didn't work for everything — that some needed to be 'corrected' for the very small and very fast. For us humble worldly folks, it's important to know that this means very, *very* small and very, *very* fast. So modern physics is not needed for our odyssey and — lest we get drawn too far from the purpose of our voyage — we must leave these matters for others.

Triggered by heat-to-work conversion during the late 18th century, phase two of engineering history was in full bloom at the start of the 20th century. The classical physics foundation was solid, but engineers needed to learn how to use that foundation more effectively. Further, they needed to better understand the constitutive relations in order to better anticipate how materials would behave — and what materials to use or to develop. Some of this learning came through tragedies. For example, when the first commercial jet airliners, the Comets, began falling out of the sky it was learned the accidents resulted from catastrophic structural failures caused by metal fatigue.

It seems to me that as engineering entered the 20th century the business of building things, especially things that wouldn't break and kill people, took engineers away from fundamentals — got them used to looking in handbooks for empirical data about material behavior and for routine design procedures. Some look back with fondness saying this was a time when engineering was an 'art' rather than a 'science'. I'm not so sanguine.

Engineers are in the business of getting things done, not in the business of delaying getting things done until they can explain, using only fundamental principles, why a technique that can get it done works. (Watt knew nothing of the first or second law of thermodynamics, but he still designed the first practical steam engine.) As an undergraduate, I was introduced to engineering at the end of phase two. We were taught the fundamentals of classical physics during the first years of university. Then when that was finished, most of our undergraduate education was spent doing things like designing beams and gear trains by looking up specifications in handbooks. I thought it mind-deadening, boring, stuff — skipped 'design' laboratories, paid for it in grades.

Sputnik shaped engineering and especially engineering education because it shaped the American vision of what engineering should be: a profession that would put Americans on the moon before Russian engineers put Russians. This *required* that engineering be firmly founded upon the sciences. It required that engineering leave empiricism and return to fundamentals. Engineers had to design new things, things not in the handbooks, from the ground up, meaning from classical physics up. There were no handbooks for rockets. Fortunately, space flight is a wonderful task for classical physics because in essence it *is* classical physics.

And so Sputnik came to shape me. Because a few years after graduating and seeing (what I thought to be) the boring aspects of industry, I decided to go back to university for a doctorate as a ticket to becoming a professor. Being a professor would give me (I thought) lots of time off for sailing and skiing, and it could probably be fun. I decided to go to the United States, because — in response to Sputnik — America had taken vigorous steps to

[6] I've stressed Maxwell's work in electromagnetic theory — a giant contribution. But he also worked in the then maturing field of thermodynamics, developing important general relationships between thermodynamic properties and making important contributions to the kinetic theory of gases.

encourage engineering doctoral students. One initiative was the Ford Foundation Fellowships at selected US universities for students who intended to become engineering professors in either Canada or the United States. Wonderful! There was money to keep my young family fed, and the Ford Foundation had simplified things by selecting only the best schools (for wannabe graduate students) to choose from.

I chose Northwestern. Being a private university it could change quickly and it had. The Department of Mechanical Engineering had changed its name to Mechanical Engineering and Astronautical Sciences. And they had enriched their professorial complement with new staff so that, by the time I arrived, they probably had as many professors trained as physicists as trained as engineers. They had rapidly turned towards engineering science and away from the engineering empiricism. I loved it. It was a marvelous way to look at the world. Engineering was now really becoming fun. And I knew that (for me) graduate school was a good decision — although *why* it was good had little to do with skiing or sailing.

I returned to Canada as an exuberant new assistant professor of mechanical engineering at the University of Toronto determined to 'do it right' — which I believed meant to teach and research engineering based solidly on classical physics spiced with a bit of modern physics. Five other assistant professors started the same year. Most of this new guard favored science over empiricism. In a few short years of debate between the old guard and new guard, the new guard won — which meant engineering science won, engineering empiricism lost. Throughout the 1960s it was happening, in different ways, in engineering schools all over the world.

The two decades following Sputnik became decades of 'the space race'. The public mind was re-awakened to the marvels of engineering — of engineering that was almost all based on the laws of classical physics. And what was both remarkable and fortunate is that these laws were even easier to apply to the task of flying to the moon than to any major task engineering had previously attempted. Two things made it easy:

- To fly to the moon, the laws of classical physics are simple to use. For example, the conservation of momentum and the acceleration force law, $\mathbf{F} = m\mathbf{a}$, not only work, but are uncluttered by earthly things like friction or road dust. On Earth the laws are equally valid. But on Earth the effects of things like friction and drag mean they are often difficult to apply with precision.
- To fly to the moon, no established infrastructure needed to be displaced. A frequent barrier to exploiting new technological opportunities is the existing infrastructure — the people who will lose jobs, the industries that will be displaced, and the lifestyles that will be disrupted. But the path to the moon was empty, no buildings needed to be raised, no land needed to be appropriated, no industries and jobs were put in jeopardy.

