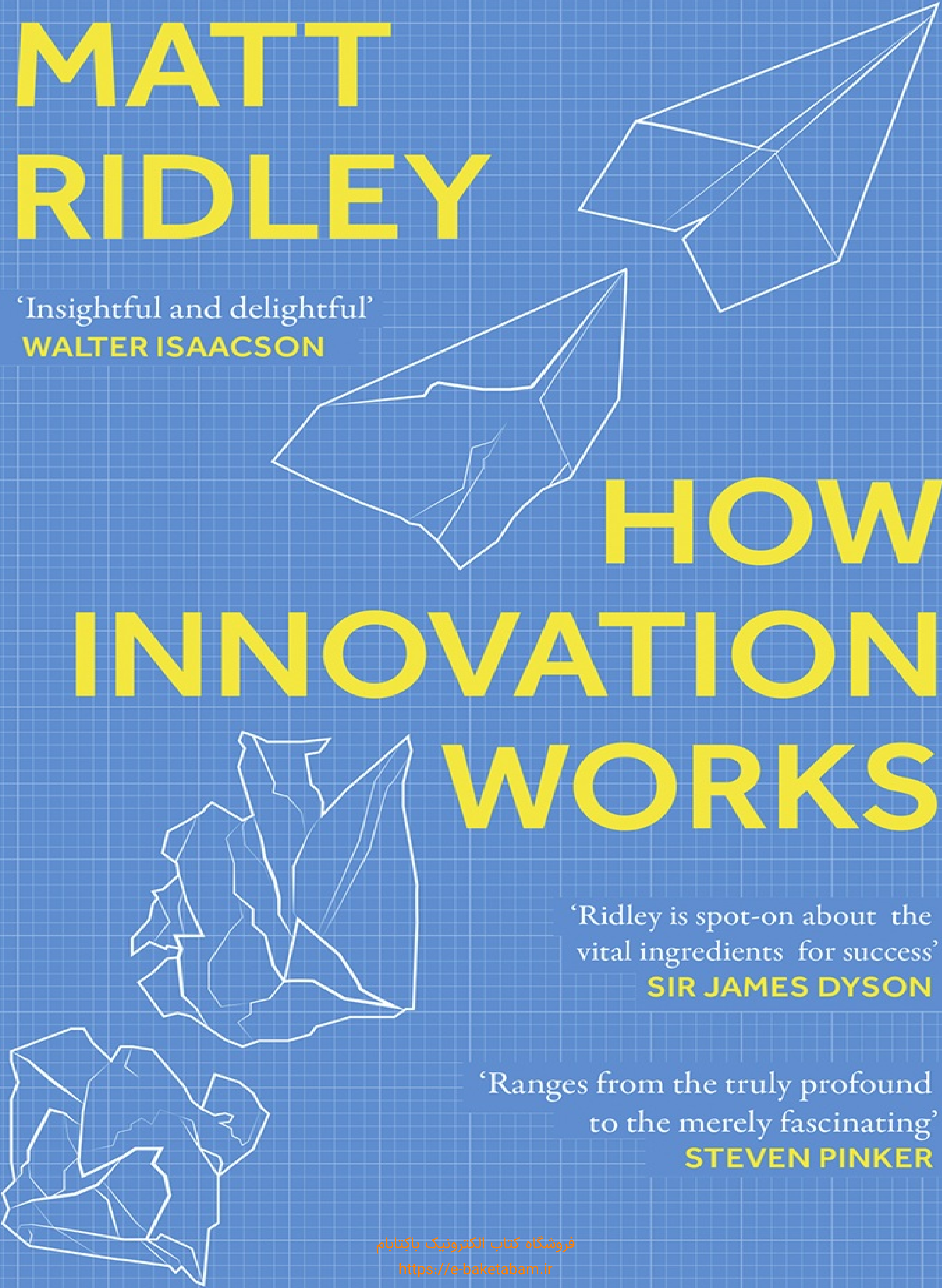

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HOW INNOVATION WORKS

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HOW INNOVATION WORKS

Matt Ridley

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Dedication

For Felicity Bryan

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INTRODUCTION

The Infinite Improbability Drive

Innovation offers the carrot of spectacular reward or the stick of destitution.

JOSEPH SCHUMPETER

I am walking along a path on the Inner Farne, an island off the coast of north-east England. By the side of the path, amid the sea-campion flowers, sits a female eider duck, dark brown and broody, silently incubating her clutch of eggs. I stoop to take a picture of her with my iPhone from a few feet away. She is used to this: hundreds of visitors come here every day in summer and many will take her picture. For some reason, an idea pops into my head as I click: a riff on the second law of thermodynamics based on a remark by my friend John Constable. The idea is this: the electricity in the iPhone's battery and the warmth in the eider duck's body are doing roughly the same thing: making improbable order (photographs, ducklings) by expending or converting energy. And then I think that the idea I've just had itself, like the eider duck and the iPhone, is also an improbable arrangement of synaptic activity in my brain, also fuelled by energy from the food I have recently eaten, of course, but made possible by the underlying order of the brain, itself the evolved product of millennia of natural selection acting on individuals, each of whose own improbabilities were sustained by energy conversion. Improbable arrangements of the world, crystallized consequences of energy generation, are what both life and technology are all about.

In Douglas Adams's *The Hitchhiker's Guide to the Galaxy*, Zaphod Beeblebrox's starship *Heart of Gold* – a metaphor for wealth – is powered by a fictional 'infinite improbability drive'. Yet a near-infinite improbability drive does indeed exist, but here on Planet Earth, in the shape of the process of innovation. Innovations come in many forms, but one thing they all have in common, and which they share with biological innovations created by evolution, is that they are enhanced forms of improbability. That is to say, innovations, be they iPhones, ideas or eider ducklings, are all unlikely, improbable combinations of atoms and digital bits of information. It is astronomically improbable that the atoms in an iPhone would be neatly arranged by chance into millions of transistors and liquid crystals, or the atoms in an eider duckling would be arranged to form blood vessels and downy feathers, or the firings of neurons in my brain would be arranged in such a pattern that they can and sometimes do represent the concept of ‘the second law of thermodynamics’. Innovation, like evolution, is a process of constantly discovering ways of rearranging the world into forms that are unlikely to arise by chance – and that happen to be useful. The resulting entities are the opposite of entropy: they are more ordered, less random, than their ingredients were before. And innovation is potentially infinite because even if it runs out of new things to do, it can always find ways to do the same things more quickly or for less energy.

In this universe it is compulsory, under the second law of thermodynamics, that entropy cannot be reversed, locally, unless there is a source of energy – which is necessarily supplied by making something else even less ordered somewhere else, so the entropy of the whole system increases. The power of the improbability drive is therefore limited only by the supply of energy. So long as human beings apply energy to the world in careful ways, they can create ever more ingenious and improbable structures. The medieval castle at Dunstanburgh I can see from the island is an improbable structure, and its partial ruin after 700 years is more probable, more entropic. The castle in its prime was the direct consequence of the expenditure of lots of energy, in this case mainly in the muscles of masons who were fed with bread and cheese that was made from wheat and grass that was grown in sunlight and eaten by cows. John Constable, a former Cambridge and Kyoto academic, points out that the things we rely on to make our lives prosperous are

> all of them, without exception, physical states far from thermodynamic equilibrium, and the world was brought, sometimes over long periods of time, into these convenient configurations by energy conversion, the use of which reduced entropy in one corner of the universe, ours, and increased it by an even larger margin somewhere else. The more ordered and improbable our world becomes, the richer we become, and, as a consequence, the more disordered the universe becomes overall.

Innovation, then, means finding new ways to apply energy to create improbable things, and see them catch on. It means much more than invention, because the word implies developing an invention to the point where it catches on because it is sufficiently practical, affordable, reliable and ubiquitous to be worth using. The Nobel Prize-winning economist Edmund Phelps defines an innovation as ‘a new method or new product that becomes a new practice somewhere in the world'. In the pages that follow I will trace the path of ideas from the invention to the innovation, through the long struggle to get an idea to catch on, usually by combining it with other ideas.

And here is my starting point: innovation is the most important fact about the modern world, but one of the least well understood. It is the reason most people today live lives of prosperity and wisdom compared with their ancestors, the overwhelming cause of the great enrichment of the past few centuries, the simple explanation of why the incidence of extreme poverty is in global freefall for the first time in history: from 50 per cent of the world population to 9 per cent in my lifetime.

