



## Engineering and classical physics

*In which we remember that the eleven laws of classical physics are the foundation of engineering — and then we begin to sense something special about the entropy law*

We climbed down from our hillside and into our little ship-of-ideas to begin an odyssey in search of what Earth is extracting from energy flows. Now we have completed the first leg of our journey. We've found our first waypoint: nature's fundamental law of energy conservation. Having sailed to this waypoint, having seen the power of this single law, it makes sense to ask: what other fundamental laws are there? It turns out that there are very few. So let's climb the mast, look around the horizon, and get a fix on this small package of nature's laws. They will be our aids to navigation.

Over the past few hundred years, civilization has emerged from the dark of mysticism, revelation, numerology, astrology, sheep's entrails and so forth. At least those who want to emerge have emerged — some still prefer astrology and entrails. The ability to depart the dark of myth and so to enter the light of rationality is a gift — a gift conferred by our increasing intimacy with nature. The last sentence might shock. Today's congealed wisdom repeatedly tells us we are steadily becoming *less* intimate with nature. At some relatively trivial levels — like how much time we spend personally catching and gathering our food — congealed wisdom might be correct. But at a much deeper level it misses the point. For just as becoming intimate with a fellow human is to learn what makes that person tick, to become intimate with nature is to learn what makes nature tick. Over the last two centuries we've learned a lot about how nature ticks.

You're about to help your favorite nine-year-old assemble a tabletop soccer game. Instructions flutter from the box. Besides telling you how to assemble the toy, the instructions explain the rules of soccer — how soccer works. In contrast we don't need instructions for assembling our world — that's been done for us. But living in our world is a game we play every second of our lives. It can be a lot more enjoyable if we know the rules.

Nature's rules describe how our world works — for that matter how our universe works, because the nice thing about nature is that she doesn't change her rules when you move from place to place or from time to time. Nature's rules are not like the rules of football that change when you cross the border between Canada to the United States,<sup>1</sup> or the rules of sailboat racing which are updated every five years. So we call nature's rules, laws.

There are at least two other differences between the rules of sport and the laws of nature.

First, no written instructions describing nature's laws have fallen out of a box. To learn nature's laws we must watch nature work and, by clever watching, sometimes by smelling land, deduce her laws. Imagine you had never played baseball, or knew nothing about its rules. Still, after a period of clever watching, carefully recording the events of many games — perhaps setting up spread sheets to help you find repeating patterns — you might be able to write down something close to what the rules of baseball must be.

Second, the fundamental laws of nature that people had discovered by the early part of the 20th century, that small package of universal laws we've come to call classical physics, are much simpler than the rules of baseball, or yacht racing, or just about any sport you can imagine. Indeed, the extraordinary simplicity of nature's most funda-

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<sup>1</sup> In both the United States and Canada 'football' is something very different than what is called football everywhere else in the world. What the Argentinians, Austrians, Indians, Germans and Poles call football, North Americans — except Mexicans — call soccer. In Canada and the US, 'football' is reserved for a game played with an oblate spheroid, rather than spherical, ball — which probably goes back to a lineage in British rugby.

mental laws makes it tempting to believe they were *purposely* structured to permit easy de-coding — at least it would be tempting if it weren't so damned anthropocentric.

By 1920 the trail of clues had led to the group of laws we now call classical physics. Then, standing upon this platform, civilization was positioned to unravel the trickier laws. Trickier only because the clues lie further and further from people's everyday experience. Building upon the platform of classical physics, the ideas of relativity and quantum mechanics came next. Today scientists are expanding our understanding out further and further, out to where nature's behavior is more and more remote from our everyday experience, out to all the wonders, uncertainties, paradoxes and contradictions about our expanding universe (or universes), black holes and so on. At the same time, scientists are delving inwards — to sub-nuclear things like quarks,  $\mu$ - and  $\pi$ -mesons, gluons and so forth. These stunning ideas — ideas steadily being uncovered on the expanding, fascinating and surprise-ridden frontiers of modern physics — are all built upon the platform of classical physics. The laws of classical physics seem immutable. And they are all we'll need for our odyssey.

The fact that people came to understand the sparse, efficient, precise group of laws we call classical physics has changed civilization more than all of history's empires, religions and pestilences. So we better lay them out in front of us — set them out, so to speak, on the table.

There are 11 laws that come in three groups. One group of four laws describes classical electromagnetics. A second group of four laws describes classical mechanics. A third group, this time of three laws, describes forces — and thereby provides the link between electromagnetics and mechanics.

