Innovation's essentials

> Liberty is the parent of science and of
> virtue, and a nation will be great in both
> in proportion as it is free.
>
> THOMAS JEFFERSON

Innovation is gradual

The history of innovation, laid out in the stories I have told here, reveals some surprisingly consistent patterns. Whether it happened yesterday or two centuries ago, whether it was high technology or low, whether it was a big device or a tiny one, whether real or virtual, whether its impact was disruptive or just helpful, a successful innovation usually
follows roughly the same path.

For a start, innovation is nearly always a gradual, not a sudden thing. Eureka moments are rare, possibly non-existent, and where they are celebrated it is with the help of big dollops of hindsight and long stretches of prepar-ation, not to mention multiple wrong turns along the way. Archimedes almost certainly did not leap out of his bath, shouting 'Heureka'; he probably invented the story afterwards to entertain people.

You can tell the story of the computer in lots of ways, starting with Jacquard looms or starting with vacuum tubes, starting with theory or starting with practice. But the deeper you look, the less likely you are to find a moment of sudden breakthrough, rather than a series of small incremental steps. There is no day when you can say: computers did not exist the day before and did the day after, any more than you could say that one ape-person was an ape and her daughter was a person.

That is why it is possible to tell the stories of unconscious, 'natural' innovation such as fire, stone tools and the origin of life itself as part of a continuum with modern technological inventions. They are essentially the same phenomenon: evolution. In the case of the motor car, the closer you look, the more the early versions look like older versions of preceding technologies, like carriages, steam engines and bicycles, reminding us that, with very few exceptions, man-made technologies evolve from previous man-made technologies, and are not invented from scratch. This is a key characteristic of evolutionary systems: the move to the 'adjacent possible' step.

Perhaps I am exaggerating. After all, there was a moment when the Wright brothers' flier became airborne, on 17 December 1903. Surely this was a sudden, breakthrough moment? No, far from it. Once you know the story, nothing could be more gradual. The flight that day lasted for a few seconds. It was barely more than a hop. It would not have been possible without a stiff head wind and it was preceded by a failed attempt. It came after several years of hard slog, experiment and learning, in which very gradually all the pieces necessary for powered flight came together. Lawrence Hargreaves, an early Australian aviation experimenter, wrote in 1893 that his fellow enthusiasts must root out the idea that by 'keeping the results of their labours to themselves, a fortune will be assured them'. The genius of the Wright brothers was precisely that they realized they were in an incremental, iterative process and did not expect to build a flying machine at the first attempt. And the Kitty Hawk moment came before several more years of hard slog, tinkering and retinkering, till the Wrights knew how to keep a plane aloft for hours, how to lift off without a head wind, how to turn and how to land. The closer you examine the history of the aeroplane, the more gradual it looks. Indeed, the moment of lift-off itself is gradual, as the weight on the wheels gradually declines.

This is true of every invention and innovation I have looked at in this book so far, and of many that I have not. It is the same with the double helix, a discovery with what looks like a clear 'eureka moment' on 28 February 1953 when Jim Watson suddenly saw that the two base pairs had the same shape, Francis Crick realized that this explained the strands running in opposite directions, and they both saw how a linear digital code must lie at the heart of life. But, as Gareth Williams has written in his book on the prehistory of this work, *The Unravelling of the Double Helix*: 'this was just one episode in a long, grumbling crescendo of discovery.'

Oral rehydration therapy, the medical innovation that has saved more lives in recent decades than any other, is another good example. Some time in the 1970s in Bangladesh a number of doctors began using solutions of sugar and salt to stop children dying of diarrhoea-induced dehydration. Superficially, it looks like a sudden innovation. But the closer you examine the history, the more you find earlier experiments with the idea, in the Philippines in the 1960s, which themselves built upon rat experiments in the 1950s, and gradual improvements in intravenous rehydration therapy in the 1940s.

True, there followed something of an experimental breakthrough in 1967 when scientists at the Cholera Research Laboratory in Dacca (now Dhaka) in East Pakistan (now Bangladesh), led by Dr David Nalin, realized that adding glucose to a salty mixture improved the retention of sodium, but arguably they were only rediscovering the hints of studies in earlier years and testing them at scale. Similar results from Calcutta around the same time confirmed the finding. Even then the Dacca laboratory was slow to push the idea on physicians and aid workers. Some experts concluded that oral rehydration could help a little but was not a substitute for intravenous rehydration, and the conventional wisdom was that this must be accompanied by starving the gut. And when a plan to try oral rehydration in rural East Pakistan (where intravenous was not practical) was mooted in 1968, it met strong opposition from the very scientist who had first found the effect of glucose in the Philippines, Robert Philips. By the early 1970s, especially during the Bangladesh war of independence, oral rehydration therapy proved its worth as by far the best treatment for cholera and other diarrhoeas, and the innovation had arrived.

If innovation is a gradual, evolutionary process, why is it so often described in terms of revolutions, heroic breakthroughs and sudden enlightenment? Two answers: human nature and the intellectual property system. As I have shown repeatedly in this book, it is all too easy and all too tempting for whoever makes a breakthrough to magnify its importance, forget about rivals and predecessors, and ignore successors who make the breakthrough into a practical proposition.

