Invent or Discover

the art of useful science

[Sample Chapter 6: Lasers]

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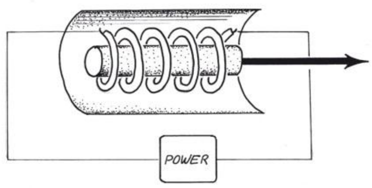

'At least the Wright brothers could look up into the sky and see birds flying'

(Ted Maiman)

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 mounted a short rod of ruby inside the spiral of a powerful flash lamp, all within a neatly polished aluminum cylinder. Step by step they increased the electrical power to the lamp, each time recording the trace of light that the energy induced in the ruby. The results were ordinary: a couple of broad peaks at fixed points along the spectral scale – the normal red fluorescence from ruby. They stepped up the controls until 950 volts, making the flash lamp more intense than the Sun. Suddenly our world changed. The recording trace shot up rapidly to a sharp peak of intense and pure red light from the ruby. They had created laser light, for the first time anywhere. Anywhere in the known Universe.

What they had made was, in essence, the same as the laser pointer you can now use in the classroom, the same as a mundane 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 too simple to believe, but Maiman and D'Haenens knew their invention was possible only by applying an understanding of quantum physics. That 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 no one believed a rod of ruby at room temperature could be the heart of a laser. The pair at Malibu kept to their working motto: 'Just do it'.

Stimulated emission of radiation

Albert Einstein was fascinated by light. To be more precise, fascinated by electromagnetic radiation of any sort including the small part of its spectrum that we call visible light. After his extraordinary papers on relativity he went on to probe mathematically into the new data and ideas of how light works coming from various researchers.

Heinrich R. Hertz's at the University of Karlsruhe was the first person to experimentally demonstrate electromagnetic waves. His idea of how they originate was that objects called oscillators that vibrating within atoms produced the energetic waves. Max Planck at the University of Berlin, who would become known as the father of quantum theory, had explained a strange property of radiation from hot objects. This was known as the blackbody problem, from the laboratory name of the heated dark cavity producing the radiation. Neils Bohr at Universities of Cambridge, Manchester, then Copenhagen in turn, had developed a theory of the structure of atoms that included the new idea of electrons.

Planck, in a paper of 1901, invented an equation that explained the radiating waves of Hertz by the extreme device of dividing up energy of the radiation into what he called energy-elements. This was instead of allowing it to vary smoothly from one level to the next because that did not work mathematically in a way that could explain blackbody radiation. Very small elements, one of them is equivalent to what is now called Planck's Constant, a decimal fraction with 26 zeros after the point. Bohr's idea of atoms allowed for a dense central nucleus surrounded by electrons at distinct levels, orbits, away from the nucleus. The further away the more energy required to keep the unit at that level. The electrons could oscillate and Einstein's crucial insight was to link oscillators to energy-elements. The faster the oscillation the greater the energy. Radiation became again thought of as particulate, just as Isaac Newton had originally thought of light.

As an example, Einstein considered fluorescent materials that glow when bathed with ultraviolet light. (Ordinary fluorescent light tubes internally produce ultra-violet light that makes the white inner lining of the tube fluoresce with visible light.) The vast majority of the atoms would be in their lowest state of energy, that is the electrons would be in the lowest orbits around the nucleus appropriate to their energy. Some particles of radiation would interact with electrons, imparting sufficient energy to raise them by a step into a higher orbit. That orbit would be unstable. 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. Einstein simply called this absorption of radiation.

Then, considering atoms with these raised energy levels, Einstein proposed they could spontaneously emit a particle of radiation by collapsing down to their stable ground state of energy. The combined effect of absorption of radiation and spontaneous emission of radiation would produce fluorescence. So far, what Einstein proposed explained known physical phenomena, and he produced a confirmatory derivation of Planck's law of blackbody radiation.

What came next was one of Einstein's leaps into the unknown. He thought of an electron in an orbit of higher than normal energy level, there for some reason of unlikely and random fluctuation. If a particle of radiation were to interact with this electron then the incoming particle would not be absorbed. Instead it would interact with the electron 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. But crucially, the incoming particle of radiation would continue on its way. Moreover, the newly emitted particle would travel with the incoming particle as a pair. He called this stimulated emission of radiation.

Of central importance to the story of lasers 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.

Into the public domain came 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 took a big bold step of enormous scientific and technological potential. Did anyone notice? If so, did they ask themselves what could be achieved with amplified light? Einstein published this idea in 1916 and followed it with a review of his ideas on light the next year. Thereafter, he returned to earlier work to consolidate his ideas about relativity, despite having 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 in those days. As an ardent follower of Einstein's ideas, Bose decided to attempt another derivation of Planck's law of radiation without using any theory involving waves. He attempted a statistical explanation of the interaction of atoms and radiation. When Bose sent his paper for publication, the journal editors rejected it. They thought he had made a simple mistake in his calculations. In exasperation Bose sent a copy to Einstein, asking for an opinion and help. Einstein not only approved but also added his name to the submission letter addressed to another journal. Bose demonstrated that all radiation particles must be identical. Because of this they have a statistical tendency to travel together. Bose had consolidated Einstein's idea of coherent radiation.

