Magical inventions or the art of discovery

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a sample from Chapter 4

From blackbodies to bar codes: creation of laser light

‘At least the Wright brothers could look up into the sky and see birds flying’ [1]

Just do it!

On the afternoon of 16 May 1960, in a laboratory overlooking the coast near Los Angeles, Ted Maiman and Irnee D’Haenens connected a small experimental device to recording equipment. They had constructed a short rod of ruby mounted inside the spiral of a powerful flash lamp, all within a neatly polished aluminium cylinder. Step by step they increased the electrical power to the lamp, each time recording the trace of light that the power induced in the ruby. The results were steadily routine: a couple of broad peaks at fixed points along the spectral scale — the normal red fluorescence from ruby. They pushed the controls upward until they reached 950 volts, making the flash more intense than the Sun. Suddenly everything changed. The recording trace shot up rapidly to a sharp peak of intense and pure red light from the ruby. Laser light was created, for the first time, anywhere. What they had made was in essence the same as the laser pointer you can now use in the classroom, the same as a bar-code reader at a shop counter, in your CD player, or in a factory to cut steel. To the spectators at the first public demonstration the device looked so simple, but Maiman and D'Haenens knew their it was possible only by applying an understanding of quantum physics. The arcane theory of how atoms work and what light is. Others were trying to invent devices with the same effect, but all of them were much more complicated and none of them believed a rod of ruby at room temperature could be heart of a laser. The pair at Malibu kept to their working motto: ‘just do it’.

Red hot pokers: why do hot objects glow?

If you thrust an iron poker into the blazing coals of a domestic fire, soon the end of it will glow dull red. If you place the poker by the fireside and watch it, specially in the dark, the glow will fade until the light sensors in your eyes can no longer detect anything. But if then you place your hand near the end of the poker, heat sensors in your skin detect something else warning you of danger.

Potters with their clay wares turning into ceramics in a kiln knew that these glows can be used as a scale of the temperature of the kiln. Dark red is about 550^{o}C and white is 1200^{o}C; very useful before more direct thermometers for kilns were invented. Specially useful, although a mystery, was the fact that any material in the kiln, ceramic or metal, would glow the same colour at the same temperature. The more people thought about this the more they realized they could not explain even why hot objects glow. Where does this light come from and why can you feel the heat at a distance even when there is no glow to see?

This was about as far as physics based directly on sensory perception by humans was able to carry this story. New ways of observing nature were needed. Gustav R. Kirchhoff, working in Heidelberg and Berlin, was a physicist with many interests but importantly for this story he invented spectroscopy.[2] This improves on the sort of investigation done by Isaac Newton in his studies of light, using a prism of glass to split sunlight or lamplight into its component colours, from red through to violet, as a rainbow. A spectroscope, at its heart, is a prism (or now usually a diffraction grating) mounted in an angular arrangement of light tubes. Through it a glowing object can be observed and the composition of the emitted light recorded as a series of coloured lines. Cooking salt, sodium chloride, thrown onto your fire heating the poker, will flash bright yellow. Repeating that systematically with a spectroscope, suggests that what you have thrown on the flame contains the element sodium. The flame is important — the chemist Robert Bunsen collaborated at the University of Heidelberg with Kirchhoff in this invention, using a special burner (originally invented by Michael Faraday) to give a consistent flame. In all its varieties the highly versatile spectroscope remains the quintessential scientific instrument, more so than the iconic microscope of cartoon boffins.

In 1859 Kirchhoff published what would become his law of thermal radiation and by 1862 introduced the term *blackbody* to explain his concepts. This is a body that absorbs all light rays falling on it, hence its colour from the absence of visible light. It also emits light if heated. The concept was embodied as a container (usually called a cavity) with a small hole through which light could enter or be emitted, the hole itself was the experimental blackbody and was observed conveniently with a spectroscope as the container was heated. Data from this banal apparatus were to challenge physics to its foundations.

The light is emitted from the walls of the cavity. It is generated there, not reflected from somewhere else, so that heating the cavity should change the nature of the light emitted. At this time light was known as a form of electromagnetic radiation, thought of as waves. The type of radiation visible to humans is called light and was then the most convenient to experiment with, but the principles apply to all types. The numbers of peaks of waves that travelled past a fixed point in a fixed time was known as the frequency. The intensity of the light was the energy delivered to a fixed area and time. Kirchhoff wanted to know the relationship between the intensity of the light, its frequency, and the temperature of the cavity. This was important because he needed his theory to balance energy absorbed by the walls of the cavity with energy emitted by the walls. In other words it needed to obey the second law of thermodynamics, just recently formulated. A utilitarian need was better knowledge to improve lighting in public places using gas or electrical energy. He formulated a simple law to describe the phenomenon that the radiant energy emitted from the blackbody depended on its temperature and the frequency of the radiation and nothing else, no matter what the blackbody is made of. So a blackbody at room temperature emits low frequency radiation, invisible infrared, and at the temperature of a ceramics kiln it would emit radiation of the frequency of green to blue light, appearing white hot.

So far so fairly simple, but researchers with spectroscopes wanted to know more and Kirchhoff wanted experimental verification of his propositions. Josef Stefan and his student Ludwig E. Boltzmann, at the University of Vienna, were researchers fascinated by this blackbody business. They had results from John Tyndall who in 1865 had used a blackened and heated platinum wire as a blackbody and found an intriguing relation between the increase in energy emitted as the wire got hotter and the ratio of the temperatures when expressed in degrees Kelvin (that is, starting from absolute zero or -273^{o}C). Stefan and Boltzmann found that as a blackbody gets hotter the radiant energy it emits increase as the fourth power of its temperature.[3] This is why it takes so much more energy as heat to get that poker from dull red to bright red than from cold black to dull red. A domestic fire will not suffice. It may seem implausible that something cold radiates energy, but anything above absolute zero radiates some energy. Sitting reading this, your low metabolic and muscle activity will generate a gentle 100 watts or so, much of it dispersed as infrared radiation.

Wilhelm Wien was another researcher fascinated by this radiation and working at the government Physical Technical Institute in Berlin, concerned with standards and constants. There he could find time to measure emission from heated blackbodies. Although the instruments available at the time were adequate for high frequency radiation they were unable to operate at low frequency. Nevertheless, he formulated a law, using two arbitrary constants and an assumption that the radiation was emitted from miniscule structures which vibrated. The hotter these structures, the faster they vibrated and the higher the frequency of radiation they emitted. Wien's law fitted the results of other workers well enough at high frequencies, but could the poor fit at low frequencies be entirely the fault of poor instrumentation? The explanatory power of his ideas was limited. What were these vibrators? Did any such thing actually exist? Were they the hypothetical atoms as proposed by some researchers? Boltzmann was one of the physicists at that time who did think that atoms existed but he was in a minority. Chemists, since the studies of John Dalton decades before, had been using the idea of atoms very constructively. But at that time the consensus of physicists was that their superior brand of science had no need of atoms.[4]

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The solid emptiness of the atom — how can that be?