The laurels that garland the forehead of a true 'in- ventor' are irresistible. But it is not just the inventor who likes to portray innovation as sudden and world-changing. So do journalists and biographers. In fact, very few people, not even the furiously disappointed rival who just failed to beat the inventor to it, have much incentive to argue that invention and innovation are gradual. As I discussed in The Evolution of Everything, this is, of course, a version of the 'great man' theory of history, namely that history happens because particular chiefs, priests and thieves make it happen that way. It's mostly untrue of history in general, and of the history of innovation in particular. Most people want to think they have more control over their lives than is objectively the case: the idea of decisive and discontinuous human agency is both flattering and comforting.

Nationalism exacerbates the problem. All too often, the importing of a new idea gets confused with the inventing of a new idea. Fibonacci did not invent zero, and nor did Al Khwarizmi and the other Arabs that he borrowed it from. The Indians did. Lady Mary Wortley Montagu did not invent inoculation, and probably nor did the Ottoman doctors she learned it from.

But it is the existence of patents that makes the problem of the heroic inventor worse. Again and again, I have docu-mented in this book how innovators wrecked their lives battling to establish or defend patents on their innovations.

Samuel Morse, Guglielmo Marconi and many others tied themselves up in courts for years trying to rebut challenges to their priority. In some cases, the establishing of a patent that was too broadly drawn then deterred further innovation. This was the case with Captain Savery's patent on the use of fire to raise water, which caught Newcomen's steam engine, or Watt's patents on high-pressure steam, which slowed down improvements for some decades. I shall return in a later chapter to the point that intellectual property is now a hindrance not a help to modern innovation.

Innovation is different from invention

Charles Townes, who won the Nobel Prize for the physics behind the laser in 1964, was fond of quoting an old cartoon. It shows a beaver and a rabbit looking up at the Hoover dam: 'No, I didn't build it myself,' says the beaver. 'But it's based on an idea of mine.' All too often discoverers and inventors feel short-changed that they get too little credit or profit from a good idea, perhaps forgetting or overlooking just how much effort had to go into turning that idea or invention into a workable, affordable innovation that actually delivered benefits to people. The economist Tim Harford has argued that 'the most influential new technologies are often humble and cheap. Mere affordability often counts for more than the beguiling complexity of an organic robot.' He calls this the 'toilet-paper principle' after a simple but vital technology that we take for granted.

Fritz Haber's discovery of how to fix nitrogen from the air, using pressure and a catalyst, was a great invention. But it was Carl Bosch's years of hard experiment, overcoming problem after problem and borrowing novel ideas from other industries that eventually led to the manufacture of ammonia on a large scale and at a price that society could afford to pay. You could say the same of the Manhattan Project, or the Newcomen steam engine, but it is not only big industrial innovations that this rule applies to. Again and again in the history of innovation, it is the people who find ways to drive down the costs and simplify the product who make the biggest difference. The unexpected success of mobile telephony in the 1990s, which few saw coming, was caused not by any particular breakthrough in physics or technology, but by its sudden fall in price.

As Joseph Schumpeter put it in 1942:

> Electric lighting is no great boon to anyone who has money enough to buy a sufficient number of candles and to pay servants to attend to them. It is the cheap cloth, the cheap cotton and rayon fabric, boots, motorcars, and so on that are the typical achievements of capitalist production, and not as a rule improvements that would mean much to the rich man. Queen Elizabeth owned silk stockings. The capitalist achievement does not typically consist in providing more silk stockings for queens but in bringing them within the reach of factory girls in return for steadily decreasing amounts of effort.

Innovation is often serendipitous

The word serendipity was coined by Horace Walpole in 1754 to explain how he had tracked down a lost painting. He took it from a Persian fairy tale, 'The Three Princes of Serendip', in which, as Walpole put it in a letter, the clever princes were 'always making discoveries, by accidents and sagacity, of things which they were not in quest of'. It is a well-known attribute of innovation: accidental discovery.

Neither the founders of Yahoo! nor those of Google set out in search of search engines. The founders of Instagram were trying to make a gaming app. The founders of Twitter were trying to invent a way for people to find podcasts. At Dupont in 1938, Roy Plunkett invented Teflon entirely by accident. While trying to develop improved refrigerant fluids, he stored about 100 pounds of tetrafluoroethylene gas in cylinders at dry-ice temperatures, intending to chlorinate it. When he opened a cylinder not all of it came out: some of the chemical had polymerized and turned to a solid, white powder, polytetrafluoroethylene or PTFE. It was useless as a refrigerant, but Plunkett decided to work out what it was like. It proved to be heat-resistant and chemically inert, but also strangely friction-less, or non-stick. PTFE went on to find uses in the Manhattan Project in the 1940s, as a container for fluorine gas; as coating for non-stick pans in the 1950s; as Goretex clothing in the 1960s; and on board the Apollo missions to the moon.