Physicists soon were thinking of electromagnetic radiation as packets of wave energy. These were endowed with a new name, photon, coined by the physical chemist Gilbert N. Lewis in 1926. Photons, however, remained extremely difficult to handle and it took until the 1970s for experimenters to pull from nature's grip conclusive evidence of their actual existence.

Electrons were a little easier. The riddle of the solid-emptiness of the atom, with its vast of empty space between the nucleus and the electrons, was soon to be partly solved by concepts of electrons as both particles and as 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.

Such theories of the atom, radiation and developing quantum physics then stagnated. It was all so obscure and counter-intuitive at its frontiers that the leaders in the field would soon be admitting their own incomprehension. The flow of these ideas was further impeded by the first world war, the great depression, dispersal of scientists fleeing fascism, political opposition to the sort of physicists who were prepared to venture theoretically so far from experimental facts, followed by the next world war.

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Richard C. Tolman studied statistical mechanics at the California Institute of Technology and was one of the first to take up the challenge of stimulated emission of radiation. By the 1920s, detailed information on the spectra of emissions from many atoms and molecules was available but little was known of how long an atom might stay in a higher energy state. Tolman used existing data from spectroscopic studies of atoms such as iodine and mercury to calculate this. Mathematically he derived a figure of a fraction of a second represented by seven zeros after the point.

Very insignificant that may seem at our human scale but Tolman reckoned that at the scale of atoms it could be long enough to allow stimulated emission. That is, light radiating onto mercury atoms for example, could be reinforced by light emitted as a result of collisions with electrons that were very temporarily in higher energy levels of the atoms. With the benefit of much hindsight, this was a distinct move towards the laser, but at that point Tolman left off with some observations on how his conclusions relate to Einstein's recent papers on radiation: '. . . hence somewhat indirectly to the extreme point of view of the existence of light quanta.' Physicists really were reluctant to accept quantum theory, but a few bold souls speculated on practical uses of the subject.

So many questions, so many experiments remained undone in those glory days of physics. Why does a beam of sunlight, shone onto a prism, disperse into an array of rainbow colors? This problem of dispersion, a problem of explaining what is it within the structure of a glass prism that splits light, intrigued Rudolf W. Ladenburg, working at the University of Breslau. He investigated the quantum physics explanation of dispersion using a spectroscope to measure radiation produced by electrical discharges through neon gas. His apparatus resembled neon advertising tubes of today. What he found contributed to the improving theory of dispersion of light but importantly for the development of lasers he also described how delivery of electrical energy into the gas stimulated the emission of light.

The electrons streaming from the electrical discharge point hit the atoms of neon and excited them to higher energy levels. The atoms very briefly stayed there then dropped to a lower energy level and emitted light in the process. Ladenburg had produced what is now known as an inverted population in the energy states of the neon. Without the electrical energy, the vast majority of the population of neon atoms in the container would be at their lowest energy level. When extra energy was supplied, a small sub-population would be moved into a higher energy level. This was referred to as a state of negative temperature, using concepts of thermodynamics. Ladenburg came very close to amplifying radiation by stimulated emission, but neither he nor his peers understood the achievement.

They were asking other questions, seeking other things: a better theory of the dispersion of light and a way to close the apparently widening gap between the wave and particle theories of light. In any case, this all seemed a bit absurd, the idea of negative temperatures. Not the minus 20 degrees of an ice-cube, this was meant to be a temperature *less* than absolute zero defined by the laws of thermodynamics as 0 on the Kelvin scale, or minus 273 degrees on the Celsius scale. Which was impossible according to the second law of thermodynamics. Absolute meant what it said – nothing goes beyond here. Don't even think about it!

Who was to be bold enough to venture into these forbidden territories? Valentin A. Fabrikant seems to have been the only person at that time to break through this conceptual barrier in a direction heading towards lasers. A doctoral student, he was completing his thesis in the Moscow of 1940. Thus unlikely to be over burdened by knowledge of what his elders and betters knew to be impossible. He claimed that an inverted population was attainable and that under such conditions an output of coherent radiation of a single frequency could be achieved; in other words an amplification of light. The thesis was left unpublished – life in Moscow in the 1940s was tough. So the details of this work were not revealed until 1951 when they were used to apply for a patent. A document that would have increasing significance in the fights to come over priority on invention of lasers. In the meantime, our story was about to take a diversionary path of science research around a blockage thrown up by dire political circumstances.