John Dalton was one of the first researchers to use constructively the idea of atoms. This had been discussed by philosophers ages ago, but not in a form useful to scientists. At about 1800 in Manchester, better information available to Dalton was on the nature of elements such as hydrogen and oxygen, and how they might combine with each other. Information on what happens to a piece of rusting iron for example. As was obvious to anyone who looked, it must lose weight; until a researcher such as Antoine-Laurent Lavoisier in Paris did the equally obvious thing of actually weighing the iron as it rusted and found it gained weight. Oxygen was combining with it: less obvious. Dalton studied gases: oxygen, the oxides of nitrogen, carbon dioxide, and so on. He was one of the splendidly named pneumatic chemists. Dalton asked similar questions of water: why does it absorb various gases at different rates, and how can it absorb them at all? He constructed a complex scheme, based on the simple idea of matter being composed of minute particles. So each element of matter in a measurable amount of say iron or carbon, is composed of vast numbers of particles that are all identical, whilst unique to that element. This type of particle could combine with others to form larger but still minute particles of a different type. For the first type he used the term atom and for the second type compound. Of crucial importance was his proposition, based on his own measurements of the interactions of gases and liquids, that atoms combine with other atoms only in fixed proportions to form compounds. Thus the structure of compounds can be represented by fixed numerical ratios.[12]

Lavoisier and Dalton make a tragically contrasting pair. Lavoisier was born into a rich family, then inherited a large sum. He invested in a scheme running a private business for tax collection to pay for his own research laboratory. Both factors contributed to him being beheaded during the French Revolution despite his faith that respect for science and reason would save him from La Terreur. Dalton was a man of humble origins who developed a strong social and religious conscience which led him to be an outspoken advocate of that revolution. In Britain this made him the target of violent anti-revolutionary protest, but at least he survived through those desperate times.

Atomic theory was a huge boost to chemistry during the 19th century, but despite this, by the end of that period there were many scientists who studiously ignored atoms. Specially physicists were sceptical, on the reasonable basis that nobody had any direct evidence for their existence. A useful concept it may have been, but thoughts do not have mass, they cannot be measured.

Ernest Rutherford was typical of such sceptics in his supercilious dismissal of any field of research other than physics, but he was untypical in his daring open mindedness to ideas at the fringe of research. Rutherford arrived at the University of Cambridge from New Zealand, to study on a scholarship at the recently built Cavendish Laboratory. From there he moved to McGill University in Montreal and then to the University of Manchester. By the time he was there the existence of atoms had been indicated by Einstein in his theory of the phenomenon of Brownian motion. This is named after a botanist who observed, using an ordinary microscope, that pollen grains in water jiggle about ceaselessly, never settling. They are being knocked back and forth by molecules of water which constantly move and are best described statistically. It seems Einstein had never actually observed this but hopefully the school pupils who now see this in class, the real and actual thing, gain some glimmer of appreciation of its significance despite appearing absurdly simple. At the Cavendish lab J.J.Thomson had recently discovered electrons in the form of cathode rays and proposed these as part of atoms in the form of a rounded matrix of positively charged matter within which were the negatively charged electrons. He imagined them as fruit in a pudding. Or could the negative electrons be arranged in rings around some central form of the positive charge, as conceived by Hantaro Nagaoka in Tokyo?

Rutherford seemed to prefer Nakaoka’s concept of the atom, like Saturn with its rings. He asked: where can these charges be positioned in this atom? The problem he had with answering this was how to study an atom. How can a human researcher observe, manipulate, prod and probe something unimaginably small? By then they knew they were dealing with things of at least the scale of the fraction of one metre represented by eight zeros after the point. Little did they know just how much they would have to expand their imaginations.

The answer to their technical problem was radioactivity. This was a freshly discovered phenomenon, scarcely understood and a danger to those who worked with it. Henri Becquerel, working in France during 1896 on the problem of phosphorescence, found almost accidentally that salts of uranium produced a blackening reaction in photographic plates. It could not be phosphorescence because it occurred in the dark. This was soon followed up by Marie and Pierre Curie. Maria Skłodowska, as originally known, had started research as a student of Becquerel at the University of Paris. Whilst using the same ore that uranium was extracted from, she discovered first the element polonium, named after her homeland, and then radium. Both are characterised by decaying spontaneously in a process that produces particles they named alpha. Beta became the name for radiation in the form of electrons, and gamma for pure electromagnetic radiation slightly higher in frequency than X-rays.

Rutherford had taken an early interest in radioactivity and in 1909 he directed Hans Geiger and Ernest Marsden to set up an experiment where alpha particles were beamed at thin foils of metal. They expected that the particles would penetrate the metal to some extent and in doing so possibly be scattered by interacting with the charged constituents of the atoms. They detected and measured this scattered radiation by the tiny flashes of scintillating light it produced when it hit a plate of zinc sulphide beyond the foil. This was long before the days of automatic scintillation counters; they peered for hours on end down a microscope focussed at the back of the zinc sulphide detector. The results astounded them. Rarely, but reliably, the massive alpha particles were bounced straight back from gold foil rather than merely deflected a little. It was like firing a gun into fog and having the shell come straight back. The only conclusion was that the alpha particles were hitting a very dense and positive charge somewhere in the atom. To be so dense this charge had to be incredibly small. The inevitable corollary of this, with the crude knowledge they had of the size of atoms, was that atoms of gold entirely making up that material so iconic for its massiveness, were mostly empty space![13]

In some senses they still are empty space. Despite many details of Rutherford's ideas of the atom having later been proved false, there remains the bizarre knowledge that atoms are almost entirely empty space. The proportions of particulate matter to space are at the level of a penny piece at the centre of a football stadium; about 1 to 1 billion. Modern knowledge shows the stadium represents about four ten-millionths of one millimetre.

The physicists still sceptical of the existence of atoms must have felt gratified, for according the laws of physics as understood then such an atom could not exist. The Geiger-Marsden experiment was repeatable and incontrovertible but the conclusions were then, and remain today, at the outer margins of human comprehension. How can a knife made of hard iron gouge a piece of softer gold if the iron is mostly empty space; and simultaneously, if the gold also consists mostly of empty space why does the knife not slice through it like butter?