Two decades later, Stephanie Kwolek developed Kevlar, also serendipitously and also at Dupont. An expert on polymers who had joined the firm in 1946, she stumbled on a new form of aromatic polyamide that could be spun into a fibre. Persuading a reluctant colleague to spin the gunky fibre into a textile, she discovered that it was stronger than steel, lighter than fibre-glass and heat-resistant. The application to bullet-proof garments only became obvious a little later. 'Some inventions,' said Kwolek, 'result from unexpected events and the ability to recognize these and use them to advantage.'

In the search for a strong and permanent glue, Spencer Silver at 3M in Minneapolis found a weak and temporary adhesive instead. This was in 1968. Nobody could think of a use for it, until five years later a colleague named Art Fry remembered it when irritated by his place-markers falling out of a hymn-book while singing in a church choir. He went back to Silver and asked to apply the glue to small sheets of paper. The only paper lying around was bright yellow. The Post-it note was born.

Or take the invention of genetic fingerprinting, a technology that has proved invaluable in the conviction of the guilty, but even more so in the exoneration of the innocent; and that has been so widely applied in paternity and immigration disputes that it is safe to say DNA unexpectedly had a far greater impact outside medicine than inside it, in the 1990s.

Alec Jeffreys, the scientist at Leicester University who made the discovery of how to use DNA to identify people and their relatives, began working on the variability of DNA in 1977, hoping to find a way of spotting gene mutations directly. In 1978 he first detected DNA variations in people, with a view to diagnosing diseases. He was still thinking in terms of medical applications. But on the morning of 10 September 1984 he realized that he had found something different. Samples from different people, including the lab's technician and her mother and father, were proving to be always different and therefore unique.

Within months the technique was being used to challenge the decisions of the immigration authorities, and to identify paternity. Then, in 1986, the Leicestershire police arrested a young man with learning difficulties, Richard Buckland. A fifteen-year-old girl had been beaten, raped and strangled in a wooded area near the village of Narborough. Buckland lived locally, seemed to know details of the crime and soon confessed under questioning to committing it. Case closed, it seemed.

The police wanted to know if Buckland had also committed a very similar crime nearly three years before and just a short distance away, in which another fifteen-year-old girl had been raped and killed. Buckland denied it. So the police asked Jeffreys, at the local university, if his new DNA fingerprinting technique could help, given that semen had been found on both bodies. Jeffreys ran a test and came back with a clear answer: the same person had committed both crimes - but it was not Buckland. The police were understandably reluctant to accept this conclusion, based on such a novel technique, but they eventually conceded that they could not convict Buckland in the light of Jeffreys' evidence and he was freed. Buckland therefore became the first person to be exonerated by DNA.

The police then asked all men of a certain age in the area to take a blood test. After eight months they had 5,511 samples. None matched the evidence from the crime scenes. A dead end. But in August 1987 a man admitted over a beer in a pub to having impersonated a work colleague when taking the test. An eavesdropper passed the news to the police. Colin Pitchfork, a 27-year-old cake decor-ator at a bakery, had asked his friend to take the test on his behalf, using some excuse about a previous brush with the police. The police arrested Pitchfork, who quickly con-fessed and whose DNA matched that found at both crime scenes.

Thus, the very first use of forensic DNA exonerated an innocent man, convicted a guilty one, and probably saved several girls' lives. Jeffreys had serendipitously set DNA on the path of making a far bigger difference in the 1990s to criminal investigation than it had made to medicine by then.

Innovation is recombinant

Every technology is a combination of other technologies; every idea a combination of other ideas. As Erik Brynjolfsson and Andrew McAfee put it: 'Google self-driving cars, Waze, Web, Facebook, Instagram are simple combinations of existing technology.' But the point is true more generally. Brian Arthur was the first to insist on this point in his 2009 book *The Nature of Technology: What It is and How It Evolves*. He argued that 'novel technologies arise by combination of existing technologies and that (therefore) existing technologies beget further technologies.' I defy the reader to find a technological (as opposed to a natural) object in his or her pocket or bag that is not a combination of technologies and of ideas. Looking at my desk as I write I see a mug, a pencil, some paper, a telephone and so on. The mug is perhaps the simplest object but even it is glazed ceramic with a printed logo and combines the ideas of baking clay, glazing, printing, adding a handle and holding tea or coffee in a receptacle.

Recombination is the principal source of variation upon which natural selection draws when innovating biologically. Sex is the means by which most recombination happens. A male presents half his genes to an embryo and so does a female. That is a form of recombination, but what happens next is even more momentous. That embryo, when it comes to make sperm and egg cells, swaps bits of the father's genome with bits of the mother's in a process known as crossing over. It shuffles the genetic deck, creating new combinations to pass on to the next generation. Sex makes evolution cumulative and allows creatures to share good ideas.

The parallel with human innovation could not be clearer. Innovation happens, as I put it a decade ago, when ideas have sex. It occurs where people meet and exchange goods, services and thoughts. This explains why innovation happens in places where trade and exchange are frequent and not in isolated or underpopulated places: California rather than North Korea, Renaissance Italy rather than Tierra del Fuego. It explains why China lost its innovative edge when it turned its back on trade under the Ming emperors. It explains the bursts of innovation that coincide with increases in trade, in Amsterdam in the 1600s or Phoenicia 3,000 years earlier.