Thinking back to those times I recall we often heard sentences that began "If we can put a man on the moon, why can't we..." (and then sentence would continue with examples like) "... find a cure of cancer ..." or "... get people to live together peacefully..." During the euphoria brought by landing on the moon it wasn't recognized that, compared to finding a cure for cancer and certainly compared with getting to people to live together peacefully, rocket science is easy. One reason is because flying to the moon is such a sweet, uncluttered application of classical physics.

By the 1980s the space race was over and, although not abandoned, space programs were predictably but unfortunately left to struggle for public attention. Concurrently, while not abandoning its foundation, engineering paid classical physics less and less homage. So began the gradual transition to phase four.

The emerging information-age brought this re-emphasis. All branches of engineering turned towards building, programming and finding new uses for computers. The engineering school at the University of Victoria (my employer as I write this article) came into existence in the mid-1980s. As we enter the 21st century, UVic has one department called Electrical and Computer Engineering and another called Computer Science — both within the Faculty of Engineering. The engineering 'laboratories' consist of room after room of computer terminals, with almost no rooms containing what we used to call engineering equipment. Some call these 'ersatz engineering laboratories'. This is not to be dismissive, for you can learn a lot of engineering and examine many engineering configurations by flying computers. Moreover, the graduates can surely find jobs. But you don't always learn which end of a screwdriver to hold.

Like many engineering schools, UVic now has a program called 'imbedded systems'. Imbedded systems are small computers imbedded in 'appliances' such as your car that adjust the spark advance and mixture to account for altitude, temperature and so on and that tell you when your car needs an oil change. The architecture of information systems is, necessarily, artificial — that is, it is not directly based on the laws of classical physics or, for that matter, any other of nature's fundamental laws. At the beginning of the 21st century, a lot of engineering is going that way.

While writing this article, I took time-out to chair the oral examination of a master's thesis titled 'Application of Artificial Neural Networks to Geoacoustic Inversion'. (Chairing doesn't mean you need to understand the thesis,

only that you know how complete the paperwork after the experts have examined and pronounced upon the research.) The thesis was about designing a neural network that could determine the nature of an ocean floor by interpreting the acoustic signal received by transducers after an acoustic pulse had been bounced off that same ocean floor. Sitting in the examination room, thinking about the underlying phenomena, I mused that the sound propagation through the ocean was determined by energy and momentum equations, and the sound attenuation had to satisfy the entropy law. Moreover the electric currents running though the hardware that used the student's 'algorithm' conformed to Maxwell's electromagnetic field theory. But none of those realities were addressed in either the thesis (which was well written) or the oral defense (which was well spoken). Instead, the focus was on artificial intelligence — none of which had any tangible tie to classical physics.

This thesis is one small illustration of how engineering curricula are drifting further from its classical physics foundation. I wonder where it will lead. I have an uneasy feeling when engineering drifts too far from its roots, especially when these roots remain the roots everything engineering does. But I'm also a tad uncertain about my uncertainty, because now I am the old guard.

Still, old guard or not I have a few thoughts on where we are and where we might go from here.

Watt's walk upon the Green marked a giant advance for civilization, because it marked the time when heat engines allowed work to escape the energy source ghetto of wind, falling water and muscle. It also marked the beginning of a phase when building technologies went hand-in-hand with uncovering the most fundamental laws of nature. Later engineering may have pushed these laws to back burners, while the front burners cooked away using 'practical' empirical design techniques. Suddenly a few beeps yanked engineering back to its roots in physics. Now it's drifting away once more, lured by the siren of information technologies.

Two events could pull us back.

The first event *might* be if life science researchers begin to exploit the insights that thermodynamics could bring to understanding life's most fundamental processes. If this occurs, then almost certainly engineers (and physicists and chemists) will collaborate in developing a field that will likely be called 'the thermodynamics of living systems'. This will take us back to seeking a still better appreciation of the third and fourth laws of classical mechanics — because, for most people, knowing the fundamentals of how *we* work is even more interesting than knowing the fundamentals of how steam engines work.

The second event *will* be when hydrogen technologies begin to colonize our energy system during the early 21st century. To develop the technologies for this colonization, engineers will be required to return to their classical physics foundation — just as did "putting a man on the moon and bringing him home again safely".

Curiously, these two events could be linked.

That's because fuelcells will be the key enabling technology for the hydrogen age — just as the microelectronics chip is the key enabling technology for our present information age. Fuelcells use electrochemical processes — not heat engine processes — for power generation. Therein lies the connection. Living systems have *never* used heat engines to power their walking, swimming or growing. Rather, life's energy conversion processes are remarkably analogous to electrochemical processes — although much more sophisticated than the processes used in today's fuelcells. So today's strong ties between modern medicine and modern engineering will have another bond as we launch the hydrogen age.

Launching the hydrogen age will employ engineers using the fundamentals of classical physics — mixed with some modern physics, a lot of chemistry and, of course, information technologies — to design the innards of fuelcells and hydrogen liquefiers, to build refueling stations and liquid hydrogen fuelled aircraft… and on and on.

More important, they will build systems to deliver services that are now beyond our imagination. Rich fodder for dreamers. Because launching the hydrogen age will further the maturing of civilization, in ways and with significance, not seen since James Watt walked upon the Green of Glasgow "thinking upon the engine".

This is the thirteenth in a series of articles by

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