Rutherford reformulated Nagaoka's Saturnian image of the atom with a solar system image, the central sun as the positively charged mass and the planets as circulating electrons. This clearly required some explanation of what kept the electrons where they are. Can their positions, or orbits be described by the same Newtonian mechanics that astronomers use to trace the paths of Mercury and Venus? Why does Mercury not spiral inward under the massive pull of the Sun until obliteration — because it is travelling so fast in what would be a straight line except for the pull of the Sun. But if electrons travelled rapidly around the central mass, then according to Maxwell’s theorems of electromagnetic radiation, they should radiate energy and thus lose momentum and spiral inwards. Rutherford knew his model was implausible and unstable but had no alternative until a new student arrived at his lab in Manchester.

Niels Bohr came from Denmark originally to work with J.J.Thomson at the Cavendish laboratory, but found he could not agree with Thomson’s fruit pudding model of the atom. When he met Rutherford incidentally at the Cavendish lab he easily persuaded the New Zealander to take him on in Manchester. Two larger than life men working on things unimaginably small. Not Englishmen and not at Cambridge; thus with the triple advantage for lateral thinking of being a pair of double outsiders. Bohr knew the explanations by Max Planck and Albert Einstein of blackbody radiation. They gave him the strong hunch that the obvious stability of the atom was due in some way to these energy packets, these quanta. By this time physicists had borrowed the term nucleus, from Robert Brown’s naming of the body in plant cells, to describe their central mass. Bohr’s first tentative model used this proposition of quantum levels to produce a model of the atom with the electrons around the nucleus at discrete levels, thought of as shells rather than orbits. Crucially nothing was allowed between the shells. An electron could be in one orbit or another orbit, but never somewhere in between. Bohr needed some empirical evidence to support his idea. It was already available, and from an amateur researcher.

Johann Balmer earned a living as a school mathematics teacher in Switzerland. He devoted his private time to collating the spectroscopic results of many others on the four visible lines from hydrogen. He also predicted invisible lines in the infrared and ultraviolet ranges, which when experimentally demonstrated proved his formula of 1885. He suggested a concept of electrons spaced out around the nucleus at positions represented by whole numbers, not by tiny fractions. Then Bohr used this in a colossal intellectual effort, published as a triplet of papers in 1913. The result was a mixture of Newtonian mechanics to describe the momentum of electrons and quantum theory to confine electrons to orbits separated from each other in ratios of whole numbers. His key theory used four physical constants, including Planck’s. The equation Bohr obtained by this means could be used to derive accurately Balmer’s formula on the spectral lines of hydrogen, that Bohr had recently come across. This was just the beginning of quantum explanations of the atom — there was a long way for Bohr and many others to go and the further they went the weirder it got, as if steel knives consisting mostly of empty space were not sufficiently bizarre.[14]

Things that glow in the dark: what makes phosphorescence?

Albert Einstein remained fascinated by the nature of light. He embarked on another theoretical analysis of Planck’s law of radiation in the light of Bohr’s developing ideas of the structure of the atom. Of special use for thinking about light was the phenomenon of fluorescence. This is named after the mineral fluorite, or calcium fluoride. When illuminated with invisible ultraviolet a lambent glow of visible light is produced. Similarly a domestic fluorescent light tube produces visible light by passing electricity through a thin vapour of mercury to produce ultraviolet which then interacts with a fluorescent coating on the inner wall of the tube.

Einstein considered atoms in a mass of material that was lit with electromagnetic radiation, say ultraviolet. The vast majority of the atoms would be in their ground state of energy, that is the electrons would be in their minimum permissible lowest orbits around the nucleus. Some particles of radiation would interact with electrons imparting sufficient energy to them to raise them step-wise into an unstable higher orbit. The particle of radiation would be absorbed in the process and excess energy from the collision would dissipate as heating of the mass of atoms. This he simply called absorption of radiation. Then, considering atoms with such raised energy levels, Einstein proposed that they could spontaneously emit a particle of radiation by collapsing down to their stable ground state of energy. The two processes combined produce fluorescence. So far what was proposed explained known physical phenomena and produced a confirmatory derivation of Planck's law of radiation. But Einstein went a step further. Using the same reasoning he proposed that if a particle of radiation were to interact with an electron in an orbit of high energy level, that was in that condition for some reason of chance fluctuation, then the incoming particle would not be absorbed. Instead it would interact with the electron so as to knock it down to a lower energy orbit. In so doing it would emit a particle of radiation in a way similar to spontaneous emission. However, the incoming particle would continue on its way and the newly emitted particle would do so as well — a pair of them. He called this stimulated emission of radiation.

Of central importance to the rest of this story is that he predicted that these paired particles would proceed in exactly the same direction and be exactly in phase with each other. That is, the pattern of the waves would exactly match in every way. The pair of particles would be coherent. Thus there was publicised a glimmer of a theoretical possibility that radiation could not only be amplified, but when amplified it would also be coherent and of a single frequency. Einstein had taken a big bold step indeed, but did anyone take any notice? And if so, did they ask themselves what on Earth could be the value of amplifying light? Einstein published this idea in 1916 and followed it with a review of his ideas on light the next year.[15] Thereafter he moved on to consolidate his earlier ideas about relativity. But he still had a little more work to promote on the nature of light.

Satyendra Bose was a lecturer in physics at the University of Calcutta, then at Dacca University, so named during that period. He was an ardent follower of Einstein's ideas and decided to attempt another derivation of Planck's law of radiation without using any Maxwellian wave theory of radiation. He attempted a statistical explanation of the interaction of atoms and radiation using the principle, recently developed by Werner Heisenberg, of uncertainty concerning the characteristics of electrons around the atomic nucleus. When Bose sent his paper for publication it was rejected because the editors thought he had made a simple mistake in his calculations. So he sent a copy to Einstein, soliciting his opinion. Einstein not only approved but assisted the paper into print by making a paired submission to another journal.[16] The paper established that all radiation particles must be identical. Because of this they have a statistical tendency to travel together. This proposition consolidated the concept of coherent radiation. Bose had established the last of the four cornerstones of original quantum theory: Planck's law of radiation, Einstein's explanation of the photo-electric effect, Bohr's theory of the atom.