What made most of us, not just in the West but in China and Brazil too, unprecedentedly rich, so the economic historian Deirdre McCloskey says, was 'innovationism': the habit of applying new ideas to raising living standards. No other explanation of the great enrichment of recent centuries makes any sense. Trade had been expanding for centuries, and colonial exploitation with it, and these alone were unable to give anything like the order of magnitude of improvement in incomes that happened. There was no sufficient accumulation of capital to make such a difference, no 'piling of brick on brick, or bachelor's degree on bachelor's degree' in McCloskey's words. There was no sufficiently great expansion in the availability of labour. Nor was the scientific revolution of Galileo and Newton responsible, for most of the innovations that changed people's lives at least at first owed little to new scientific knowledge and few of the innovators who drove the changes were trained scientists. Indeed many, such as Thomas Newcomen, the inventor of the steam engine, or Richard Arkwright of the textile revolution, or George Stephenson of the railways, were poorly educated men of humble origins. Much innovation preceded the science that underpinned it. The Industrial Revolution therefore was in effect, as Phelps has argued, the emergence of a new kind of economic system that generated endogenous innovation as a product in itself. I will argue that some machines themselves made this possible. A steam engine proved to be 'autocatalytic': it drained the mines, which cut the cost of coal, which made the next machine cheaper and easier to make. But I am getting ahead of myself.

The word 'innovation' is invoked with alarming frequency by companies trying to sound up to date but with little or no systematic idea about how it occurs. The surprising truth is that nobody really knows why innovation happens and how it happens, let alone when and where it will happen next. One economic historian, Angus Maddison, wrote that 'technical progress is the most essential characteristic of modern growth and one that is most difficult to quantify or explain'; another, Joel Mokyr, said that scholars 'know remarkably little about the kind of institutions that foster and stimulate technological progress'.

Take sliced bread, for example. Best thing since, and all that. Looking back it is obvious that somebody would invent a way of automatically pre-slicing bread to make uniform sandwiches. It is fairly obvious that this would probably happen in the first half of the twentieth century when electrical machines were all the rage for the first time. But why 1928? And why in the small town of Chillicothe, in the middle of Missouri? Lots of people tried to make bread-slicing machines, but they either worked poorly or they led to stale bread because it was not well packaged. The person who made it work was Otto Frederick Rohwedder, who was born in Iowa, was educated as an optician in Chicago and set up shop as a jeweller in St Joseph, Missouri, before moving back to Iowa determined – for some reason – to invent a bread slicer. He lost his first prototype in a fire in 1917 and had to start all over again. Crucially he realized that he must invent automatic packaging of the bread at the same time lest the slices go stale. Most bakeries were not interested, but the Chillocothe bakery, owned by one Frank Bench, was and the rest is history. What was special about Missouri? Beyond a general mid-twentieth-century American affection for innovation and the means to make it happen, the best guess is that it was a slice of random luck. Serendipity plays a big part in innovation, which is why liberal economies, with their free-roving experimental opportunities, do so well. They give luck a chance.

Innovation happens when people are free to think, experiment and speculate. It happens when people can trade with each other. It happens where people are relatively prosperous, not desperate. It is somewhat contagious. It needs investment. It generally happens in cities. And so on. But do we really understand it? What is the best way to encourage innovation? To set targets, direct research, subsidize science, write rules and standards; or to back off from all this, deregulate, set people free; or to create property rights in ideas, offer patents and hand out prizes, issue medals; to fear the future; or to be full of hope? You will find champions of all these policies and more, fervently arguing their cases. But the striking thing about innovation is how mysterious it still is. No economist or social scientist can fully explain why innovation happens, let alone why it happens when and where it does.

In this book I shall try to tackle this great puzzle. I will do so not by abstract theorizing or argument alone, though there will be some of both, but mainly by telling stories. Let the innovators who turned their (or other people's) inventions into useful innovations teach us, by the examples of their successes and failures, how it happened. I tell the stories of steam engines and search engines, of vaccines and vaping, of shipping containers and silicon chips, of wheeled suitcases and gene editing, of numbers and water closets. Let’s hear from Thomas Edison and Guglielmo Marconi, from Thomas Newcomen and Gordon Moore, from Lady Mary Wortley Montagu and Pearl Kendrick, from Al Khwarizmi and Grace Hopper, from James Dyson and Jeff Bezos.

I cannot hope to document every important innovation. I have omitted some very important and well-known ones for no particular reason: the automation of the textile industry, for example, or the history of the limited company. I have left out most innovation in art, music and literature. My main examples are drawn from the worlds of energy, public health, transport, food, low technology, and computers and communications.

Not all the people whose stories I tell are heroes; some are frauds, fakers or failures. Few worked alone, for innovation is a team sport, a collective enterprise, far more than is generally recognized. Credit and authorship are confused and mysterious if not downright unfair. Yet unlike most team sports innovation is not usually a choreographed, planned or managed thing. It cannot be easily predicted, as many a red-faced forecaster has discovered. It runs mostly on trial and error, the human version of natural selection. And it usually stumbles on great breakthroughs when looking for something else: it is heavily serendipitous.

I will plunge back in time to the very start of human culture to try to understand what triggered innovation in the first place and why it happens to people but not to robins or rocks. Chimpanzees and crows do innovate, by developing and spreading new cultural habits, but very occasionally and rather slowly; most other animals not at all.

In the ten years since I published *The Rational Optimist*, arguing unfashionably that the world has been, is, and will go on getting better, not worse, human living standards have grown rapidly higher for nearly everybody. I finished that book as the world was plumbing the depths of a terrible recession, but the years since have been ones of faster economic growth for much of the poor of the world than ever before. The income of the average Ethiopian has doubled in a decade; the number of people living in extreme poverty has dipped below 10 per cent for the first time in history; malaria mortality has plummeted; war has ceased altogether in the western hemisphere and become much rarer in the Old World, too; frugal LED lights have replaced both incandescent and fluorescent bulbs; telephone conversations have essentially become free on Wi-Fi. Some things have got worse, of course, but most trends are positive. All this is due to innovation.

The chief way in which innovation changes our lives is by enabling people to work for each other. As I have argued before, the main theme of human history is that we become steadily more specialized in what we produce, and steadily more diversified in what we consume: we move away from precarious self-sufficiency to safer mutual interdependence. By concentrating on serving other people's needs for forty hours a week – which we call a job – you can spend the other seventy-two hours (not counting fifty-six hours in bed) drawing upon the services provided to you by other people. Innovation has made it possible to work for a fraction of a second so as to be able to afford to turn on an electric lamp for an hour, providing the quantity of light that would have required a whole day's work if you had to make it yourself by collecting and refining sesame oil or lamb fat to burn in a simple lamp, as much of humanity did in the not so distant past.

Most innovation is a gradual process. The modern obsession with disruptive innovation, a phrase coined by the Harvard professor Clayton Christensen in 1995, is misleading. Even when a new technology does upend an old one, as digital media has done to newspapers, the effect begins very slowly, gathers pace gradually and works by increments, not leaps and bounds. Innovation often disappoints in its early years, only to exceed expectations once it gets going, a phenomenon I call the Amara hype cycle, after Roy Amara, who first said that we underestimate the impact of innovation in the long run but overestimate it in the short run.

Perhaps the most puzzling aspect of innovation is how unpopular it is, for all the lip service we pay to it. Despite the abundant evidence that it has transformed almost everybody's lives for the better in innumerable ways, the kneejerk reaction of most people to something new is often worry, sometimes even disgust. Unless it is of obvious use to ourselves, we tend to imagine the bad consequences that might occur far more than the good ones. And we throw obstacles in the way of innovators, on behalf of those with a vested interest in the status quo: investors, managers and employees alike. History shows that innovation is a delicate and vulnerable flower, easily crushed underfoot, but quick to regrow if conditions allow.

This strange phenomenon of innovation, and the resistance to it, was eloquently celebrated more than three centuries ago, before the start of the great enrichment, by an innovator – though he would not have used that word. William Petty went from being a teenage cabin boy on a ship who was marooned on a foreign shore with a broken leg, to getting a Jesuit education and becoming secretary to the philosopher Thomas Hobbes. Then, following a spell in Holland, he began a career as a physician and scientist, before emerging as a merchant, an

Irish land speculator, a Member of Parliament, then a wealthy and politically influential pioneer of the study of economics. He was a better innovator than inventor. Early in his career, while a professor of anatomy in Oxford in 1647, Petty invented and patented a double-writing instrument – by which he could produce two copies of the first chapter of Hebrews in one go, in fifteen minutes – as well as a scheme for making a bridge with no supports on the river bed, and an engine for planting corn. None of them seemed to catch on. With feeling, Petty later wrote this lament about the lot of the inventor, in 1662:

> Few new inventions were ever rewarded by a monopoly; for although the inventor, oftentimes drunk with the opinion of his own merit, thinks all the world will encroach and invade upon him, yet I have observed that the generality of men will scarce be hired to make use of the new substances which themselves have not thoroughly tried, and which length of time hath not vindicated from latent inconvenience, so as when a new invention is first propounded in the beginning every man objects and the poor inventor runs the gauntloop of all petulant wits, every man finding his several flaw, no man approving it unless mended according to his own device. Now, not one of a hundred outlives this torture, and those that do are at length so changed by the various contrivances of others, that not any one man can pretend to the invention of the whole, nor well agree about their respective share in the parts. And moreover this commonly is so long adoing, that the poor inventor is either dead, or disabled by the debts contracted to pursue his design; and withal railed upon as a projector or worse, by those who joined their money in partnership with his wit; so as the said inventor and his pretences are wholly lost as vanished.