The fact that fishing tackle in the Pacific was more diverse on islands with more trading contacts, or that Tasmanians lost out on innovation when isolated by rising sea levels, shows the intimate, mandatory connection between trade and the development of novelty. This explains too why innovation started in the first place. The burst of technology that began in dense populations exploiting rich, marine ecosystems in southern Africa more than 100,000 years ago was caused by the fact that – for whatever reason – people had begun exchanging and specializing in a way that *Homo erectus* and even Neanderthals never did. It is a really simple idea, and one that anthropologists have been slow to grasp.

Darwinians are beginning to realize that recombination is not the same as mutation and the lesson for human innovation is significant. DNA sequences change by errors in transcription, or mutations caused by things like ultra-violet light. These little mistakes, or point mutations, are the fuel of evolution. But, as the Swiss biologist Andreas Wagner has argued, such small steps cannot help organisms cross 'valleys' of disadvantage to find new 'peaks' of advantage. They are no good at climbing slopes where one must occasionally go down on the route to the summit. That is to say, every point mutation must improve the organism or it will be selected against. Wagner argues that sudden shifts of whole chunks of DNA, through crossing over, or through so-called mobile genetic elements, are necessary to allow organisms to leap across these valleys. The extreme case is hybridization. Britain alone has seven or more new species of plant that came about by hybridization in recent decades. The honeysuckle fly of North America is a new species resulting from the cross-breeding of blueberry and snowberry flies.

Wagner cites numerous studies which support the conclusion that 'recombination is much more likely to preserve life – up to a thousand times more likely – than random mutation is.' This is because whole working genes, or parts of genes, can be given new jobs, where a step-by-step change would find only worse results. Bacteria can 'catapult themselves not just hundreds of miles, but thousands of miles, through a vast genetic landscape, all courtesy of gene transfer'.

In the same way, innovation in one technology borrows whole, working parts from other technologies, rather than designing them from scratch. The inventors of the motor car did not have to invent wheels, springs or steel. If they had done, it is unlikely that they would ever have produced working devices along the way. The inventors of modern computers took the idea of vacuum tubes from the ENIAC and the idea of storable programs from the Mark 1.

Innovation involves trial and error

Most inventors find that they need to keep 'just trying' things. Tolerance of error is therefore critical. It is notable that during the early years of a new technology – the railway, for example, or the internet – far more entrepreneurs went broke than made fortunes. Humphry Davy once said 'the most important of my discoveries has been suggested to me by my failures'. Thomas Edison perfected the light bulb not by inspiration but by perspiration: he and his team tested 6,000 different materials for the filament. 'I've not failed,' he once said. 'I've just found 10,000 ways that won't work.' Henry Booth helped George Stephenson improve the *Rocket* using trial and error. Christopher Leyland helped Charles Parsons use trial and error to perfect the design of the turbine. Keith Tantlinger helped Malcom McLean get the right fit for containers on ships, by trial and error. Marconi used trial and error in his radio experiments. The Wright brothers found out by crashing that the profile of a wing should have a shallow, not a deep ratio. The pioneers of fracking stumbled on the right formula by accident and then gradually improved it by endless experiments.

An element of playfulness probably helps, too. Innovators who just like playing around are more likely to find something unexpected. Alexander Fleming said: 'I like to play with microbes.' James Watson, co-discoverer of the double helix, described his work with models as 'play'.

Andrew Geim, the inventor of graphene, said: 'a playful attitude has always been the hallmark of my research.'

A trivial example of innovation, based on trial and error: Regan Kirk of the startup Growth Tribe gives the example of Takeru Kobayashi, who in 2001 set a spectacular new record at Coney Island for hot-dog eating: he consumed fifty in ten minutes. Slim and small, Mr Kobayashi does not look like a champion hot-dog consumer, but his secret was that he worked out by systematic experimentation that he could eat the sausages faster if he separated them from the bread, and that he could then consume the buns quickly if he dunked them in water, which was not breaking the rules.

Only slightly less trivial, Dick Fosbury was a young athlete at Oregon State University who invented the 'Fosbury flop' by which he won the High Jump gold medal at the 1968 Olympics to the surprise of his more favoured competitors and the delight of the crowd. He turned over the bar on his back, head first, landing on his neck. He later described how he had used trial and error over many months to get the technique right. 'It was not based on science or analysis or thought or design. None of those things . . . I never thought about how to change it, and I'm sure my coach was going crazy because it kept evolving.'

Using examples like this, Edward Wasserman of the University of Iowa has made the case that most human innovations evolve through a process that looks awfully like natural selection, rather than are created by intelligent design. Wasserman showed how the design of the violin changed gradually over time, not as a result of sudden improvements but as the result of small deviations from the norm being passed on if they worked and not if they did not. The hole in the centre of the instrument started out round, then became semi-circular, then elongated and finally f-shaped by this gradual means. Wasserman reckons this view of innovation runs into the same psychological resistance as natural selection faced in biology:

> According to this view, the many things we do and make – like violins – arise from a process of variation and selection which accords with the law of effect. Contrary to popular opinion, there is neither mystique nor romance in this process; it is as fundamental and ubiquitous as the law of natural selection. As with the law of natural selection in the evolution of organisms, there is staunch resistance to the role of the law of effect in the evolution of human inventions.