However, this is as far as we need to go with the development of quantum theory for this story. Just as Newtonian physics describes the way nature works with ample sufficiency for engineers to send a robot to a particular crater on Mars, so this intermediate model of the atom was sufficient for some people to consider how the quantum effects can be exploited for practical use. The concept of the atom as mostly empty space with a miniscule nucleus and electrons distributed at discrete steps away from the centre did not last long. Electromagnetic radiation was soon conceived of as packets of wave energy. They were endowed with a new name, photon, coined by the physical chemist Gilbert Lewis in 1926 to replace the 'lichtquant' of Einstein.[17] But they remained elusive and it was not until the 1970s that conclusive experimental evidence of their existence was provided. The riddle of solid-emptiness was soon to be partly solved by concepts of electrons as both particles and energy waves fully occupying the space in the atom. What mattered for many practical applications of the theory of the atom was the question of how electrons may be forced further steps out from the nucleus and thus into a useful level of higher energy.

But the flow of this story here hits a flatland and meanders slowly. Quantum theory was in the doldrums: not surprising considering it was so difficult to understand at its frontiers that the leaders in the field would soon be admitting their own incomprehension. The First World War, the Great Depression, and then the dispersal of scientists fleeing fascism and the start of the Second World War were all barriers and backwaters to the flow of ideas.

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Can the same thing be done with light?

Other researchers had a more commercial turn of mind. They saw themselves as people who could earn a good and respectable living by being an inventor. Someone who sets out to create a new device of obvious use, rather than someone who does science research that occasionally opens a door to a new device. Specially America was the place to do this. But bear in mind that Valentin Fabrikant in Moscow more than a decade previously had proposed a system that could, if constructed, amplify radiation in the radio and optical ranges. The patent for the idea was eventually granted in 1959, but by then it was superseded by developments elsewhere; property rights were of low priority in communist Russia.[32] Nevertheless, Einstein's theory of stimulated emission and more recent demonstrations of how to produce inverted populations of molecules in the laboratory continued to prod the imaginations of potential inventors.

Gordon R. Gould came to the Columbia Radiation Laboratory in 1949 to study for a doctorate. He had briefly worked on the Manhattan Project and then taught undergraduate students in physics. Also his life as an inventor had started with an idea for a type of soft contact lens he tried to develop. He was allotted to Kush as supervisor on a project to study the fine structure of the metallic element thallium using a molecular beam machine. This was a chunky metal tube several metres long complete with magnets to separate the high and low energy atoms and a furnace to vaporize the thallium. Heat was a troublesome source of energy for this so Gould struggled with it with little success. One day Rabi came to his lab and told of a his recent visit to Kastler in Paris, of how Kastler was using optical pumping successfully. As a technical novelty it excited Gould's talents as an inventor — it would be the first use of optical pumping in America. Anyone with an elementary knowledge of physics would have appreciated that if the system produced radiation of the frequency of light then it could direct more power. The energy radiated from a vibrating atom or molecule increases by the fourth power of the frequency of the radiation, so Gould knew he could pack hundreds of thousands times more power into an optical beam than a microwave beam. He would also have known the corollary, from the work of Boltzmann and Planck on their blackbodies, that to achieve higher frequency somehow vastly more energy needs to be pumped into the system.[33]

Instead of a molecule of appropriate structure to vibrate as a whole to produce microwaves, what was needed to stimulate emission of light was an atom with a structure such that its electrons would act as the vibrators, in incredibly rapid transition up and down their energy levels. The atom Gould proposed using was potassium. This was natural progression from his studies on thallium; potassium is a similar metal. It is soft and highly reactive, the stuff of dramatic demonstrations by chemistry teachers, but it can be manipulated as a vapour in a transparent tube. Most importantly, Gould considered its simple structure should permit the the creation of an inverted population of high energy atoms, followed by stimulated emission of photons. By absorbing energy in this way the potassium would act as the gain medium for the system. It would be in this medium that the initial amplification of light would occur. The basic state of lowest energy that the electrons can occupy is the ground level. Normally in a mass of atoms most will be at this ground level of energy. However, if extra energy is supplied to the atoms, such as from incoming photons, then some of the atoms will absorb photons and go into a higher energy level. These higher energy levels are designated 1, 2, 3 and so on, with sub-divisions of these levels. What Gould envisioned was that potassium atoms that had absorbed energy would then drop to a level called a metastable state where they would stay for relatively longer than in the highest state (longer in terms of minute fractions of a second). The inverted population of atoms would accumulate here so that when the atoms eventually dropped from the metastable to the ground state then stimulated emission of photons would occur. This was referred to as a three-level system. Somehow, to get light as a usefully intense and coherent beam from such a system, the initial tiny level of stimulated emission, would have to be improved. It would need to be manipulated so that a positive feedback was created and the light could be directed as a very narrow beam.

Gould lost interest in the fine structure of thallium: he was onto the Big Idea of his life as an inventor. It was, like many inventions, a novel insight of how to combine various ideas and methods of others. In this case one essential method was derived from an invention in 1899 by two researchers in France: Charles Fabry and J-B. Alfred Pérot (the same Fabry who discovered the ozone layer of the

Earth). The Fabry-Pérot interferometer is used to differentiate the frequencies of light. It consists of a pair of mirrors aligned very close and exactly parallel to each other. Gould proposed that such a pair of mirrors, placed at either end of the tube of potassium vapour, would provide the positive feedback of the light. This would entrain the light into a narrow, coherent and intense beam, to be fed out through one of the mirrors that would be partially reflective. A space in which the light would oscillate back and forth; a resonant cavity. As more and more pairs of electrons travelling together came to be travelling exactly in parallel with other pairs, a chain reaction would occur, vastly increasing the number of coherent photons produced. Thus there was great potential to extract very concentrated power from the device. To supply plenty of energy for maintaining the inverted population, the medium would be optically pumped.

However, this was not the first time that a Fabry-Pérot system had been proposed for use to produce an oscillating positive feedback for radiation. Robert H. Dicke of Princeton University had applied in 1955 and 1956 for patents for microwave oscillator systems and were both granted in 1958. The latter patent contained a proposal for using parallel mirrors to act as a resonant cavity producing a coherent beam. Prokhorov was working along the same lines, he proposed such a system in a paper of 1958.[34]

In November of 1957 Gould described his idea in this notebook as: ‘Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation’. He had the nine pages of description officially notarised at a street store near his home. Maser was transformed into laser for the first time, although as Art Schawlow teasingly pointed out at a conference, technically the acronym should have been formed from Light *Oscillation* by . . . Gould the inventor stated clear ideas of what his laser would be used for: communications, radar, television, astronomical spectroscopy, chemical reactions, even nuclear fusion.