Military microwaves

The mathematician Paul Dirac, during and continuing from his studies for a doctorate at the University of Cambridge, predicted an answer to the question of how many energy levels are possible for the single electron of the element hydrogen. There must be two equal levels. Who could resist a challenge like that if they were capable of devising a better spectroscope? Willis E. Lamb's new spectroscope used electromagnetic radiation in the form of microwaves. These are a type of radio wave with unusually high frequencies. They had the advantage over optical radiation of lower measurement error due to thermal agitation of the atoms being investigated. Working at the Radiation Laboratory of Columbia University he and Robert C. Retherford set out to test Dirac's prediction. In a series of papers from 1947 to 1952, they demonstrated that were minute differences in the energy levels, now known as the Lamb Shift. Further explanations of this shift by other workers was to lead to even deeper waters of quantum theory – the electrodynamics variety.

Similarly, Edward Purcell and Robert V. Pound, at the Massachusetts Institute of Technology and then Harvard University, used a system in which a crystal of lithium fluoride was subjected to a strong magnetic field, then rapidly transferred to a lesser magnetic field which was instantly reversed in polarity. When they returned the crystal to the original field, the remaining magnetic resonance produced in the crystal showed a trace of inversions of the population of molecules in the crystal, with induction of radiation. Alfred Kastler and Jean Brossel worked at the Ecole Normale Supérieure in Paris using spectroscopy to study atomic structure, specially resonance within atoms. They bombarded atoms with electrons, producing both absorption and spontaneous emission of photons from the atoms. The emitted photons would then absorbed by other atoms which would move from their normal ground state of energy to a higher energy state. This process they soon called optical pumping. Think of the particles as marbles and the energy levels as a staircase – difficult to push the marbles upwards, but maybe not impossible.

The creation of inverted populations was not prestigious research but it was becoming more purposeful. Surely it would prove useful for understanding atomic structure and behavior? Isidor I. Rabi at Columbia University had since the 1930s been developing methods for studying the magnetic properties of atoms and molecules. In the process, he built up one of the strongest departments of physics in America and developed the technique of atomic or molecular beams. These were streams of molecules flowing in one direction and subjected to magnetic fields which would separate out molecules in higher energy states. The first moves toward deliberate manipulation of inverted populations occurred at this lab in New York.

The work of Rabi and colleagues would eventually lead to the development of medical imaging of the human body using nuclear magnetic resonance. Obviously that is another story and to trace the path to the laser into and beyond Rabi's lab at Columbia we need to step back into a world that became dominated by dangerous politics and rapidly changing military technology. Heinrich Hertz's development of the means of producing and detecting electromagnetic radiation in the radio wave frequencies was soon put to practical use. As early as 1904 patents were filed in Germany for devices to detect ships. At that time the need for such systems was not obvious to the shipping industry. Nevertheless, the development during the first world war of bomber aircraft, and the grisly revelation of their destructiveness during the Spanish civil war of the 1930s, impelled researchers to invent a warning of the approach of bombers and try to bring the aircraft to earth. Vast acoustic mirrors where tested on the south coast of England to detect the sound of approaching bombers. The Air Ministry of Britain had a standing reward of £1000 for anyone who could kill sheep at 100 yards using radio waves.

Death rays against pilots were a fantasy but radio waves were found to be reflected well enough from aircraft to promise their detection. The early systems used radio of fairly long wavelength, emitted from transmitters and received back into antennae. It became known as radio detection and ranging, radar, and was deployed on ships and gun batteries. The equipment, however, was large, the aerials huge, and the long wavelengths limited the detail of the reflected image. Improved systems would need shorter wavelengths of greater intensity to be produced from smaller devices, especially if they were to be fitted inside aircraft.

Historians of the second world war generally recognize the single physical invention with the greatest strategic advantage to the Allied forces as being the resonant cavity magnetron. Hans Hollman in Germany for example, had long before developed a magnetron to produce microwaves. By the late 1930s, there was considerable worldwide interest in the potential of magnetrons, but the designs were of low power and the frequency tended to drift, making them difficult to control. The crucial improvement came from the physics department of the University of Birmingham, whose head was Mark Oliphant who we met in Chapter

5. He obtained a grant from the British Admiralty to work on short wave radar. He re-assigned his doctoral student Henry (Harry) A.H. Boot and the recently appointed John T. Randall to grapple with the problem. Randall we have already met in Chapter 1.

The pair devised a weird construction: a small block of copper formed into series of eight cavities, each of circular cross section and connected symmetrically to a central cavity. In the center was an electrode wire supplied with high voltage electricity. The intense field of electrons produced in the central cavity swept past the side cavities to produce resonating fields of high radio frequency which were extracted through a metal waveguide. So simple, so obvious: everyone else searching had stared straight past the design.