If error is a key part of innovation, then one of America's greatest advantages has come from its relatively benign attitude to business failure. Bankruptcy laws in most American states have allowed innovators to 'fail fast and fail often' as the Silicon Valley slogan has it. In some states, the 'homestead exemption' essentially allows an entrepreneur to keep his or her home if their business fails under Chapter 7 bankruptcy rules. Those states with homestead exemptions have shown more innovation than those without.

Innovation is a team sport

The myth of the lonely inventor, the solitary genius, is hard to shake. Innovation always requires collaboration and sharing, as exemplified by the fact that even the simplest object or process is beyond the capacity of any one human being to understand. In a famous essay called

'I, Pencil', Leonard Reed pointed out that a simple pencil is made by many different people, some cutting trees down, others mining graphite, others working in pencil factories, or in marketing or management, yet others growing coffee for the lumberjacks and managers to drink. Amid this vast team of collaborating people, not one person knows how to make a pencil. The knowledge is stores between heads, not inside them.

The same is true for innovation. It is always a collaborative phenomenon. (Even Australian magpies solve problems faster if they are in larger groups.) One person may make a technological breakthrough, another work out how to manufacture it and a third how to make it cheap enough to catch on. All are part of the innovation process and none of them knows how to achieve the whole innovation. Occasionally there is an inventor who is both scientifically gifted and good at business – Marconi comes to mind – but even then he or she is standing on the shoulders of others at the start, and relying on yet others later on.

The degrees to which innovation is a team sport becomes ever more case histories one examines and the closer one looks at each one. The famous Green Revolution in agriculture was made possible by Norman Borlaug's astonishing diligence, determination and drive, but to tell the story as his work alone is a travesty. He got the idea of short-strawed varieties of wheat from Burton Bayles who got it from Orville Vogel who got it from Cecil Salmon who got it from Gonjiro Inazuka. Borlaug shared a hard work of selling the idea in Asia with people like Manzoor Bajwa and M.S. Swaminathan.

Terence Kealey and Martin Ricketts, in a recent paper on the Industrial Revolution, Provide a long list of innovative Industries that are known to have advanced by collective research and development among many actors freely sharing their ideas the Dutch East India company's cargo ship, Holland's windmills; Lyons' silk industry; crop rotation in England; Lancashire's cotton spinning; America's engines for steam boats; Viennese furniture; Massachusetts paper makers; a patent pool among sewing machine makers. This pattern is the rule, not the exception, and it was the flowering of societies, clubs and mechanics' institutes that gave Britain its lead in the Industrial Revolution.

Innovation is inexorable

Most inventions lead to priority disputes between competing claimants. People seem to stumble on the same idea at the same time. Kevin Kelly explores this phenomenon in his book What Technology Wants, finding that six different people invented or discovered the thermometer, five the electric telegraph, four decimal fractions, three the hypodermic needle, two natural selection. In 1922 William Ogburn and Dorothy Thomas at Columbia University produced a list of 148 cases of near-simultaneous invention by more than one person, including photography, the telescope and typewriters. 'It is a singular fact,' wrote Park Benjamin in 1886, that probably not an electrical invention of major importance has ever been made but that the honour of its origin has been claimed by more than one person. Going further back still, it is striking that the boomerang, the blowpipe and the pyramid were all invented independently on different continents – as was agriculture.

I have documented in this book many striking examples of this phenomenon. Sure, some are evidence of collusion or conscious competition. But there is none the less a real pattern here. Simultaneous invention is more the rule than the exception. Many ideas for technology just seem to be ripe, and ready to fall from the tree. The most astonishing case is the electric light bulb, the invention of which was independently achieved by twenty-one people. There may have been a bit of snooping by some of these into the work of the others, and collaboration between them in a few cases, but mostly it is hard to find any evidence they even knew of each other's work. Likewise, there were scores of different search engines coming to the market in the 1990s. It was impossible for search engines not to be invented in the 1990s, and impossible for light bulbs not to be invented in the 1870s. They were inevitable. The state of the underlying technologies had reached the point where they would be bound to appear, no matter who was around.

The lesson this teaches throws up two paradoxes. First, the individual is strangely dispensable. If a carriage runs Swan or Edison over in their youth, or a car runs Page and Brin over, the world does not end up lacking light bulbs or search engines. Maybe things take longer, have a slightly different look and get different names. But the innovations still happen. This might seem a little harsh, but it is fairly undeniably true of every scientist and inventor who ever lived. Without Newcomen, steam engines would have surely been invented by 1730; without Darwin, Wallace did get natural selection in the 1850s; without Einstein, Hendrik Lorenz would have got relativity within a few years; without Szilard, the chain reaction and the fission bomb would have been invented in the twentieth century at some point; without Watson and Crick, Maurice Wilkins and Ray Gosling would have got the structure of DNA within months – William Astbury and Elwyn Beighton already had got the key evidence a year earlier but did not realize it.