Life in the stimulated emission business was getting tense, specially for Gould. By some bizarre misfortune he gained the impression that to patent his idea he needed a working device. The US Patent Office actually requires this of only one invention: a perpetual motion machine. For any other proposition, what is required is sufficient detail on paper that anyone *skilled in the art* could make the device; that is, *reduce it to practice* as patent examiners say. He should have borrowed some money to consult a patent lawyer about applying for a paper patent before his obvious competitors did. Instead, he left his doctorate studies uncompleted and sought a post in an electronics company on Long Island, New York. He calculated the Technical Research Group would be receptive to his ideas and provide the facilities to construct his laser. Not only was there potential competition from laboratories working on masers, including such powerhouses as Westinghouse and Bell Labs. Also a few doors along the same corridor that Gould did his doctoral studies was Charles Townes. Gould and Townes had consulted each other over these developments; they had a good idea of what the other was thinking and worked in a single buzz of circulating ideas, methods and gossip about what the competition in other universities and institutions were up to. On 14 September 1957 Townes had described in his notebook a system for amplifying light using thallium vapour as the gain medium, with optical pumping and a silvered reflective glass box of about 1 cm dimension to form the resonant cavity.

He titled it ‘Maser of optical frequencies’ and he had his notebook witnessed by a colleague several days later.[35]

Townes was acting as a consultant to Bell Labs where his former doctoral student Art Schawlow had recently moved. Schawlow improved Townes’s concept, changing from a fully reflective box to a Fabry-Pérot pair, and using potassium instead of thallium. They submitted in August 1958 a paper on ‘Infrared and optical masers’, using a term that was an oxymoron but at least avoided using Gould’s derivative acronym. They provided much theoretical backing and general ideas for construction. But they avoided explaining how to handle the vigorously reactive potassium vapour and other engineering difficulties. Nor were practical applications described beyond more spectroscopy studies and frequency standards. They filed for a patent in July 1958 and it was granted in 1960.[36]

The state of interest and funding for lasers about 1957 strangely was at a low ebb. Researchers were pessimistic about pumping enough power into a medium to get stimulated emission at such high frequencies. The second law of thermodynamics loomed dauntingly. Big communications and electronics companies were focussed on sending signals as electricity down wires or as radar through the air. Similarly inclined were the the military agencies. Then one day early in October a strange bleeping signal appeared from space: Sputnik! It had been launched on rocket designed to carry nuclear bombs. The shock to the psyche of American science and strategic technology knocked the establishment from their complacent assumption of superiority. By February 1958 the Pentagon set up their Advanced Research Projects Agency. All of a sudden innovative space research became a priority and researchers on masers and lasers found themselves already in there with a head start.

At the TRG lab Gould soon was able to secure a large grant from ARPA, with the support of Townes as a referee. TRG had asked for $300,000 — ARPA offered them $1 million! Naturally the Department of Defense insisted the project was classified as secret, so security clearance was required for anyone actually working on it. A crazy situation soon developed where Gould was prevented from hands-on work for his own project. Although he had served briefly on the Manhattan Project he had been dismissed, together with his girlfriend, because of their involvement with a Marxist study group. He then found himself obliged to prove he had put his communist and socialist sympathies and friends behind him. Although the Cold War and the anti-communist paranoia that had been stirred up by Senator Joseph McCarthy was waning, the bureaucratic momentum of security rolled on. Gould and the companies he worked for never did turn his original idea of a potassium laser into a working model. He did however tenaciously fight an extraordinarily long, complex and historic battle over patent rights. He and his lawyers based it largely on his original laboratory notebook and the public notary’s stamps and signatures. All the while he was working as an inventor, consultant and company director in the laser business and in one occasion of high tension Charles Townes was called to testify against his case before a jury. Unsuccessfully as it turned out — that was the case in 1987 where Gould won comprehensive patent rights.

A more starkly contrasted pair of researchers competing in the same field it would be hard to find. Charles Townes was by then an epitome of the successful and respectable scientist: Nobel Laureate, numerous fine papers and grants, serving on government committees, a family man with four children, writing about his hopes for a convergence of religion with science. Gordon Gould never recovered professionally from his prolonged problems with security clearance, specially when he had an affair with the security officer of TRG. He published one paper from his doctoral study before turning to invention and industrial work, he smoked too much and spent his weekends aboard his ocean sailing yacht. But eventually he was granted intellectual property rights on a single principle. That the mechanism of the initial amplification of light in the gain medium is more fundamental to the operation of lasers than the oscillation of light in the resonant cavity. Not just his original proposition for a laser; by then amplification in the gain medium was the starting point of the workings of all lasers. The patent lawyers at Bell Labs who handled the patent application of Schawlow and Townes for their optical maser had deliberately been non-specific about amplification in an attempt to cover many possibilities. Nevertheless, during the 17 year life of Gould's patent there were royalties of $100 million to be paid on the growing number of highly successful commercial lasers from other firms. The debts to his patent lawyers were paid, giving them a grand profit, and Gordon Gould enjoyed his well deserved riches at last.[37]

This patenting saga was confounded throughout by the interchangeable use of terms by researchers. Amplifier: the gain medium only, or gain medium plus the oscillator? Oscillator: an atom changing position relative to the rest of the molecule, or a metal box? Resonator: an electron changing position relative to the nucleus of an atom, or a pair of mirrors? Meanings evolve as research progresses; researchers in a peer group know what they mean in specific context. But if the people and the context change then the revered precision of science wobbles on shaky communications; specially if using words rather than mathematical symbols. Patent disputes in the USA are now held before judges only, not juries.[38]

Gordon Gould celebrated a rueful vindication as inventor and had already enjoyed one of the early benefits of lasers in a very personal way. After a cataract operation in 1985 one of his retinas became detached. It was fixed back in place using an argon laser specifically made for eye surgery. That use had originated in 1960 when some ophthalmologists at a hospital near the TRG lab asked to borrow one of their first working lasers from a colleague of Gould. They wanted to test these interesting new gadgets for risk of burning. The request contravened security restrictions. Nevertheless Gould helped smuggle it out of the lab, keen for any involvement with researchers who might give them some practical feedback. What the medics actually discovered was the ability of the beam to cut and weld deep within the eye without damaging intervening tissue: the beginning of optical laser surgery. Not even Gould's fertile imagination had anticipated that in his original list of potential uses.[39]

Rare gases and advertising lights – what is the message?

The optical maser proposal of Schawlow and Townes was a sharp incentive to many others to work at optical wavelengths. Although Townes and Schawlow were reticent about the commercial use of these devices others were more businesslike. The wish-list of applications was growing and lavish funding from military agencies flowed on. The close association of Bell Labs with the Columbia Radiation Laboratory enabled them to entice likely inventive researchers to their programmes. Ali Javan had made doctoral studies on molecular structure with Townes and continued at Columbia for another four years to study masers. There he innovated another method for creating an inverted population.