1

Energy

Whenever you see a successful business, someone once made a courageous decision.
PETER DRUCKER

Of heat, work and light

Possibly the most important event in the history of humankind, I would argue, happened somewhere in north-west Europe, some time around 1700, and was achieved by somebody or somebodies (probably French or English) – but we may never know who. Why so vague? At the time nobody would have noticed or realized its significance; and innovation was anyway a little-valued thing. There is confusion too about whose contribution among several candidates mattered most. And it was a gradual, stumbling change, with no eureka moment. These features are typical of innovation.

The event I am talking about is the first controlled conversion of heat to work, the key breakthrough that made the Industrial Revolution possible if not inevitable and hence led to the prosperity of the modern world and the stupendous flowering of technology today. (Here I use the word ‘work’ in its more colloquial sense, as controlled and energetic movement, rather than in the broader way physicists define it.) I am writing this on a laptop powered by electricity aboard a train also powered by electricity, and with the help of electric light. Most of that electricity is coming down wires from a power station in which enormous turbines are being spun at high speed by steam generated by the burning of gas or boiled by the heat of nuclear fission. The purpose of a power station is to turn the heat of combustion into the pressure of water expanding into steam and thence into the movement of the blades of the turbine, which moves inside an electromagnet to create the movement of electrons in wires. Something similar happens inside the engine of a car or a plane: combustion causes pressure, which causes movement. Virtually all the gigantic amounts of energy that go into making my life and yours happen come from the conversion of heat to work.

Before 1700 there were two main kinds of energy used by human beings: heat and work. (Light came mainly from heat.) People burned wood or coal to keep warm and cook food; and they used their muscles, or those of horses and oxen, or rarely a water wheel or a windmill, to move things, to do work. These two kinds of energy were separate: wood and coal did no mechanical work; wind, water and oxen did no warming.

A few years later, albeit initially on a small scale, steam was turning heat into work, and the world would never be the same again. The first practical device for doing this was the Newcomen engine, and Thomas Newcomen therefore is my first and most promising candidate for the innovator of the heat-to-work transition. Notice I do not call him an inventor; the difference is crucial.

We possess no portrait of Newcomen, and he is buried in an unmarked grave somewhere in Islington, north London, where he died in 1729. Not far away, though again we do not know where, lies the unmarked grave of one of his rivals and a possible source of his inspiration, Denis Papin, who simply faded from view around 1712 as a pauper in London. Only slightly more favourably treated by his own world was Thomas Savery, who died in 1715 in nearby Westminster. These three men, neighbours for a few years and near contemporaries (Papin was born in 1647, Savery probably around 1650 and Newcomen in 1663), all played crucial roles in the heat-to-work transition. But they may never have met.

They were not the first to notice that steam has the power to move things, of course. Toys built to exploit this principle were used in ancient Greece and Rome, and from time to time throughout the centuries clever engineers would build devices to use steam to push water about for fountains in gardens or some such trick. But it was Papin who first began to dream of harnessing this power for practical purposes rather than entertainment, Savery who turned a similar dream into a machine, albeit one that proved impractical, and Newcomen who made a practical machine that actually made a difference.

Or so goes the conventional narrative. Dig deeper and it gets more confusing. Was the French Papin robbed by one or both the Britons? Did Savery or Newcomen pinch his insights from the other? Was Papin perhaps inspired by Savery as much as the other way round? And was Newcomen even aware of the work of the other two?

Although he died in the most obscurity, Denis Papin was the star in terms of intellect and fame in his lifetime. He worked with many of the great scientists of the age. Born in Blois on the Loire, he studied medicine at university. He was recruited by the great Dutch natural philosopher and president of the Academy of Sciences in Paris, Christiaan Huygens, as one of his assistants in 1672, along with another clever young man destined for even greater renown, Gottfried Leibniz. Three years later, Papin found himself exiled in London to escape anti-Protestant persecution in Louis XIV’s France.

There, presumably with an introduction from Huygens, he became Robert Boyle’s assistant, working on an air pump. Robert Hooke then hired him briefly before Papin left for Venice, where he spent three years as a curator of a scientific society, before returning to London in 1684 to do the same job for the Royal Society. Somewhere along the line he invented the pressure cooker for softening bones. By 1688 he had become a professor of mathematics at the University of Marburg, before moving to Cassel in 1695. There is a sense either of restlessness or that nobody could stand his company for very long.

Huygens had employed Papin to explore the idea of a machine driven by a vacuum created by the explosion of gunpowder in a cylinder (an idea that is distantly ancestral to the internal-combustion engine), but he soon realized that the condensing of steam might work better. Some time between 1690 and 1695 he even built a simple piston and cylinder in which steam could condense on cooling, causing the piston to plunge, thereby lifting a weight by a pulley. He had discovered the principle of the atmospheric engine in which it is the weight of the atmosphere that does the work once a vacuum has been created under the piston. It is a machine that sucks rather than blows.

In the summer of 1698 Leibniz exchanged letters with Papin about the latter’s designs for engines that could raise water by the use of fire. Pumping water out of mines was the chief problem to be solved, for it was the one place where horses were difficult to use and where fuel was abundant. Wet mines were safer than dry ones, because the fire risk was lower, but flooding kept foiling the miners.

Yet Papin was already dreaming of powering boats by steam: ‘I believe that this invention can be used for many other things besides raising water,’ he wrote to Leibniz. ‘In regard to travel by water I would flatter myself to reach this goal quickly enough if I could find more support.’ The idea was that steam from a boiler would push a piston ejecting water through a pipe on to a paddle wheel. The piston then returned through a combination of new water being readmitted to the piston chamber and the condensation of the steam. In 1707 Papin actually built a boat with a paddle wheel, though he does not seem to have got it working by steam, but by manpower instead, to demonstrate the superiority of paddle wheels over oars. He trundled down the River Weser in it on the way to England. The professional boatmen took umbrage at this competition and destroyed the craft: Luddites before Ludd.

The historian L. T. C. Rolt concludes that Papin could have done more than he did: ‘Tantalisingly, having reached the very brink of practical success, the brilliant Papin turned aside.’ He returned to steam when Leibniz told him about Thomas Savery’s patent on the use of fire for raising water, a patent granted in 1698 on the very day that Papin boasted to Leibniz that he knew how to make such a machine. Papin then built a different steam engine, which, from the diagram he drew, is clearly a modified version of a Savery engine. Yet it is surely possible that Savery had heard of Papin’s designs from the various letters Papin sent to former colleagues at the Royal Society, though his machine is quite distinct from Papin’s. Who was copying whom?

The coincidence of timing is strange, but quite characteristic of inventors. Again and again, simultaneous invention marks the progress of technology as if there is something ripe about the moment. It does not necessarily imply plagiarism. In this case the combination of better metalworking, more interest in mining and a scientific fascination with vacuums had come together in north-western Europe to make a rudimentary steam engine almost inevitable.

‘Captain’ Savery may have been a military engineer, or the rank may have been an honorary one, but he is almost as mysterious a figure as Newcomen: there is no portrait of him and the date of his birth is unknown. Like Newcomen he came from Devon. What we do know is that on 25 July 1698, the very day that Papin wrote to Leibniz about designing steam ships, Savery was granted a fourteen-year patent on ‘raising water by the impellent force of fire’. The next year the patent was extended for twenty-one more years till 1733 – a rich gift to Savery’s undeserving heirs, as it turned out.

Savery’s machine worked as follows. A copper boiler over a fire sent steam into a water-filled tank called a receiver, where it expelled the water up a brass pipe through a non-return valve. Once the receiver was full of steam, the supply from the boiler was shut off and the receiver was sprayed with cold water, collapsing the steam inside and creating a vacuum. This sucked water up from below through a different pipe, and the cycle began again. In 1699 Savery demonstrated a version at the Royal Society with two receivers, and at some point he seems to have partly automated the mechanism of a combined valve that could fill either receiver, so the thing worked continuously.

In 1702 an advertisement said Savery’s demonstration model could be inspected ‘at his Workhouse in Salisbury Court, London, against the Old Playhouse, where it may be seen working on Wednesdays and Saturdays in every week from 3 to 6 in the afternoon’. He certainly sold some to the nobility, and he installed one at York Buildings, now just off the Strand but then on the banks of the Thames, where London got water from the river, but it was a failure. Mine owners were not interested. It raised water only a short distance, needed far too much coal to fuel it, leaked from its joints and blew up too easily. Failure is often the father of success in innovation.