The paradox is that this is precisely what makes such achievements remarkable: there was a race to make them and somebody won. Individuals do not matter much in the long run, but that makes them all the more extraordinary in the short run. They emerge from among billions of rivals to find out, or make, something that any one of those billions could do. Far from being an insult, therefore, my jibe about inevitability and dispensability is actually a compliment. How incredible to be the one human being among billions who first sees the possibility of a new device, a new mechanism, a new idea. That is arguably even more miraculous than achieving something that would never be achieved by anybody else, like the *Mona Lisa* or 'Hey Jude'.

The second paradox of the inevitability of invention is that it makes innovation look predictable, yet it is not. In retrospect, it is blindingly obvious that search engines would be the biggest and most profitable fruit of the internet. But did anybody see them coming? No.

Technology is absurdly predictable in retrospect, wholly unpredictable in prospect. Thus predictions of technological change nearly always look very foolish. They either prove wildly overblown, or equally wildly underblown. Ken Olsen, the founder and chairman of Digital Equipment Corporation, was an immensely successful pioneer of 'minicomputers'. This name, in retrospect amusingly, referred to a range of machines the size of large desks, which had largely replaced computers the size of large rooms in the 1970s. So you would think that Mr Olsen would spot that computers might get smaller still and cheaper, and might eventually find uses within homes. Yet, speaking at a World

Future Society meeting in Boston in 1977, just a few years before the launch of personal computers, he reportedly said: 'there is no reason anyone would want a computer in their home.'

Likewise, in 2007, Steve Ballmer, chief executive of Microsoft, said: 'There's no chance the iPhone is going to get significant market share. No chance.' Sometimes, as the Swedish author Hjalmar Söderberg put it, you have to be an expert in order not to understand certain things.

Paul Krugman is a Nobel Prize-winning economist who in 1998 reacted to the growth of the internet, and the hype of the dotcom boom, with an article in *Red Herring* magazine entitled 'Why Most Economists' Predictions are Wrong'. He then proceeded to give a dramatic demonstration of his point by making what turned out to be a very wrong prediction himself:

> The growth of the Internet will slow drastically, as the flaw in 'Metcalfe's law' – which states that the number of potential connections in a network is proportional to the square of the number of participants – becomes apparent: most people have nothing to say to each other! By 2005 or so, it will become clear that the Internet's impact on the economy will have been no greater than the fax machine's.

It turns out that people do have a lot to say to each other. Anticipating what people want is something innovators are often good at; academics less so.

But there are also plenty of quotes from people predicting too much technological progress as well as too little. In the 1950s Isaac Asimov forecast that we would have moon colonies by the year 2000, while Robert Heinlein expected routine interplanetary travel. Others forecast supersonic rocket ships to travel around the world, human-like robots in the home and gyrocopters for all.

Innovation's hype cycle

In my view the most insightful thing ever said about forecasting innovation was a 'law' named after a Stanford University computer scientist and long-time head of the Institute for the Future by the name of Roy Amara. Amara's Law states that people tend to overestimate the impact of a new technology in the short run, but to underestimate it in the long run. Exactly when Roy Amara first had this idea is not clear. His former colleagues told me that by the middle of the 1960s he had begun making the point, and of course, in line with most innovations, this one too had its rival precursors. You can find people saying similar things all the way back to the early 1900s. It often gets credited to Arthur C. Clarke, but there is no doubt that Amara deserves most credit.

Examples abound. In the 1990s there was a period of wild excitement about the internet that then seemed to end in disappointment around the time of the dotcom bust of 2000. Where was the growth of online retail, online news and online everything that we had been promised? Well, a decade later, it was there, disrupting and destroying business models all across the retail sector, the news media, and the music and film industries, and doing so far more radically than anybody had predicted. Likewise, at the time of the sequencing of the first human genome in 2000, there were wild promises of the end of cancer and the personalization of medicine. A decade later, there was an understandable backlash: genomic knowledge seemed to have had little impact on medicine: articles asking 'whatever happened to genomic medicine?' had begun to appear. A decade after that, things are beginning to look almost as promising as the original hype.

Rodney Brooks, MIT professor turned entrepreneur, cites GPS as a classic case of the Amara hype cycle. Beginning in 1978, twenty-four satellites were launched with a goal of giving soldiers a way of locating themselves for resupply in the field. In the 1980s the program failed to deliver on its promise and was nearly canceled several times. It began to look like a failure. Eventually, the military decided it was good enough to rely upon. It quickly spilled over into the civilian world and today GPS is so ubiquitous as to be indispensable, for hikers, map readers, farm vehicles, ships, delivery trucks, planes and pretty well everybody.

Amara's hype cycle explains a lot and it implies that, between the early disappointment and the later under-estimate there must be a moment when we get it about right; I reckon these days it is fifteen years down the line. We expect too much of an innovation in the first ten years and too little in the first twenty, but get it about right look-ing fifteen years ahead. The explanation for this pattern surely lies in the fact that until the invention is turned into a practical, reliable, affordable innovation, over many years, its promise remains unfulfilled.