In contrast to the three-level systems proposed by others, such as the ideas for potassium vapour of Schawlow and Townes with a single element as the gain medium, Javan proposed a mixture of two elements. Gases were considered suitable because they are highly homogenous; the statistical contingencies of Boltzmann notwithstanding. The gas mixture should readily absorb light and spontaneously emit it, in other words be fluorescent. Neon was the obvious gas for this property, as Ladenburg had shown, and helium was its ideal partner. Javan calculated that energy in the form of electrons absorbed by the helium would be transferred to the neon by atom to atom collisions. This would produce an inverted population of neon atoms followed by stimulated emission of radiation from them in complex paths; in total involving four energy levels.[40]

Javan accepted a post with Bell Labs at their facility in Murray Hill, New Jersey, in 1958. He was ambitious for a university professorship, so persuaded his managers to give him an open remit and funding for original research on lasers. Theoretically, the four-level system he proposed would be more efficient and more likely to produce a continuous beam than three-level systems, but he knew it would be more difficult technically. For a start the ideas on optical pumping current at the time seemed inefficient for a gas, the radiant energy would tend to pass through the thin gaseous medium without sufficient transfer to achieve an inverted population. However, light tubes containing the gas neon, excited into spontaneous emission of red light, had been in use for many years. Of course, both these light tubes are energised with electricity, so Javan thought along that line from the start rather than optical pumping. The critical needs to transfer the concept of a neon or fluorescent light tube into a laser were producing an inverted population in the gas in which stimulated emission would occur, and then increasing that using a pair of Fabry-Pérot mirrors. This soon grew into a very complex technical challenge, but Javan managed to recruit to his team firstly William R. Bennet who had studied manipulation of energy levels in gases for his doctorate at Columbia with Chien Shiung Wu as his supervisor. Then from within Bell Labs he obtained the services of an optics expert, Donald R. Herriott, who had learnt his skills at the optics company Bausch & Lomb.

Laser research was becoming intensely competitive between firms and universities. Even within Bell Labs there was John Sanders, invited there to work on sabbatical leave from the University of Oxford, proposing a similar gas laser. In September 1959 Charles Townes had, with sponsorship from the US Office of Naval Research, organised the first conference on the topic at Shawanga Lodge, in the Catskill Mountains of New York State. Over 160 workers attended, from nine countries, to present 66 papers. Laser was the topic of only two papers but it was the hot one. Essential ideas and data were out in the open, even if details on how to actually construct a laser were held back. The race was on.

The gas system proposed by Javan was a combination of helium and neon in which electrical current flowing through the mixture would energise the neon for stimulated emission to occur. The correct ratio of the two gases and their low pressure in the quartz tube containing them was the result of exceedingly difficult calculations of the possible behaviours of the atoms at their respective energy levels, coupled to endless experimental testing of the calculated predictions. The mirrors were equally difficult. The basic gain of stimulated emission expected from the system was known to be always low, about 1.5%. Thus the reflectivity and parallel alignment of the mirrors was critical. Not any old reflectivity, but that optimised for the wavelength of light anticipated from the laser, in the infrared range. At Bausch & Lomb they had first to polish silica mirror plates at a tolerance of a small fraction of the wavelength of light. Then they coated them with extremely thin layers of alternately magnesium fluoride and zinc sulphide. Thirteen layers in all, pushing the technique way beyond the state of the art. Then the mirrors had to be aligned as accurately as possible, along a tube that had to be one metre long to obtain sufficient gain in light. Of course, they needed a laser measuring tool for this. They did not have one, so fiddled with micrometer screws to move the mirrors mounted at the ends of the quartz tube. Even the radiation they were producing from the apparatus was difficult to measure because the only instruments made to record infrared were so crude that heat energy radiating from just the fabric of the laboratory interfered with their measurements. Trial and error, 'suck it 'n see' in both the gas and mirror systems was the standby, there was limited time and empirical data to try to calculate what should happen. The tolerances of the system were almost impossible. Endless hours were spent in the lab. The place filled up with very expensive equipment that, to the exasperation of the managers, seemed to produce few results. Few of their peer group believed it would work and Javan knew that Bell Labs were becoming impatient. The enterprise was a brave lonely journey of faith into the realms of increasing your luck by throwing the dice more often.[41]

'Now, all of a sudden, it looks easy.'

Hughes Aircraft Company was formed by the highly entrepreneurial and eccentric Howard Hughes and had prospered by manufacturing aircraft during the war. Later they diversified into development and manufacture of specialist electronics. In support of their commercial research they built the Hughes Research Laboratories, at Malibu, just west of Los Angeles. It included a department of Atomic Physics. A new recruit there in 1956 was Theodore H. Maiman. He had completed a doctoral study with Willis Lamb at Stanford University and then shocked his academic mentors by going straight into industrial work with Lockheed Aerospace at Van Nuys, California. He wanted to get out into what he called the 'real world'; although he soon found himself acknowledging the debt he owed to Willis Lamb for the understanding of quantum phenomena imparted to him. A major contract for spacecraft development failed to emerge from the pipeline so Maiman sought a similar firm. Hughes's Atomic Physics Department was headed by Harold Lyons. So with the background in microwave spectroscopy of helium with Lamb, coupled with Lyons's appreciation of the physics of masers, it was natural that Maiman should apply for funds to carry on with work on resonance phenomena. He obtained a grant from the Air Force, but soon found himself also dealing with a project funded by the Army Signal Corps to make a type of maser that used a solid medium to amplify microwaves based on the principles described by Schawlow and Townes. Propositions for solid state masers had been rapidly developed by Nicholaas Bloembergen at Harvard and put into practice at Bell Labs. The most robust of these had been developed by Chirhiro Kikuchi at Michigan University. They used a large artificial crystal of ruby, doped with a small amount of chromium, and the power was supplied by very powerful magnets. The ruby masing medium needed to be cooled to -269^{o}C in liquid helium (to maintain the inverted population) and to insulate that from the warmth of the laboratory the helium container had to be immersed in liquid nitrogen. All in all the cumbersome rig weighed more than two tonnes. Definitely not the sort of specialist consumer electronics product that Hughes needed most to develop its business.[42]

However, masers working on this principle became popular for new astronomical studies which used their ability to amplify minute traces of microwave radiation; from the hot surface of Venus for example. A brief but splendid moment of fame came their way as well. Two physicists working for Bell Labs, Arno A. Penzias and Robert W. Wilson, used such an astronomical maser on a project for satellite communications. As a purely incidental finding, based on meticulous efforts to eliminate an unwanted background signal of microwaves, they discovered in 1965 that the signal came from outer space. It was a ghostly remnant of electromagnetic energy from the birth of the universe, from the Big Bang.