By 1708 Papin, presumably having crossed the Channel in a conventional sailing craft rather than his own paddle boat, was in London hoping to get support to build his steam boat; we do not know if he met Savery. His hopes of being recognized as the genius of steam in England were quickly dashed. His increasingly desperate letters to Hans Sloane, Sir Isaac Newton's secretary at the Royal Society, fell on deaf ears. That he was a friend of Leibniz hardly helped. Newton's furious feud with Leibniz over who invented the calculus (they both did, but Leibniz's version was neater) was at its height, and no doubt had poisoned poor Papin's reputation by association at the Royal Society. 'There are at least six of my papers that have been read in meetings of the Royal Society and are not mentioned in the Register. Certainly, Sir, I am a sad case,' wrote Papin to Sloane in January 1712.

After that, nothing more is heard from him. He just fades away, and historians assume he must have died that year, too poor to leave a will or a record of burial. Savery would die three years later, less obscurely but hardly a national hero. He left behind one important legacy: his patent on using fire to raise water, which would force Newcomen to partner with Savery's heirs for many years.

So it is that neither of these men of science, wearing their long wigs as they mixed with grandees, managed to change the world. That was left to a humble blacksmith from Dartmouth in Devon, Thomas Newcomen. He was an ironmonger, which in those days meant something more like an engineer or blacksmith, who went into business with a glazier or plumber, John Calley, in 1685. Beyond that we know almost nothing of how he arrived at his fully fledged design of a steam engine in 1712, the year that Papin died.

Over the centuries many historians, reluctant to believe that a humble blacksmith could have succeeded where cerebral professors failed, have postulated ways in which Papin's and Savery's ideas could have reached Newcomen, including a conspiracy theory once popular in France that somebody handed Newcomen some of Papin's letters to Sloane. There is also speculation that he saw a Savery machine in a Cornish tin mine, but none of this has stood up to careful scrutiny, and it remains possible that he knew nothing of the work of the London savants. Indeed, one source insists he was at work on his first designs before 1698, the year of Savery's patent and Papin's letter to Leibniz.

That source, the only one who actually knew Newcomen, was a Swede named Mårten Triewald. He worked with Newcomen and Calley, and then built several early engines in Newcastle before taking the technology back to Sweden. He describes Newcomen as experimenting with steam for a long time before getting a workable machine, and he identifies an accidental breakthrough when the injection of cold water into the cylinder was discovered:

> For ten consecutive years Mr. Newcomen worked at this fire-machine which never would have exhibited the desired effect, unless Almighty God had caused a lucky incident to take place. It happened at the last attempt to make the model work that a more than wished-for effect was suddenly caused by the following strange event. The cold water, which was allowed to flow into a lead-case embracing the cylinder, pierced through an imperfection which had been mended with tin-solder. The heat of the steam caused the tin-solder to melt and thus opened a way for the cold water, which rushed into the cylinder and immediately condensed the steam, creating such a vacuum that the weight, attached to the little beam, which was supposed to represent the weight of the water in the pumps, proved to be so insufficient that the air, which pressed with a tremendous power on the piston, caused its chain to break and the piston to crush the bottom of the cylinder as well as the lid of the small boiler. The hot water which flowed everywhere thus convinced even the very senses of the onlookers that they had discovered an incomparably powerful force which had hitherto been entirely unknown in nature.

Newcomen’s design collapsed the steam in a cylinder by means of this cold-water injection, and it transmitted the energy of the vacuum collapsing under the weight of the atmosphere, via a piston and a beam lever, to a pump, a mechanism safer and stronger than in Savery’s design. It is probable that some full-scale versions were first built in Cornish tin mines, near where Newcomen worked, but no firm evidence has survived. The first working Newcomen engine in the world that we know of for certain was built in 1712 near Dudley Castle in Warwickshire. According to Triewald it could pump ten gallons of water twelve times a minute, lifting the water 150 feet out of the coal mine. An engraving of it by Thomas Barney in 1719 shows the beautiful complexity of the machine in sharp contrast, Rolt argues, to ‘Savery’s crude pump or the scientific toys of Papin’. He goes on: ‘Seldom in the history of technology has so momentous an invention been developed by one man so rapidly to so developed a form.’

Yet at first it was a horribly inefficient device. A Newcomen engine is by today’s standards a monster. The size of a small house, it smokes and clanks and hisses ponderously, wasting about 99 per cent of the energy in its coal fire. It would be decades before the separate condenser of James Watt, the flywheel and drive shaft, and other improvements turned it into something that could be of use in any field other than coal mining, where fuel was cheap.

I have a personal connection to this story. My ancestor, named Nicholas Ridley, got into the mining business around the end of the 1600s. Leaving a farm in the South Tyne Valley in Northumberland he became a partner in a lead-mining business and tried to smelt silver from the lead ore. He then moved to Newcastle and somehow got into coal mining. By the time of his death in 1711 he was a prosperous coal merchant and mine owner on the north bank of the Tyne and mayor of the town, then the third largest in England. His son Richard ran the mines in a buccaneering fashion, gaining a reputation as the 'stormy petrel of the coal trade' for his propensity to get into fights and break price-fixing cartels, even trying to murder a rival at one point, while the second son, Nicholas, seems to have been mostly in London, presumably receiving and marketing the coal. Coal supplied half of England's energy as early as 1700.

The younger Nicholas recruited the teenage Sam Calley, son of Newcomen's partner, John, to come north and build an engine at Byker, probably around 1715 or 1716. This might have been the third or fourth such machine in the world if the engineer John Smeaton is to be believed. The Ridleys paid an enormous £400 a year in royalty to Savery's heirs to be allowed to use this design and laid out around £1,000 on building the first engine. This was to drain a mine whose flooding had ruined two previous owners.

We know this because Nicholas (junior) persuaded Newcomen's friend Mårten Triewald to go north and oversee the youthful Calley. The Swede left an account of his dealings with the Ridley brothers. With the success of the first one, the Ridleys ordered more engines built and by 1733, when the Savery patent expired, there were two at Byker, three at Heaton, one at Jesmond and one at South Gosforth. I like to think that Richard and Nicholas Ridley must have met Newcomen.

The Newcomen steam engine was the mother of the modern world, ushering in an era in which technology could begin to amplify the work of people into fantastic productivity, freeing more and more people from the drudgery of the plough, the scullery and the workhouse. It is a key innovation. Yet the way that it emerged is mysteriously obscure. Was it because of the advance of science in Britain and France, exemplified by Denis Papin? Perhaps a bit, but Newcomen apparently knew nothing of that. Was it because of improvements in metallurgy of the late seventeenth century so that large brass cylinders and pistons could now be built? Partly. Was it because of the dramatic expansion of the coal-mining industry driven by the rising price of wood as British forests shrank, and with it the demand for pumping equipment? To some extent. Was it because of the expansion of trade in north-west Europe, begun by the Dutch and leading to the creation of capital, investment and entrepreneurs? Surely yes, in part. But why did these conditions not come together in China, or Venice, or Egypt, or Bengal, or Amsterdam, or some other trading hub? And why in 1712 rather than 1612 or 1812? Innovation seems so obvious in retrospect but is impossible to predict at the time.

What Watt wrought

In 1763 a skilled and practical Scottish instrument maker, by the name of James Watt, was asked to mend a model Newcomen engine belonging to the University of Glasgow. The thing barely worked. In trying to understand what was wrong, Watt realized something about Newcomen engines in general that should have been spotted much earlier: three-quarters of the energy of the steam was being wasted in reheating the cylinder during each cycle, after it had been cooled with injected water to condense the steam. Watt had the simple idea of using a separate condenser, so that the cylinder could be kept hot, while the steam was drawn off for condensing in a cooler container. At a stroke he had improved the efficiency of the steam engine, though as usual it took months of work to get the metalworking right to make his ideas into practical devices.

After demonstrating the principle in a small test engine, Watt went into partnership with first John Roebuck to acquire a patent, then the entrepreneur Matthew Boulton to build full-scale versions. They unveiled the machine on 8 March 1776, a day before the publication of *The Wealth of Nations*, written by another Scot, Adam Smith. Boulton wanted Watt to develop a method of converting the up-and-down motion of the piston into a circular motion capable of turning a shaft for use in mills and factories. The crank and flywheel had been patented by James Pickard, which stymied Watt for a while and forced him to develop an alternative system, known as the sun-and-planets gear. Pickard in turn had got the idea of the crank from a disloyal and drunken employee of Boulton’s own Soho factory, leaving the origin of this simple device mired in confusion.