The four laws of *classical electromagnetics* are usually presented in the form of Maxwell's four differential equations that describe electromagnetic fields — but these equations are only useful to those who can read the vector calculus. So I will use mostly words — but stick on the corresponding equations for vector calculus literate. By the way, don't worry if you have a little trouble getting a good feel for what these four electromagnetic laws mean. While they are essential for a full understand of the electromagnetic phenomena, they are minor waypoints on our special odyssey. Here come the four laws of electromagnetics:

1. Gauss's law says that the electric field through a closed surface is proportional to the total electric charge enclosed within the surface.

$$\nabla \cdot \mathbf{E} = \rho / \epsilon_0$$

2. Faraday's law says that (something we call) the “curl” of the electric field round a closed loop is proportional to the negative rate-of-change of the magnetic field passing through the loop.

$$\nabla \times \mathbf{E} = -\partial \mathbf{B} / \partial t$$

3. A magnetic field analog of Gauss's law (but not named after anyone) says that, unlike electric charges, there are no magnetic charges. (While we can think of an electric field line starting on one electric charge and ending on another electric charge, all magnetic field lines are continuous loops because magnetic charges do not exist.)

$$\nabla \cdot \mathbf{B} = 0$$

4. A magnetic field analog of Faraday's law (which might have been named after Maxwell but wasn't) says that the “curl” of the magnetic field around a closed loop is proportional to the negative of the current plus the rate-of-change of the electric field passing through the loop.

$$c^2 \nabla \times \mathbf{B} = \mathbf{j} / \epsilon_0 + \partial \mathbf{E} / \partial t$$

Why did I say that this fourth law might have been named after Maxwell, but was not? Maxwell corrected a previous version of this fourth law — by adding the  $\partial \mathbf{E} / \partial t$  term. To recognize his genius for getting-the-equation-right *and* the stunning results that blossomed for having gotten-it-right, all four laws are now called Maxwell's relations for electromagnetic fields.

When these four electromagnetic laws are used separately, they are important but not majestic. Majesty comes when they are folded together. Then, using a few simple mathematical steps, a kind of mathematical origami, the equations intertwine to pop out two wave equations describing all the wonders of light — and light's siblings like radio waves, gamma rays, X-rays and so forth. To me it seems a butterfly of physical understanding emerging from

the cocoon of Maxwell's equations. When I first saw these few steps written out in *The Feynman Lectures on Physics*,<sup>2</sup> the raw beauty of the cocoon and its emerging butterfly brought a pitter-patter to my gut similar, say, to the first time I listened, carefully, to the love–death music from *Tristan und Isolde*.

Next we'll turn to the four laws of *classical mechanics*. They are easier to describe in words without using equations. Moreover, we usually re-cast the equations to correspond to various physical circumstances. So this is one case where although the laws don't change, words can have more generality than equations. In words the four laws of mechanics come out like this:

1. Mass is *conserved* — which means that mass can neither be created nor destroyed.
2. Momentum is *conserved* — which means that when bodies collide (like billiard balls or automobiles, or molecules, or galaxies ...) the combined momentum after the collision is always the same as it was before the collision.
3. Energy is *conserved* — which is what 'Conservation, Confusion and Language' was all about.
4. Entropy is *not* conserved, rather it is *produced* — which means that after any process the entropy of the universe is almost always greater, and never less, than it was before the process occurred.<sup>3</sup> (We haven't yet described what entropy *is*, but our odyssey is taking us there.)

Thermodynamicists call the third and fourth laws of mechanics the first and second laws of thermodynamics. (I'm not trying to muddle with these different names — it's just the way engineering and physics grew up.) These two laws are the most important for understanding how an energy system ticks — whether it is the energy system that drives the universe, or Earth, or civilization, or you. And that is why our odyssey will pay special attention to the energy and entropy laws of thermodynamics. They will be our most important waypoints.

Now that we've got the two groups of four laws each for electromagnetics and mechanics, we can wrap things up with the three force laws. They are:

1. The gravitational force law, which says that the attraction between two masses is proportional to the product of the masses divided by the square of the distance between them.

$$\mathbf{F} = -\mathbf{n}Gm_1m_2/r^2$$

2. The acceleration force law, which says that the force required to accelerate a body is equal to the mass of the body times its acceleration.<sup>4</sup>

$$\mathbf{F} = m\mathbf{a}$$

3. The electromagnetic force law, which says that the force on an electrically-charged body caused by an electromagnetic field is equal to the electric charge multiplied by the *sum* of the electric field plus the velocity of the charge 'cross'-multiplied with the magnetic field.

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

That's it. Now we've got the full package. These are the eleven laws of classical physics.

About now, remembering high school physics and chemistry you might ask: what about Hook's Law for deflection of a spring under load, or Boyle's Law for the relationship between the pressure and volume of an ideal gas when temperature is constant, or the rate-of-reaction laws for chemistry?

I don't think of these as nature's *fundamental* laws. Rather they are relationships describing the special behavior of different materials. Sometimes, by historical accident, we've elevated them with the title 'law' — like Hook's Law

<sup>2</sup> By Feynman, Leighton and Sands, originally published by Addison-Wesley.