Maiman already had been thinking about the possibilities of making a laser. The working maser and then the paper on optical masers of Schawlow and Townes of 1958 had enthused many to attempt a working laser. However, Maiman had a low opinion of vaporised potassium as a medium. To him the practical advantage of using a solid medium to amplify light was obvious and on this maser project he soon revealed his creativity. He put a small permanent magnet directly around the ruby and put both into a small container full of liquid helium. A neat device of about 10 kilos that could be fitted to the focus of a radar receiving dish was soon delivered to the Signal Corps, who used it as a research tool. Maiman became hooked on the business of amplifying radiation but vowed it would produce light, be small, and work at room temperature. He sought the essentials of something that could be sold in large numbers to ordinary customers. He intended to make his fame and fortune as an inventor.

He would need all the determination he could muster. The Hughes Research Laboratory is in a romantic location at Malibu but scenery is not what you need as a researcher, it is contacts and ideas. Research on masers and stimulated emission was principally an east coast business, still with the focus at university labs but increasingly in commercial labs. There were International Business Machines, General Electric, Westinghouse, and Radio Corporation of America in addition to the original Bell Labs, all of whom kept their information to themselves. Maiman was not only isolated but the lab at Malibu was at first uncongenial for such work. His managers considered maser and laser a research sideline and Maiman had to duck and weave to fit his enthusiasm into other commitments to properly funded development contracts. At first he had difficulty to persuade them to spend $1,500 on a monochromator device from Bausch & Lomb for measuring the radiation output of ruby. He had one of these available at Stanford as a doctoral student. Hughes's business was dominated by contracts with defence agencies for electronics development and manufacture but they did have a General Research Fund supplied from overheads on these contracts and Maiman's prestige from his success with the maser for the Signal Corps was sufficient for him to obtain $50,000 from it.

Rubies and sapphires are gemstones consisting of corundum, a crystalline form of aluminium oxide. Ruby owes its beautiful red glow to a small proportion of chromium oxide; other metal impurities give the blue to sapphire. The hard crystals can be grown in the laboratory and are made for bearings in watches and similar instruments. The chromium ions are, serendipitously, crucial to the quantum dynamics of the production of an inverted population of molecules within a crystal in a maser or laser. They impart to ruby its ability to fluoresce, by absorption and spontaneous emission of red light, when the chromium ions are energised to higher levels by ultraviolet radiation. A few specialist manufacturers could produce very high quality ruby to specification for research. The precise shape of the ruby to be used was a crucial part of the innovative process at Malibu. At first Maiman used a one centimetre cube, mirrored into a Fabry-Pérot formation for resonance, but that design owed more to work on masers, and it was probably more than coincidence that the optical maser of Schawlow and Townes specified a similar resonant cavity to achieve oscillation. The purity and uniformity of the crystals was also very important. In contrast to the gaseous media being tested by Javan and others, where the mixture of pure gases is without inconsistencies in its structure, tiny flaws in the crystal lattice of a solid-state medium sent light bouncing everywhere. Furthermore, what Maiman had to do with his crystals was to energise them sufficiently to produce a large inverted population of chromium ions. Thus they would stimulate emission of light in a three-level system. Maiman tried the largest conventional lamp he could find, a monster at 1000 watts from General Electric, using a mercury vapour arc. It needed special cooling and to get the light onto the relatively small ruby it had to be focussed. At least the light was intense and in the blue to green spectrum theoretically ideal for the ruby medium but handling these bulbs was inconsistent with Maiman's concept of a consumer device.

A glowing light bulb to represent an inventor inventing has become iconic. Probably it derives from Thomas Edison, but it suits Maiman's flash of inspiration. He tried what at that time was a specialist type of photographic lighting, an electronic flash lamp. These produce, from a jolt of electricity at high voltage and current, a very short and intense light. The colour temperature, relating to blackbody radiation, as measured in degrees kelvin is about 8000 degrees, considerably greater than that of the surface of the sun. Maiman calculated that 5000 degrees would suffice for ruby. Best of all for his concept was the serendipity that the highest intensities were available from lamps in the form of short tight helices. So the ruby, as a cylindrical rod, could fit inside the helix. It would be mirror coated at both ends and be massively pumped along its length with high intensity light. Rising like a phoenix on the laboratory bench in Malibu was a device remarkably convergent with Gould's proposition as a notebook sketch. There only one snag, but a big one. These bulbs are made specifically for photographers and researchers to give a movement-stopping flash of milliseconds. If lasing action was to be achieved with this device it would have to be at the expense of continuous action; pulses only — so be it.

Maiman was short of funds and moral support, but at least at this stage he had the assistance of Irnee D’Haenans, who patiently performed the experiments and calmed his boss’s frayed nerves. They formed a pragmatic pair with one objective. To beat the competition from all the big players to produce the first working laser. For that they needed to demonstrate that this entirely theoretical proposition, relying on quantum phenomena still poorly understood, could actually exist. This was not a case of developing a design for a consumer laser product. It was a case of producing an entirely new physical phenomenon: photons at the wavelengths of light that were coherent, monochromatic and in an intense beam. Could they reveal themselves as a tiny spot of bright pure light projected onto the far wall? Too bad if their laser was pulsed: first demonstrate it works. Anyway it could still be useful and well adapted for something so powerful.

By time D’Haenans set up a test run on 16 May 1960 they had refined their device to something, that to later observers, looked absurdly simple in comparison with the ungainly contraptions in the typical university physics lab. They now had a neatly engineered device that looked like a product for sale off the shelves of an electronics supplier. The ends of the rub rod were finely polished and mirrored but the tolerances of this Fabry-Pérot system could be generous because the ruby provided such a high gain of light. The energy for optical pumping was provided by robust flash lamps available through catalogues. It was all housed in a small aluminium container whose form pleasingly matched its function. On a Hughes’s Memscope, an oscilloscope for recording flashes, the recording from the device suddenly shot up to a tight peak totally unlike the previous traces. This was it! For the first time ever and anywhere, incoherent light had stimulated molecules into a vibrating inverted population in which stimulated emission of monochromatic light was amplified, and this light was then oscillated in the resonant cavity to form a coherent and intense beam. Before, stimulated emission of radiation was an obscure idea of Einstein in a dusty old paper — the weird equations of quantum mechanics. Now it was being made to happen in little box of tricks at the flick of a switch. The totally deceptive simplicity of this laser was a mark of genius at engineering design. To explain the physics used in the invention, starting somewhere about where Schawlow and Townes had left off with their optical maser paper later, took Maiman and his colleagues 12 pages of dense description and equations in two research papers.[43]