Despite this example of patents getting in the way of improvement, as Savery’s had for Newcomen, Watt himself was an enthusiastic defender of his own patents, and Boulton was adept at using his political contacts to acquire long-lasting and broad patents on Watt’s various inventions. Just how much Watt’s litigiousness delayed the expansion of steam as a source of power in factories is a hotly contested issue, but the ending of the main patent in 1800 certainly coincided with a rapid expansion of experiments and applications of steam. Indeed, one source of steady and incremental improvement in the efficiency and penetration of steam engines came as a result of the publication of a journal, *Lean’s Engine Reporter*, founded by a Cornish mining engineer named John Lean, which acted like an open-software movement, disseminating suggestions for improvement among many different engineers. My point is simple: Watt, brilliant inventor though he undoubtedly was, gets too much credit, and the collaborative efforts of many different people too little.

Five years after Watt died in 1819, there was a subscription to build a monument to him, unusual in those days when monuments were mostly to those who won wars. The editors of a journal called *The Chemist* had this to say, rather perceptively: ‘He is distinguished from other public benefactors, by never having made, or pretended to make it his object to benefit the public … This unpretending man in reality conferred more benefit on the world than all those who for centuries have made it their especial business to look after the public welfare.’

Thomas Edison and the invention business

Some time later came an energy innovation that stands symbolically for the whole field of invention: the light bulb. As a patriotic north-easterner, I cannot resist pointing out that one of the light bulb’s innovators lived within a few miles of the River Tyne in Gateshead. His name was Joseph Wilson Swan. It was at the Literary and Philosophical Society in Newcastle on 3 February 1879, in front of an audience of 700 people, that he first demonstrated that he could illuminate a room – for his lecture – with an evacuated glass bulb containing a carbon filament, through which a current passed.

Electricity was already providing light by then, in the form of arc lights. The problem was that it could only be very bright. The ‘subdivision’ of light was the problem Swan was trying to solve, splitting a current into small flows to produce lots of sources of modest light. The realization that a glowing wire or filament did not burn up if electrified in a vacuum was critical. Creating a sufficiently empty vacuum inside blown glass and finding a material that would work reliably as a filament were the two problems Swan was trying to solve. For more than twenty years after his first prototype in 1850 he made only slow progress.

But, hang on, didn’t Thomas Edison invent the light bulb? Yes, he did. But so did Marcellin Jobard in Belgium; and so did William Grove, Fredrick de Moleyns and Warren de la Rue (and Swan) in England. So too did Alexander Lodygin in Russia, Heinrich Göbel in Germany, Jean-Eugène Robert-Houdin in France, Henry Woodward and Matthew Evans in Canada, Hiram Maxim and John Starr in America, and several others. Every single one of these people produced, published or patented the idea of a glowing filament in a bulb of glass, sometimes with a vacuum, sometimes with nitrogen inside the bulb, and all before Thomas Edison.

The truth is that twenty-one different people can lay claim to have independently designed or critically improved incandescent light bulbs by the end of the 1870s, mostly independent of each other, and that is not counting those who invented critical technologies that assisted in the manufacture of light bulbs, such as the Sprengel mercury vacuum pump. Swan was the only one whose work was thorough enough and whose patents were good enough to force Edison to go into business with him. The truth is that the story of the light bulb, far from illustrating the importance of the heroic inventor, turns out to tell the opposite story: of innovation as a gradual, incremental, collective yet inescapably inevitable process. The light bulb emerged inexorably from the combined technologies of the day. It was bound to appear when it did, given the progress of other technologies.

Yet Edison, frankly, deserves his reputation, because although he may not have been the first inventor of most of the ingredients of a light bulb, and although the tale of a sudden eureka breakthrough on 22 October 1879 is largely based on retrospective mythmaking, he was none the less the first to bring everything together, to combine it with a system of generating and distributing electricity, and thereby to mount the first workable challenge to the incumbent technologies of the oil lamp and the gas lamp. So much more impressive, all told, than a blinding flash of inspiration, but vanity, vanity: people prefer to be thought brilliant rather than merely hard-working. Edison was also the one who made light bulbs (almost) reliable. Having hubristically claimed to have made a light bulb that would reliably last a long time before failing, he began a frantic search to prove his boast true. This is known today in Silicon Valley as ‘fake it till you make it’. He tested more than 6,000 plant materials in his bid to try to find the ideal material for making a carbon filament. ‘Somewhere in God Almighty’s workshop,’ Edison pleaded, ‘there is a vegetable growth with geometrically powerful fibers suitable to our use.’ On 2 August 1880 Japanese bamboo was the eventual winner, proving capable of lasting more than 1,000 hours.

Thomas Edison understood better than anybody before, and many since, that innovation is itself a product, the manufacturing of which is a team effort requiring trial and error. Starting his career in the telegraph industry and diversifying into stock-ticker machines, he then set up a laboratory in Menlo Park, New Jersey, in 1876, to do what he called ‘the invention business’, later moving to an even bigger outfit in West Orange. He assembled a team of 200 skilled craftsmen and scientists and worked them ruthlessly hard. He waged a long war against his former employee Nikola Tesla’s invention of alternating-current electricity for no better reason than that Tesla had invented it rather than he. Edison’s approach worked: within six years he had registered 400 patents. He remained relentlessly focused on finding out what the world needed and then inventing ways of meeting the needs, rather than the other way around. The method of invention was always trial and error. In developing the nickel-iron battery his employees undertook 50,000 experiments. He stuffed his workshops with every kind of material, tool and book. Invention, he famously said, is 1 per cent inspiration and 99 per cent perspiration. Yet in effect what he was doing was not invention, so much as innovation: turning ideas into practical, reliable and affordable reality.

And yet for all the gradual nature of the innovation of the light bulb, the result was a disruptive and transformational change in the way people lived. Artificial light is one of the greatest gifts of civilization, and it was the light bulb that made it cheap. A minute of work in 1880 on the average wage could earn you four minutes of light from a kerosene lamp; a minute of work in 1950 could earn you more than seven hours of light from an incandescent bulb; in 2000, 120 hours. Artificial light had come within the reach of ordinary people for the first time, banishing the gloom of winter, while expanding the opportunity to read and learn, plus incidentally reducing fire risk. There was no significant downside to such innovation.

The incandescent bulb reigned supreme for more than a century, being still the dominant form of lighting, at least in domestic settings, well into the first decade of the twenty-first century. When it gave way to a new technology, it did so under duress. That is to say, it had to be banned, because its replacement was so unpopular. The decision by governments all over the world around 2010, lobbied by the makers of compact fluorescent bulbs, to ‘phase out’ incandescents by fiat in the interest of cutting carbon dioxide emissions, proved to be a foolish one. The compact fluorescent replacements took too long to warm up, did not last as long as advertised and were hazardous to dispose of. They were also much more expensive. Their energy-saving did not make up for these drawbacks in most consumers’ eyes, so they had to be forced on to the market. The cost to Britain alone, of this coerced purchase and the subsidy that accompanied it, has been estimated at about £2.75bn.

Worst of all, had governments waited a few more years, they would have found a far better replacement coming along that was even more frugal in energy and had none of the disadvantages: light-emitting diodes, or LEDs. The reign of the compact fluorescents lasted just six years before they too were rapidly abandoned and manufacturers stopped producing them because of the falling cost and rising quality of LEDs. It is as if the government in 1900 had forced people to buy steam cars instead of waiting for better internal-combustion vehicles. The whole compact fluorescent light bulb episode is an object lesson in misinnovation by government. As the economist Don Boudreaux put it: ‘Any legislation forcing Americans to switch from using one type of bulb to another is inevitably the product of a horrid mix of interest-group politics with reckless symbolism designed to placate an electorate that increasingly believes that the sky is falling.’

LED lights have actually been waiting in the wings for a long time. The phenomenon behind them, that semiconductors sometimes glow when conducting electricity, was first observed in 1907 in Britain and first investigated in 1927 in Russia. In 1962 a General Electric scientist named Nick Holonyak stumbled on how to make bright red LEDs of gallium arsenide phosphide, while trying to develop a new kind of laser. Yellow ones soon followed from a Monsanto lab, and by the 1980s LEDs were in watches, traffic lights and circuit boards. But until Shuji Nakamura, working for Nichia in Japan, developed a blue LED using gallium nitride in 1993, it proved impossible to make white light, which kept LED lights from mainstream lighting.

Even then it took twenty years to bring the price of this solid-state lighting down to reasonable levels. Now that has happened, however, the implications are remarkable. LED lights use so little power that a house can be well lit while not on the grid, perhaps using solar panels, a valuable opportunity for remote properties in poor countries. They have put bright flashlights inside smartphones. They emit so little heat that they make indoor ‘vertical’ farming of lettuces and herbs possible on a grand scale, especially using tunable LEDs to produce the wavelengths best suited to photosynthesis.