<sup>3</sup> Sometimes engineers and scientists will 'idealize' a process by assuming that no entropy is produced. And some real processes come very close to zero entropy production. But entropy is never destroyed.

<sup>4</sup> This law is sometimes written as stating that the force is proportional to the rate-of-change of momentum, rather than proportional to mass times acceleration. For 'worldly' speeds, the former gives the same result as the latter but it has the advantage of being properly carried over to relativistic speeds. But since I'm restricting this discussion to classical physics, and because the  $\mathbf{F} = m\mathbf{a}$  law is simpler and better known as mass times acceleration, I've written it this way. While we're at it, I would mention that bold symbols, like  $\mathbf{F}$ , mean vector quantities, and that the  $\mathbf{n}$  in the gravitational law is a unit vector pointing towards the mass on which the force is acting.

or Boyle's Law. But these are legacies of earlier times when we weren't clear on the difference between the fundamental laws of nature (all of which govern material behavior but are independent material properties) and relations that account for the properties of *specific* materials. Often these material-specific relations are called 'constitutive' or 'phenomenological' relations. Yet some people continue to call them 'laws'. If they do, I don't really mind because I don't think it results in any important confusion. Still I prefer to reserve the word 'law' for the fundamental rules of nature.

The difference between a phenomenological relation and a fundamental law is that the former describes *specific* properties of *individual* materials while the latter describes how *every* material behaves under *every* circumstance. When saying this, perhaps naturally, I first think of engineering things like bridges or rockets. But I could also think about you. Your 'constitutive properties' are weight, height, age, ratio of body fat to muscle, and other things we can leave unmentioned. Such constitutive properties change from person to person. That is what contrasts these properties from a fundamental law, applied to everyone, which says we all must die.<sup>5</sup> No matter who you are if, as a pedestrian, you're attacked by a speeding car, the conservation laws of mass, momentum and energy, together with the law of entropy production and the acceleration force law, will determine the overall event. But constitutive relations that set out details of how you differ from someone else — such as the difference in the resilience of your soft tissue and the brittleness of your bones — will influence the results.

Let's get back to inanimate things. If we are designing a rocket to fly to the moon, we must first employ the relevant laws of classical physics to determine the trajectories, required thrust, etc. But later, when we are selecting specific materials for the rocket, we will need constitutive data. Finding this data is simply a matter of looking it up in a book or plucking it from a piece of software.<sup>6</sup> The point is, there is seldom anything deep about *understanding* the data once you've got it. Moreover, you shouldn't carry this data about in your head or it will consume headspace better used for other things. Consider the 'spring constant' data you will need while using Hook's relation to design the astronauts' seats. If you intend to carry 'spring constant' data about in your head then you must carry bits of data for all the alloys of steel, whether the steel had been annealed, so on and so forth. And even after you have all that stuff, stuffed in your head, then you'll need to stuff stuff about aluminum, rubber, carbon fibers and so on. And we haven't begun to talk about reaction rates (that we'll need for designing the space vehicle's fuelcells), magnetic permeability (that we'll need for designing instruments) ...

The business of engineering design is the business of employing the laws of classical physics, spiced with applicable constitutive relations, to make a better world. To be an engineer, the laws of classical physics are all the *fundamental* laws you really need to know — and, of course, how to use them. It's one reason engineering can be a great career for the memory-challenged but logically-gifted.

Yet it gets even simpler. Electrical engineers must be intimate with Maxwell's laws of electromagnetic theory, but often get by with only a hazy sense of the others. Mechanical engineers must be intimate with the four laws of mechanics, but usually get by with only a hazy sense of electromagnetic theory. And even simpler again. Because within mechanical engineering, fluid mechanics — the people who design the shape of things like propellers, airfoils or racing yacht hulls — live in a world dominated by two laws, momentum and energy. While energy systems engineers — people who design the engines to power the propellers — rarely worry about momentum. Instead they live in a world dominated by the energy and entropy laws. Structural engineers quickly become imbedded in constitutive relations.

Sometimes — rarely as engineers — we need to go *beyond* classical physics to employ modifications provided by modern physics. This happens if we want to consider phenomena taking place at the *extraordinarily small* scales of atomic and sub-atomic sizes — when we need to correct classical physics with quantum theory. You can expect quantum theories to become important when we must understand sub-atomic statistical processes like 'tunneling' when designing microelectronic transistors. We also need quantum theory to design the reactor kinetics within nuclear power stations (because these kinetics depend upon collisions between nuclides, fission fragments and so on) — but not for designing the containment vessels, piping and turbines that constitute the bulk of these same stations. At the other end of things, relativity adjusts classical physics to account for the *extraordinarily vast* and *fast* — but it almost never enters an engineer's working world and has never influenced our technologies. Still, for the bright

<sup>5</sup> Curiously, the requirement to be mortal is not a fundamental law of physics — which, if you like, can bring hope (or fear) when thinking about the distant future.