Hughes Research Laboratories became interested. Harold Lyons rallied round and made sure Maiman obtained good publicity and a supply of ruby crystals of favourable dimensions and purity, specially grown at the Linde company, part of Union Carbide and the only US manufacturer. This enabled the team finally to project their beam to show as a bright spot of red light on the far wall; something that had eluded them at the first demonstration done with a cruder crystal and imperfect mirrors. Maiman had entered the Hughes company with a determinedly independent attitude; refusing to sign their standard form on patent rights. He wanted full credit for his discovery and invention, both as a research paper, to be followed by a patent application within the year allowed after publication of a paper. The problems that he then encountered resembled those of Gould in severity, if not in duration. Firstly his paper staking his claim to priority for the working laser sent to *Physical Reviews,* was returned by the editor without even being refereed. Maiman had reluctantly used the term maser in the title for tactical reasons. By then the journal had so many papers on the burgeoning topic of masers that the editor had imposed a moratorium on any more of that routine. In frustrated shock Maiman submitted a substitute paper of 260 words to the journal *Nature* where it was promptly published in August 1960. Priority was duly claimed, but with embarrassingly few details. Then to Maiman's horror he found a pre-print version of the paper with full technical details that he had alternatively got accepted for the *Journal of Applied Physics*, in print as an unauthorized paper in a British trade publication.[44] Maiman's eagerness to get out of academia and into the real world seemed to have isolated him from staff-room gossip about the games needed to weave through the obscurely competitive workings of journal publication.

There was worse to come. Hughes initially declined to proceed with patenting the laser. Maybe it was, as someone at a conference in the early 1960s said, a solution looking for a problem. Possibly the managers of a military electronics manufacturer held similar opinions, despite Maiman's clear statement of four significant uses in the press release about the invention. Some of the competitors thought otherwise; Javan and team had both demonstrated a working device and filed for a patent to their gas laser in December 1960.[45]

To anyone unfamiliar with the quantum mechanics on which the device was based could be forgiven for thinking that the simple appearance of the first working laser was the work of a plumber. Death-rays were not on Maiman's list, but some newspapers soon promoted that desolation. Neither did it help that the competitors, the big teams in the east, found it hard to believe that this pair of outsiders, in an outsider company, could have gained such a coup. Specially so since they seemed to arrive on the scene from nowhere — it took Maiman and D'Haenans about nine months to produce their first working laser. After much politicking within the company an application was made in April 1961, with Maiman conceding his rights in exchange for a small sum of money. Eventually, the first patent for a ruby laser was issued in 1967, assigned to Hughes, with Maiman as the inventor.[46] Hughes made a lot of money on that patent which was of the type known as reduced to practice in contrast to a paper patent. There was little chance of successful counter claims by others developing lasers, the original working device preceded the patent application. By this time Maiman had formed his own company, Korad, after coherent radiation, to design and manufacture very powerful ruby lasers for range-finding and similar uses. He continued as a successful businessman, and in his own words, maverick inventor. He once asked: 'What is an inventor.' Despite his feisty individuality he acknowledged, in reply to his question, that Valentin Fabrikant was the innovator of the concept of lasers, but no one else.[47]

Obviously Maiman and D'Haenans were the inventors of the laser because they were the first to produce a working device. They had beaten Ali Javan and colleagues by six months. The Bell Labs team acted as if they did not believe it, but eventually they enjoyed a massive compensatory victory. By March of 1960 they achieved the first amplification of light at the required wavelength with their helium-neon gas apparatus, the HeNe system. The technical difficulties with their very demanding proposition delayed them until December 1960. The mirrors in the apparatus operated at such fine tolerances that small vibrations in the lab would misalign them. At last on the 12th of December Javan, Bennett and Herriott achieved genuine laser light. Not only that: because it was continuous it could achieve very high coherence. Very soon they found, accidentally, that this continuous beam would vary in strength as the mirrors were displaced out of perfect alignment just by vibration from their voices. The Bell Telephone Company had been formed in 1877, a year after Alexander Graham Bell had been issued with the first patent for the telephone. The team's response to the prompt of history prompt was to connect the apparatus to a telephone and then try to remember Bell's famous first words over the wires in demonstration of the communications potential of their laser beam: 'Come here Watson, . . . (?)'. The patent for the gas laser of the team at Bell Labs was issued in 1964; the first for any type of laser as a working device.

Communication applications came later, transmitted by laser light down fibre optic cables. The first commercial use of lasers, of the HeNe type, was soon to be barcode readers. As Maiman explained, once the unknown has been shown possible '. . . all of a sudden, it looks easy.' Hopes and propositions metamorphose into physical presence and everyone's attitude changes. A massive business was born and matured to the state where now, in the room where I type this, I can identify four lasers; cheap, out of sight and mind. Magic-like tiny semi-conductor devices in the compact disc readers of this computer, and the best one of course is the laser pointer beam for my lectures. Too easy to shrug shoulders and think it some some clever version of an ordinary torch; far better is the flash of being reminded of some of the quantum dynamics that are manipulated to create the beam. Too easy it is to be fooled by assumptions about how such things may be invented. Various authors have speculated why the laser was not invented during the heyday of optical spectroscopy, using Einstein's basic theory. They conclude it needed a joining together of understanding and technical capacities from electronics and short-wave radar, microwave spectroscopy and the study of structure of atoms, from optics and the study of fluorescence. But more obviously, there was only the vaguest demand for jobs that could be done by masers and lasers. Such devices were inconceivable to nearly everyone, so who would set out to invent one? As Charles Townes wrote in his autobiography: 'What research planner, wanting a more intense light, would have started by studying molecules with microwaves? What industrialist, looking for new cutting and welding devices, or what doctor, wanting a new surgical tool as the laser has turned out to be, would have urged the study of microwave spectroscopy? The whole field of quantum electronics is almost a textbook example of broadly applicable technology growing unexpectedly out of basic research.' Let the laser's inventor, Ted Maiman, have the last word: 'Keep in mind, it was not a given that anyone would ever succeed in making coherent light. It had never been done before! At least the Wright brothers could look up into the sky and see birds flying.'[48]

[End of this selection from Chapter 4. It is supported by a *Notes* section of 48 entries and a full *References* list at the end of the book]