The ubiquitous turbine

If Newcomen was from humble origins, poor and illiterate in his younger days, the same cannot be said of another key name in the story of steam. Charles Parsons was the sixth son of the wealthy Earl of Rosse, an Irish peer. He was born and raised at Birr Castle in County Offaly, Ireland, and given private tuition in place of school before going up to Cambridge University to read mathematics.

But this was no typical aristocratic household. The earl was an astronomer and engineer. He encouraged his sons to spend time in his workshops rather than libraries. Charles and his brother built a steam engine with which to provide the power for grinding the reflector on his father’s telescope. When he left university it was not for a comfortable berth in the law, politics or finance, but for an apprenticeship in an engineering firm on the Tyne. He proved a brilliant engineer and in 1884 he designed and patented the steam turbine that would prove to be, with very few modifications, the indispensable machine that gave the world electricity and that powered the navies and liners of the sea and later the jets of the air. To this day, it is basically Parsons’s design that keeps the lights on, navies afloat and airliners aloft.

A turbine is a device that spins on its axis. There are two ways to use steam (or water) to make something turn: impulse or reaction. Directing the steam from a fixed nozzle at buckets on a wheel will turn that wheel; and squirting the steam at an angle out of nozzles on the outsides of a wheel itself will also turn the wheel. A spinning sphere driven by steam shooting out of two angled nozzles had been built as a toy by Hero of Alexandria in the first century AD. Parsons concluded early on that impulse turbines were inefficient and stressful to the metal. He realized too that a series of turbines, each turned by some of the steam, would gather more of the energy more efficiently. He redesigned dynamos to generate electricity from turbines and within a few years the first electric grids were being built with larger and larger Parsons turbines.

Parsons set up his own company but had to leave behind the intellectual property in his original designs, and he spent five years trying to build radial-flow turbines before he was able to revert to parallel-axial-flow turbines. He tried and failed to interest the Admiralty in the devices as a way of powering ships. So in 1897 he sprang a cheeky surprise on the Royal Navy.

Parsons, who was fond of boats and yachting, had made a sleek little ship, *Turbinia*, powered by steam turbines turning a screw propeller. The first results were disappointing, mainly because of the propeller, which caused ‘cavitation’ in the water – small vacuum pockets behind the screw blades that wasted energy. Parsons and Christopher Leyland went back to the laboratory, trying many designs to find one that might solve the cavitation problem. It was trial and error. They stayed up all night at times and were still at the water tank when the housemaids arrived in the morning. It was frustrating work, but by 1897 Parsons had replaced the single radial-flow turbine with three axial-flow ones, and the single propeller shaft with three shafts, each armed with three screws. He knew by now, from sea trials, that his little craft, with nine propellers, could achieve 34 knots, much faster than any ship of the time. He even gave a public talk about it in April 1897, which the *Times* newspaper reported, concluding dismissively that turbine technology was ‘in a purely experimental, perhaps almost in an embryo stage’ as far as ships were concerned. How wrong they were.

As the Grand Fleet assembled at Spithead on 26 June in the presence of the Prince of Wales, to mark the Diamond Jubilee of Queen Victoria, Parsons was planning an audacious stunt. Over 140 ships were drawn up in four lines over twenty-five miles long in all. Between them steamed a royal procession of ships: *Victoria and Albert*, carrying the Prince of Wales, the P&O liner *Carthage*, with other royal guests aboard, *Enchantress*, with the Lords of the Admiralty, *Danube*, with members of the House of Lords, *Wildfire*, with colonial prime ministers, the Cunard liner *Campania*, with members of the House of Commons, and finally *Eldorado*, carrying foreign ambassadors. A line of invited foreign battleships included the *König Wilhelm* with Prince Henry of Prussia aboard.

Defying the rules and evading the fast steam boats on picket duty, Parsons took *Turbinia* between the ranks of battleships at full speed and then steamed up and down in front of the grandees, pursued in vain by Royal Navy vessels, one of which almost collided with the little greyhound of the sea. It was a sensation. With surprisingly little umbrage – it helped that the Germans were there to witness the episode, and Prince Henry of Prussia took care to send a congratulatory message to Parsons – the Navy took the hint and by 1905 had determined that all future warships would be turbine-powered. HMS *Dreadnought* was the first. In 1907, the vast liner *Mauretania*, powered by Parsons turbines, was photographed alongside her little predecessor, *Turbinia*.

The Spithead moment is in some ways misleading. The history of turbines and electricity is profoundly gradual, not marked by any sudden step changes. Parsons was just one of many people along the path who incrementally devised and improved the machines that made electricity and power. It was an evolution, not a series of revolutions. The key inventions along the way each built upon the previous one and made the next one possible. Alessandro Volta made the first battery in 1800; Humphry Davy made the first arc lamp in 1808; Hans Christian Oersted made the connection between electricity and magnetism in 1820; Michael Faraday and Joseph Henry made the first electric motor in 1820 and its opposite, the first generator, in 1831. Hippolyte Pixii made the first dynamo in 1832; Samuel Varley, Werner von Siemens and Charles Wheatstone all came up with the full dynamo-electric generator in 1867; Zénobe Gramme turned this into a direct-current generator in 1870.

Parsons’s turbine was about 2 per cent efficient at turning the energy of a coal fire into electricity. Today a modern combined-cycle gas turbine is about 60 per cent efficient. A graph of the progress between the two shows a steady improvement with no step changes. By 1910, using waste heat to preheat the water and the air, engineers had improved the efficiency to 15 per cent. By 1940, with pulverized coal, steam reheating and higher temperatures, it was nearer 30 per cent. In the 1960s, as the combined-cycle generator effectively brought a version of the turbojet engine in alongside the steam turbine, potential efficiency had almost doubled again. To single out clever people who made the difference along the way is both difficult and misleading. This was a collaborative effort of many brains. Long after the key technologies had been ‘invented’, innovation continued.

Nuclear power and the phenomenon of disinnovation

The twentieth century saw only one innovative source of energy on any scale: nuclear power. (Wind and solar, though much improved and with a promising future, still supply less than 2 per cent of global energy.) In terms of its energy density, nuclear is without equal: an object the size of a suitcase, suitably plumbed in, can power a town or an aircraft carrier almost indefinitely. The development of civil nuclear power was a triumph of applied science, the trail leading from the discovery of nuclear fission and the chain reaction through the Manhattan Project’s conversion of a theory into a bomb, to the gradual engineering of a controlled nuclear fission reaction and its application to boiling water. No individual stands out in such a story unless it be Leo Szilard’s early realization of the potential of a chain reaction in 1933, General Leslie Groves’s leadership of the Manhattan Project in the 1940s, or Admiral Hyman Rickover’s development of the first nuclear reactors and their adaptation to submarines and aircraft carriers in the 1950s. But as these names illustrate, it was a team effort within the military and state-owned enterprises, plus private contractors, and by the 1960s it had culminated in a huge programme of constructing plants that would use small amounts of enriched uranium to boil enormous amounts of water reliably, continuously and safely all over the world.

Yet today the picture is of an industry in decline, its electrical output shrinking as old plants close faster than new ones open, and an innovation whose time has passed, or a technology that has stalled. This is not for lack of ideas, but for a very different reason: lack of opportunity to experiment. The story of nuclear power is a cautionary tale of how innovation falters, and even goes backwards, if it cannot evolve.

The problem is cost inflation. Nuclear plants have seen their costs relentlessly rising for decades, mostly because of increasing caution about safety. And the industry remains insulated almost entirely from the one known human process that reliably pulls down costs: trial and error. Because error could be so cataclysmic in the case of nuclear power, and because trials are so gigantically costly, nuclear power cannot get trial and error restarted. So we are stuck with an immature and inefficient version of the technology, the pressurized-water reactor, and that is gradually being strangled by the requirements of regulators acting on behalf of worried people reacting to anti-nuclear activists. Also, technologies pushed on the world by governments, before they are really ready, sometimes falter, where they might have done better if allowed to progress a little more slowly. The transcontinental railroads in the United States were all failures, resulting in bankruptcies, except the one privately funded one. One cannot help thinking that nuclear power developed in less of a hurry, and less as a result of a military spin-off, might have done better.

In a book published in 1990, *The Nuclear Energy Option*, the nuclear physicist Bernard Cohen argued that the reason we stopped building nuclear plants in the 1980s in most of the West was not from fear of accidents, leaks or the proliferation of atomic waste; it was instead the inexorable escalation of costs driven by regulation. His diagnosis has proved even more true since.