<sup>6</sup> If the material is very new — as it might be if developed for a rocket — its properties might not be in tables or software packages. You might need to perform a series of tests to experimentally determine its properties.

and curious the expanding vistas of modern physics provide endless fascination — as we follow what our physics brethren are up to.

For the purpose of our odyssey, my point is this. You must never lose confidence in the dominance of classical physics for governing the behavior of things that shape our lives — from our daily weather to our technologies. Our odyssey will concentrate on the first and second laws of thermodynamics.

My second point is that good engineering requires a clear understanding of what the laws of classical physics mean — supported by an ability to define the system, the knowledge to select the right constitutive or phenomenological data and, most important, the wisdom to ask the right questions. In the end we usually quantify things with a few calculations. Numeracy gives tight answers.

Returning to our odyssey, let's look at some patterns. The most striking thing about these eleven fundamental laws is that *all but one* are conservation laws. Some are in-your-face conservation, like the conservation of momentum or energy. Others are subtler, like the acceleration force law or Coulomb's law — where the conservation idea is expressed by equality signs in the equations. The single exception is the *production* of entropy law.

With the exception of the entropy law, the mathematical representation of all the laws of classical physics are written as *equations*. This is not necessarily true for the law of entropy, which can either be written as an *inequality*, or written as an equation by inserting an *additional* quantity to account for entropy production. There are no production terms — like energy production or momentum production — in any of the other ten fundamental equations. Many people consider nature's law of entropy production — nature's requirement that the entropy of the universe is always growing — to be the most profound of all eleven.

Perhaps they think it the most profound because it is the only one of nature's laws that gives the *direction* of time. Every other law allows time to run forward or backward without prejudice.

Perhaps they think it the most profound because it is the most abstract and difficult for embryo engineers and scientists to grasp. This may also be the reason it is often misunderstood by popular writers who, too frequently, build nonsensical doomsday scenarios founded on their misunderstanding.

Perhaps they think it the most profound because all the others describe the statistically averaged behavior of an extraordinarily large ensemble of sub-atomic, atomic and molecular particles (including photons) while the law of entropy explicitly accounts for the statistical distribution of these particles.

Perhaps, as Lovelock has stated,<sup>7</sup> it's because it “is the most fundamental and unchallenged law of the Universe.” I wonder if Lovelock said this because — unlike the ten conservation laws that need modification or reformulation when applied to the unworldly domains of the very small, the very fast or the exceptionally massive — the non-conservation law of entropy appears inviolate throughout the universe.

Or perhaps, and this is my view, it is the most profound because it is the law of nature that best illuminates that which is unique about life.

Of course, the label ‘most profound’ should not be taken to mean ‘most important’. We need all eleven to properly describe how our universe and technologies work. To select any one as the most important would be like selecting, as the most important, one leg of a three-legged stool.

We use all eleven as a rock-solid foundation on which to develop and design our technologies. Indeed, this foundation is so rock-solid that many designers rarely think about it in their day-to-day work. It's a bit like decorating a Christmas tree. When you reach out to put the star on the top of the tree you may wonder about the stability of your stepladder. But you don't give much thought to the stability of the floor on which you've placed the stepladder — or the foundation that, in turn, supports the walls, floor, stepladder and you.

In childhood we heard the Mother Goose<sup>8</sup> rhyme,

*“Humpty Dumpty sat on a wall.*

*Humpty Dumpty had a great fall.*

*All the King's horses and all the King's men, could not put Humpty Dumpty together again.”*

We may not have realized it, but we were being introduced to a very special law of nature; the fourth law of mechanics — the second law of thermodynamics.

It was the entropy law that prevented the splattered bits coming together again, leaping back up on the wall, leav-

<sup>7</sup> See p. 22 of *The Ages of Gaia*.

<sup>8</sup> Some friends reading early versions of this chapter suggested that I identify the ‘real’ author of Mother Goose. But the name(s) of the person(s) who wrote Mother Goose is (are) unavailable — lost, as they say, in the mists of time.

ing a healthy, smug Humpty sitting there chortling. Any of the other ten, like the conservation of energy and momentum, would have permitted a happy conclusion with a healthy Humpty. But Mother Goose got it right. The entropy law gives the direction of time. Like Thomas Wolfe,<sup>9</sup> Mother Goose says we cannot go back. For children who might someday want to understand entropy, perhaps while becoming mechanical engineers, Humpty's martyrdom is a nudge towards their future.

For our odyssey, Mother Goose points to the most important waypoint.

*This is the twelfth in a series of articles by*

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<sup>9</sup> American author of *You Can't Go Home Again*.