I suspect that the Amara hype cycle can be detected today in the story of artificial intelligence, a technology whose promise has long disappointed. Thanks to graphics chips, new algorithms and lots of data, at last AI might be on the brink of not fading away. The 'Al winters' that closed down earlier bursts of excitement about machine learning may not come this time.

By contrast, I cannot help thinking that blockchain is in the early stages of the hype cycle: we are overestimating its impact in the short run. Blockchain promises to bring smart contracts that cut out middlemen, enhance trustworthiness and reduce transaction costs. But there is no way it can do so overnight in the complex ecosystem of the service econ-omy. There is almost bound to be a burst of disappointment about what blockchain has achieved, and how many block-chain firms have failed, in around ten years' time. Yet, one day, blockchain could be huge.

Facebook's Libra currency, though not a true blockchain, is undoubtedly a harbinger of things to come. Why would consumers not shi& to a currency available to a third of the world population and not subject to the inflationary temptations and tax greed of politicians?

Even more is this true of self-driving cars. I keep having conversations with people who think there will be no jobs for drivers within a few short years, of trucks or taxis or limos, and that this will create so much unemployment that we need to be acting now to deal with that problem. This feels premature. The truth is that autonomous vehi-cles are possible but in fairly limited circumstances, and that this may not change as fast as people think, in the real world. Huge amounts of driver assistance will surely come, or are here already, so that cars can detect and avoid obstacles, cruise on motorways and freeways, parallel-park and warn the driver of delays in traffic. But in the real, messy world of crowded streets, rules and etiquette, bad weather and remote rural tracks, it is a huge jump from these kinds of increasingly smart assistance to the moment you can go to sleep at the wheel secure in the knowledge that your car will go all the way to your destination. Hand-ing over total control of a road vehicle to a computer is a much harder problem than the equivalent in the air, for example. And then there is the need to re-engineer the entire infrastructure around roads to suit automated vehicles, not to mention the insurance market. These things take time.

I am not saying autonomous cars won't happen, just that we are likely to be underestimating the time it will take and the disappointments along the way. I am pre-pared to bet that ten years from now there will be stories in the media about the failed forecasts for driverless cars made in the twenty-teens; and that there will be more, not fewer, professional drivers on the planet than today. Then a decade or more after that, in the 2040s, things will indeed be changing fast. I hope to live long enough to be pleased or embarrassed by this prediction!

Innovation prefers fragmented governance

One of the peculiar features of history is that empires are bad at innovation. Though they have wealthy and educated elites, imperial regimes tend to preside over gradual declines in inventiveness, which contribute to their eventual undoing. The Egyptian, Persian, Roman, Byzantine, Han, Aztec, Inca, Hapsburg, Ming, Ottoman, Russian and British empires all bear this out. As time goes by and the central power ossifies, technology tends to stagnate, elites tend to resist novelty and funds get diverted into luxury, war or corruption, rather than enterprise. This despite empires being effectively giant 'single markets' for ideas to spread within. Italy's most fertile inventive period was in the Renaissance, when it was the small city states, run by merchants, that drove innovation: in Genoa, Florence, Venice, Luca, Siena and Milan. Fragmented polities proved better than united ones. Ancient Greece teaches the same lesson.

In the 1400s Europe rather rapidly adopted printing, a technology developed originally in China, which utterly transformed the economics, politics and religion of western Europe. The fact that Europe was politically fragmented at the time played a large role in making sure that printing caught on. Johann Gutenberg himself had to leave his home city of Mainz and move to Strasbourg to find a regime that would let him get to work. Martin Luther became a wildly successful printing entrepreneur and survived only because of the protection afforded at Wartburg by the Elector Friedrich the Wise. William Tyndale published his explosively subversive, and aesthetically beautiful, English translation of the Bible while in hiding in the Low Countries. None of these projects would have been possible in a centrally run empire.

By contrast, the Ottoman and Mughal empires managed to ban printing for more than three centuries. Istanbul, a great city of culture on the edge of Europe administering a vast empire of Christians as well as Muslims, resisted the new technology. It did so, precisely because it was the capital of an empire. In 1485 printing was banned by order of Sultan Bayezid II. In 1515 Sultan Selim I decreed that printing by Muslims was punishable by death. This was an unholy alliance: the calligraphers defending their business monopoly in cahoots with the priests defending their religious monopoly, by successfully lobbying the imperial authorities to keep printing at bay. Foreigners were eventually allowed to print books in foreign languages within the Ottoman Empire, but it was not until 1726 that a Hungarian convert to Islam, Ibrahim Muteferrika, managed to persuade the imperial authorities to allow secular (but not religious) books to be printed in Arabic. Had the lands ruled by the Sultans been fragmented into different political territories and different religions, it is impossible to believe that printing would not have happened sooner and spread faster.