This is not for want of ideas for new kinds of nuclear power. There are hundreds of different designs for fission reactors out there in engineers' PowerPoint presentations, some of which have reached working-prototype design in the past and would have gone further if offered as much financial support as the conventional light-water reactor. Liquid-metal and liquid-salt reactors are two broad categories. The latter would work using salts of thorium or uranium fluoride, probably with other elements included such as lithium, beryllium, zirconium or sodium. The key advantage of such a design is that the fuel comes in liquid form, rather than as a solid rod, so cooling is more even and the removal of waste easier. There is no need to operate at high pressure, reducing the risks. The molten salt is the coolant as well as the fuel and has the neat property that the reaction slows down as it gets hotter, making meltdown impossible. In addition, the design would include a plug that would melt above a certain temperature, draining the fuel into a chamber where it would cease fission, a second safety system. Compared with, say, Chernobyl, this is dramatically safer.

Thorium is more abundant than uranium; it can in effect breed almost indefinitely by creating uranium 233; it can generate almost 100 times as much power from the same quantity of fuel; it does not give rise to fissile plutonium; it generates less waste with a shorter half-life. But although a submarine with sodium coolant was launched in the 1950s and two experimental thorium molten-salt reactors were built in the 1960s in the United States, the project eventually expired as all the money, training and interest focused on the light-water uranium design. Various countries are looking at how to reverse this decision, but none has really taken the plunge.

Even if they did, it seems unlikely that they would achieve the notorious promise made in the 1960s that nuclear power would one day be 'too cheap to meter’. The problem is simply that nuclear power is a technology ill-suited to the most critical of innovation practices: learning by doing. Because each power station is so big and expensive, it has proved impossible to drive down the cost by experiment. Even changing the design halfway through construction is impossible because of the immense regulatory thicket that each design must pass through before construction. You must design the thing in advance and stick to that design or go back to square one. This way of doing things would fail to bring down costs and raise performance in any technology. It would leave computer chips at the 1960 stage. We build nuclear power stations like Egyptian pyramids, as one-off projects.

Following the Three-Mile Island accident in 1979, and Chernobyl in 1986, activists and the public demanded greater safety standards. They got them. According to one estimate, per unit of power, coal kills nearly 2,000 times as many people as nuclear; bioenergy fifty times; gas forty times; hydro fifteen times; solar five times (people fall off roofs installing panels) and even wind power kills nearly twice as many as nuclear. These numbers include the accidents at Chernobyl and Fukushima. Extra safety requirements have simply turned nuclear power from a very, very safe system into a very, very, very safe system.

Or maybe they have made it less safe. Consider the Fukushima disaster of 2011. The design at Fukushima had huge safety flaws. Its pumps were in a basement easily flooded by a tidal wave, a simple design mistake unlikely to be repeated in a more modern design. It was an old reactor and would have been phased out long since if Japan had still been building new nuclear reactors. The stifling of nuclear expansion and innovation through costly over-regulation had kept Fukushima open past its due date, thus lowering the safety of the system.

The extra safety demanded by regulators has come at high cost. The labour that goes into the construction of a nuclear plant has hugely increased, but mostly in the white-collar jobs, signing off paperwork. According to one study, during the 1970s new regulations increased the quantity of steel per megawatt by 41 per cent, concrete by 27 per cent, piping by 50 per cent and electrical cable by 36 per cent. Indeed, as the ratchet of regulation turned, the projects began to add features to anticipate rule changes that sometimes did not even happen. Crucially this regulatory environment forced the builders of nuclear plants to drop the practice of on-the-spot innovation to solve unanticipated problems, lest it lead to regulatory resets, which further drove up cost.

The answer, of course, is to make nuclear power into a modular system, with small, factory-built reactor units produced off production lines in large quantities and installed like eggs in a crate at the site of each power station. This would drive down costs as it did for the Model T Ford. The problem is that it takes three years to certify a new reactor design, and there is little or no short-cut for a smaller one, so the cost of certification falls more heavily on a smaller design.

Meanwhile, it is now likely that nuclear fusion, the process of releasing energy from the fusion of hydrogen atoms to form helium atoms, may at last fulfil its promise and begin to provide almost unlimited energy within the next few decades. The discovery of so-called high-temperature superconductors and the design of so-called spherical tokamaks have probably at last defused the old joke that fusion power is thirty years away – and has been for thirty years. Fusion may now come to commercial fruition, in the form of many relatively small reactors generating electricity, maybe 400 megawatts each. It is a technology that brings almost no risk of explosion or meltdown, very little in the way of radioactive waste and no worries about providing material for weapons. Its fuel is mainly hydrogen, which it can make with its own electricity from water, so its footprint on the earth will be small. The main problem fusion will still have to solve, as with nuclear fission, is how to drive down the cost by mass production of the reactors, with the ability to redesign from experience along the way so as to learn cost-cutting lessons.

Shale gas surprise

One of the most surprising stories of the twenty-first century has been the rise of natural gas, a fuel that just a decade ago was thought to be on the brink of running out and is now both cheap and plentiful. It is mainly the story of the innovation that led to the production of gas from shale. Right up till 2008 or so, it was conventional wisdom among energy experts that cheap natural-gas supplies would be exhausted to all practical extent fairly early in the twenty-first century. Oil and coal would last longer. This prediction had been made before, repeatedly. In 1922 the US Coal Commission, set up by President Warren Harding, interviewed 500 people in the energy industry over eleven months, and came to the conclusion that ‘already the output of gas has begun to wane’. In 1956 the oil expert M. King Hubbert predicted that natural-gas production in the United States would peak in 1970 at 38 billion cubic feet per day and decline. In fact it was 58 bcf a day then and still rising. Today it is over 80 bcf per day.

These predictions proved gloriously wrong, for two reasons. First, in America, strict price regulation of gas in the 1970s, based on the theory that it was scarce, effectively halted gas exploration in its tracks. Companies flared off or shut down gas as a nuisance, and pursued oil instead. This did indeed produce a peak in production which many mistook for the beginning of exhaustion of reserves. Incredibly, the US government passed several measures in the 1970s to forbid the generation of electricity by oil or gas in any utility that could get access to coal, and forbade the building of plants that could not use coal. Deregulation of the gas industry under President Reagan led to a surge in production.

The second reason for the gas glut of the second decade of the twenty-first century was innovation. Throughout the United States, gas and oil exploration companies set out to find ways to squeeze more out of each field, and to squeeze gas and oil out of 'tight' rocks, whence it did not flow naturally. This resulted in the serendipitous discovery of 'slick-water' hydraulic fracturing in the 1990s in Texas, which, combined with the new ability to drill round corners, and thus go horizontally within seams of rock for miles on end, made tight shales, where most hydrocarbons are stored, into huge sources of gas and oil. Add in offshore gas, plus the ability to liquefy gas for transport by sea, and it becomes clear why the world now has ample supplies of gas, the cleanest, lowest-carbon and safest of the fossil fuels.

The key location of the slick-water fracking breakthrough was the Barnett shale near Fort Worth, where an entrepreneur named George Mitchell, born to a Greek goatherd father, had grown rich supplying Chicago with gas. He had a good fixed-price contract. If he moved elsewhere he would have to drop his price. So he was desperate to squeeze more from the Barnett shale, where he had lots of drilling rights. By the late 1990s output was dropping, and so was Mitchell Energy's share price, which was causing Mitchell personal difficulties, because of commitments he had made to philanthropy, backed by loans against his shares. His wife had Alzheimer's and he had prostate problems. By rights the 78-year-old multimillionaire should have been reasonable, should have given up on America as the oil majors were already doing, and cut his losses. The future of gas lay offshore, or in Russia and Qatar. But Mitchell, like many innovators, was not reasonable, so he kept trying to get the gas to flow.

The Barnett shale was known to be rich in hydrocarbons, but they would not flow easily, so the rock needed to be cracked deep underground, and the microscopic cracks propped open. A technology to do this was well known, and relied on gels to prop open the cracks and let the gas out. It worked well in some rocks but not in shale. Mitchell sank $250m into trying to make it work in the Barnett field without success.

One day in 1996 a Mitchell employee named Nick Steinsberger noticed an odd result. He was employing contractors to pump a stiff gel with large amounts of sand in it down the well. But since gel and sand were expensive, he had been forcing the service companies to lower the amount of gel and chemicals in the mixture pumped down the hole in an attempt to lower costs and pump less of the viscous material into the shale. On this day, the gel was so dilute it would not 'gel' properly. Steinsberger pumped it down the hole anyway and noticed the well produced a decent surge of gas. He tried some more wells with similar results. Attending a baseball game with a friend from another company, Mike Mayerhofer, he heard a similar story – water with a little lubricant and much less sand was working well in a different kind of rock, in this case tight sandstone in east Texas.

So in 1997 Steinsberger then began deliberately using a more watery liquid, basically water mixed with less sand and a very small quantity of ordinary kitchen sink chemicals (bleach and soap, essentially), instead of gel. He tried this on three wells, but it did not work. 'The pressure went up too high, forcing me to terminate the pump job, because the slickwater wouldn't carry the sand in shale like it would in much more permeable tight sands.' In early 1998, getting pretty desperate and with his bosses ready to give up on the Barnett shale, he convinced management to let him try three more wells. This time he pumped a lot more slick water but increased the sand from extremely low concentrations to higher over the course of the job. The first well, S. H. Griffin Estate 4, produced a surge of gas and kept on doing so for weeks and months. He realized he had stumbled on a formula that was not just half as expensive, but twice as productive. A flash in the pan? No, the other two wells had similar results.

Steinsberger's breakthrough transformed the last years of George Mitchell's life, turning him into a billionaire when he sold his company. It turned the Barnett shale into America's largest gas producer. Copied elsewhere, and steadily improved by further innovation, it had the same effect in shale after shale, in Louisiana, Pennsylvania, Arkansas, North Dakota, Colorado, then Texas again. Soon the same technique was being adapted to get oil out as well. Today America is not only the world's biggest producer of gas; it is also the world's biggest producer of crude oil, thanks entirely to the shale-fracking revolution. The Permian basin in Texas alone now produces as much oil as the whole of the United States did in 2008, and more than any OPEC country except Iran and Saudi Arabia. America was building huge gas import terminals in the early 2000s; these have now been converted into export terminals. Cheap gas has displaced coal in the country's electricity sector, reducing its emissions faster than any other country. It has undermined OPEC and Russia, leaving the latter frantically supporting anti-fracking activists to try to defend its markets – with much success in innovation-phobic Europe, where shale exploitation has been largely prevented.

A cheap-gas, cheap-oil glut brought on deliberately by OPEC in 2015 to try to bust the frackers had the opposite effect, killing weaker companies but forcing the survivors to work out how to remain competitive at sixty, fifty and forty dollars per barrel of oil. The availability of cheap hydrocarbons gave American manufacturing an edge, resulting in a rapid 'reshoring' of chemical industries to the United States and a surge of chemical companies leaving Europe. The energy policies of a dozen countries like Britain, predicated on ever-rising fossil-fuel energy prices to make wind and nuclear look less expensive, became expensive follies almost overnight.

Why did this revolution happen in America, an old, played-out and well-explored oil and gas region? The answer lies partly in property rights. Because of mineral rights belonging to local landowners, rather than the state, and because oil companies had never been nationalized, as they were in so many other countries, from Mexico to Iran, America had a competitive, pluralistic and entrepreneurial oil-drilling mindset, manifested in a 'wild-cat' industry, backed by deep pockets of risk capital – the early frackers spent vast sums of borrowed money before turning cash-positive. As one account of the story by the key innovators put it:

> Small companies often have the upper hand in leasing mineral rights from landowners as their interaction with landowners is generally more personalized. Shale production was hotly pursued by many small companies resulting in a multitude of varied drilling and completion methods being implemented and tested across multiple basins. These 'laboratories' have resulted in continuous improvements and fostered economic success.

So trial and error was vital to innovation in fracking. Steinsberger made a series of lucky mistakes, failing many times along the way. And when he had found the formula, he did not know why it worked. A seismology expert, Chris Wright, soon explained it. Wright, an engineer whose company, Pinnacle, was using new tiltmeter devices to help track the progress of fractures underground for Mitchell, figured out that slick-water fracs created large networks of multiple fractures. He had developed a model of simultaneous growth of multiple fractures in the early 1990s 'which was widely derided by all the old-timers in the frac world as they insisted multiple fracs would always rapidly coalesce into a single frac'. It turned out Wright was right. The pressurized water was creating cross-cutting fractures in the rocks, greatly increasing the surface area exposed to the sand. Fractures were propagating a mile or more in one direction, but spreading hundreds of metres either side of this axis too. In this case science came in behind the technology, rather than vice versa. Recent attempts to credit the federal government with starting this innovation mostly miss the point. Yes, lots of research was done at government laboratories, but much of it under contract to the gas industry, and largely because there were entrepreneurs like Mitchell and Wright (now one of the industry leaders) creating the demand for such research.

At first environmentalists welcomed the shale gas revolution. In 2011 Senator Tim Wirth and John Podesta welcomed gas as ‘the cleanest fossil fuel’, writing that fracking ‘creates an unprecedented opportunity to use gas as a bridge fuel to a 21st-century energy economy that relies on efficiency, renewable sources, and low-carbon fossil fuels such as natural gas’. Robert Kennedy, Jr, head of the Waterkeeper Alliance, wrote in the *Financial Times* that ‘In the short term, natural gas is an obvious bridge fuel to the “new” energy economy.’ But then it became clear that this cheap gas would mean the bridge was long, posing a threat to the viability of the renewable-energy industry. Self-interest demanded a retraction by Kennedy, which he duly provided, calling shale gas a ‘catastrophe’.

In the heartlands where fracking began, Texas, Louisiana, Arkansas and North Dakota, there was little opposition. A lot of empty land, a long tradition of oil drilling and a culture of can-do enterprise ensured that the shale revolution prospered unhindered by much if any local protest. But when it spread to the East Coast, to Pennsylvania and then New York, suddenly shale gas began to attract enemies, and environmentalists spotted an opportunity to fund-raise on the back of opposition. Recruiting some high-profile stars, including Hollywood actors such as Mark Ruffalo and Matt Damon, the bandwagon gathered pace. Accusations of poisoned water supplies, leaking pipes, contaminated waste water, radioactivity, earthquakes and extra traffic multiplied. Just as the early opponents of the railways accused trains of causing horses to abort their foals, so no charge was too absurd to level against the shale gas industry. As each scare was knocked on the head, a new one was raised. Yet despite millions of ‘frac jobs’ in thousands of wells, there were very few and minor environmental or health problems.

The reign of fire

One of the flaws in the way we recount stories of innovation is that we unfairly single out individuals, ignoring the contribution of lesser mortals. I have chosen to tell the stories of Newcomen, Watt, Edison, Swan, Parsons and Steinsberger, but they were all stones in an arch or links in a chain. And not all of them ended up wealthy, let alone their descendants. There is no foundation named after any of them today and funded by their wealth. It was the rest of us who reaped most of the benefit of their innovations.

Yet energy itself does deserve to be singled out. It is the root of all innovation if only because innovation is change and change requires energy. Energy transitions are crucial, difficult and slow. For the vast majority of history, argues John Constable, the supply of energy, from wheat and wind and water, was just too thin to generate complex structures on a sufficient scale to transform people's lives. Along came the heat-to-work transition of 1700 and suddenly it became possible to create ever more improbable and complex material structures from the harnessing of fossil fuels with their huge energy yield on energy invested. The fossil-fuel dependence of the modern world is roughly the same today – at about 85 per cent of primary energy – as it was twenty years ago. The vast majority of society's need for energy is supplied by heat. What will eventually depose the 'impellent use of fire', that strange link between heat and work that came into the lives of humanity around the year 1700 and is still vital to the world? Nobody yet knows.

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Public health

> An operation invented not by persons conversant in philosophy or skilled in physic, but by a vulgar, illiterate people; an operation in the highest degree beneficial to the human race.
>
> GIACOMO PYLARINI on smallpox inoculation, 1701

Lady Mary's dangerous obsession

In the same year that Thomas Newcomen was building his first steam engine, 1712, and not far away, a more romantic episode was in train, and one that would indirectly save even more lives. It was much higher up the social scale. Lady Mary Pierrepoint, a well-read, headstrong young woman of twenty-three, was preparing to elope in order to escape the prospect of a dull marriage. Her wealthy suitor, Edward Wortley Montagu, with whom she had carried on a voluminous correspondence characterized by furious disagreement as well as outrageous flirtation, had failed to agree a marriage settlement with her even wealthier father, the Earl (later Duke) of Kingston. But the prospect of being forced by her father to marry instead a pecunious dullard, the Honourable Clotworthy Skeffington, persuaded Mary to rekindle the romance with Wortley (as she called him). She proposed elopement, and he, despite thus missing out on her dowry, and in a fit of uncharacteristic impetuosity, agreed. The episode turned to farce: he was late, she set off for the rendezvous alone, he overtook her at an inn but did not realize she was there, but after further mishaps they found each other and married on 15 October 1712 in Salisbury.

After this romantic start the marriage was a disappointment, Wortley proving a cold and unimaginative husband. His bride – learned, eloquent and witty – cut a swathe through literary London, writing eclogues with Alexander Pope in the style of Virgil, and befriending the literary lions and social tigers of the day. Joseph Spence would later write: 'Lady Mary is one of the most extraordinary shining characters in the world; but she shines like a comet; she is all irregular