In China, too, the periods of explosive innovation coincided with decentralized government, otherwise known as 'warring states'. The strong empires, most notably the Ming, effectively put a stop to innovation as well as trade and enterprise more generally. David Hume, writing in the eighteenth century, already realized this truth, that China had stalled as a source of novelty because it was unified, while Europe took off because it was divided.

America may appear an exception, but in fact it proves this rule. Its federal structure has always allowed experiment. Far from being a monolithic imperium, the states were for most of the nineteenth and twentieth centuries a laboratory of different rules, taxes, policies and habits, with entrepreneurs moving freely to whichever state most suited their project. Recently the federal government has grown stronger, and at the same time many Americans are wondering why the country is not as fleet of foot at innovation as it once was.

This fragmentation works best when it results in the creation of city states. These beasties have always been the best at incubating innovation: states dominated by a single city. For at least a thousand years, innovation has disproportionately happened in cities, and especially self-governing ones. The physicist Geoffrey West of the Santa Fe Institute made a remarkable discovery about cities. He found that cities scale according to a predictable mathematical formula called a power law. That is to say, from the population of a city he can tell you with surprising precision not just how many petrol stations, miles of electrical cable and miles of roads it will have, but how many restaurants and universities and what level of wages.

And the really interesting thing is that cities need fewer petrol stations and miles of electrical cable or road – per head of population – as they get bigger, but have disproportionately more educational institutions, more patents and higher wages – per head of population – as they get bigger. That is to say, the infrastructure scales at a sublinear rate, but the socio-economic products of a city scale at a superlinear rate. And this pattern holds throughout the world wherever Geoffrey West and his colleagues look. This fact is not true of companies. As they grow bigger, beyond a certain point they become less efficient, less manageable, less innovative, less frugal and less tolerant of eccentricity. That, says West, is why companies die all the time, but cities never do. Not even Detroit or Carthage. Sybaris was the last city to vanish altogether – in 445 BC.

Innovation increasingly means using fewer resources rather than more

The bigger cities get, the more productive and efficient they become, in terms of their use of energy to create improbability, just as the bodies of animals do: a whale burns proportionately less energy than a shrew and so lives longer, has a bigger brain and behaves in a more complicated way. London proportionately burns less energy than Bristol, has a bigger collective brain and behaves in a more complicated way. The same is true throughout the economy. Those who say that indefinite growth is impossible, or at least unsustainable, in a world of finite resources are therefore wrong, for a simple reason: growth can take place through doing more with less.

Much 'growth' is actually shrinkage. Largely unnoticed, there is a burgeoning trend today that the main engine of economic growth is not from using more resources, but from using innovation to do more with less: more food from less land and less water; more miles for less fuel; more communication for less electricity; more buildings for less steel; more transistors for less silicon; more correspondence for less paper; more socks for less money; more parties for less time worked. A few years ago Jesse Ausubel of Rockefeller University discovered the surprising and unexpected fact that the American economy has begun 'dematerializing': using not just less stuff per unit of output, but less stuff altogether. (Chris Goodall had already spotted the same to be true of Britain.) By 2015 America was using 15 per cent less steel, 32 per cent less aluminium and 40 per cent less copper than at its peaks of using these metals, even though its population was larger and its output of goods and services much larger. Its farms use 25 per cent less fertilizer and 22 per cent less water yet produce more food thanks to better targeting of fertilizer and irrigation. Its energy system generates fewer emissions (of carbon dioxide, sulphur dioxide and nitrogen oxides) per kilowatt-hour. In the ten years from 2008, America's economy grew by 15 per cent but its energy use fell by 2 per cent.

This is not because the American economy is generating fewer products: it's producing more. It is not because there is more recycling – though there is. It's because of economies and efficiencies created by innovation. Take aluminium drinks cans. When first introduced in 1959 a standard aluminium can weighed 85 grams; today it weighs 13 grams, according to Professor Vaclav Smil. This has a counterintuitive implication: those who say growth is impossible without using more resources are simply wrong. It will always be possible to raise living standards further by lowering the amount of a resource that is used to produce a given output. Growth is therefore indefinitely 'sustainable'.

The nineteenth-century economist William Stanley Jevons discovered a paradox, since named after him, whereby saving energy only leads to the use of more energy. We react to cheaper inputs by using more of them. When electricity is cheap we leave the lights on more. But Andrew McAfee, in his book *More from Less*, argues that in many sectors the economy is now exhausting the Jevons paradox and beginning to bank the savings. Thus LEDs use less than 25 per cent of the electricity that incandescent bulbs use for the same amount of light, so you would have to leave them on for more than ten times as long to end up using more power: that is unlikely to happen.

McAfee argues that dematerialization is one reason why the many pessimistic predictions of the 1970s, about the probability of running short of oil, gas, coal, copper, gold, lead, mercury, molybdenum, natural gas, oil, silver, tin, tungsten, zinc and lots of other non-renewable resources early in the current century, proved to be so spectacularly wrong: 'The image of a thinly supplied spaceship Earth hurtling through the cosmos with us on board is compelling but deeply misleading. Our planet has amply supplied us for our journey. Especially since we're slimming, swapping, optimizing and evaporating our way to dematerialization.'