With delicate diplomacy and great secrecy one of these devices was demonstrated, on 6 October 1940 at Bell Telephone Laboratories, to the US Department of Defense. Britain was by then in desperate need of financial and technical assistance to develop this new magnetron to large scale manufacture. The MIT in Boston achieved this within a few months and mass-production led to these powerful compact radars being installed in Allied aircraft by 1941. The biggest contribution of this new radar was detection of submarines during the six year Battle of the Atlantic when supply convoys to Europe were at the mercy of packs of U-boats. Liberator and Wellington aircraft fitted with centimetric radar patrolled the seas for enemy submarines that needed to surface.

Henry Tizard had headed the team that sailed across the Atlantic with their precious magnetron. He went on to encourage the recruitment of nuclear physicists for this research and development because he argued they would adapt more flexibly to this field than radio engineers. The same device was also destined for a more mundane use in early microwave ovens. Percy Spencer of Raytheon company, in 1945 had stood before an experimental magnetron. He felt his hand warming and candy in his pocket melting. The company saw the opportunity and introduced their Radarange brand of ovens for commercial kitchens.

The impact of the magnetron and similar products of physicists during that technological war on the attitude toward research was enormous. Centrally managed science research in the aid of technology was promoted in America by the highly influential Vannevar Bush, with his book addressed to the Presidency, '*Science, the Endless Frontier'*. This philosophy of massive team work to solve big problems, combined with the slide toward the cold war, meant that university departments of physics were showered with money as leaves on an autumn wind. After Isidor Rabi won the Nobel Prize in 1944, the Pentagon soon offered $500,000 per year to support his department. Rabi replied that so much money was more than he needed and the Pentagon reduced the offer. Meanwhile money fluttered down from other military agencies.

As well as money, the same universities were suddenly blessed with experienced people. Many researchers, mobilized from their pre-war studies into military work were now welcomed back to science with greatly increased technical skills. Many of them also had a fresh attitude toward obtaining funds for inventing machines.

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Charles H. Townes had studied for his doctorate at the California Institute of Technology where one of his professors was Richard Tolman. He used spectroscopy to resolve a controversy about the structure of the isotope carbon-13. In 1939 he moved to New York for a job with Bell Telephone Laboratories, where he hoped to continue with such fundamental studies. Bell Labs had a strong reputation for encouraging a higher proportion of their research to be on fundamental problems than was typical of commercial firms. Nevertheless, this was not the academic post Townes wanted; jobs were scarce in the late 1930s. Soon he found himself mobilized for military work within Bell Labs and by 1943 he had filed a patent for a bomb aiming system.

Later Townes diversified to the problem of the absorption of microwave radar at short wavelengths by water in the atmosphere. Dry air is very transparent to radio waves but if air is very humid, with a high concentration of water molecules, the water absorbs microwaves. This imposed an environmental limit on the definition and range of radar using certain wavelengths, 1.25 centimeters in this case. Another compound that absorbs microwaves similarly is ammonia. This is a simple molecule, consisting of a single nitrogen atom connected to a trio of hydrogen atoms in the shape of a pyramid. When irradiated with microwaves at a certain wavelength ammonia atoms absorb the electromagnetic energy and the trio of hydrogen atoms oscillate relative to the nitrogen atoms with the same frequency as the microwaves. In other words, the pyramid goes inside out and back again billions of times per second.

Townes found the opportunity to get back to his earlier studies of molecular fine structure when he finished his commitment to military research at Bell Labs and gained an academic post in Isidor Rabi’s lab at Columbia University in 1948. Atomic and molecular fine structure was a thriving research topic and Linus Pauling’s seminal book on the chemical bond was making its full impact. There were endless interesting molecules to study using spectroscopy. Funding was available from a Joint Services Contract (Army, Navy, Airforce) for a general program of work on microwaves and their potential military applications. The environment of such a powerful department was ideal for Townes to return to the secrets of the ammonia molecule, with molecular beam machines of Rabi. Vendors on the streets of New York made good offers for sale of war-surplus electronic equipment, but research funding was already ample.

A property of ammonia molecules oscillating at a specific frequency when energized by microwaves is that the frequency is fixed. At an atomic scale, they can act like a musical tuning fork which has been energized by knocking it. In those days time was best measured using quartz crystals energized to oscillate with a small supply of electricity. Increasingly this was insufficiently accurate for many technical needs and a demand grew for a standard of time not based on the rotation of the Earth, which astronomers by then reluctantly accepted as slowing due to friction of the tides. Townes at Bell Labs, in collaboration with Robert Pound at the MIT Radiation Laboratory, proposed that an atomic clock could be based on ammonia. The absorption of microwaves by ammonia molecules peaks at a precise frequency (23.83 gigahertz), the ammonia line of spectroscopy. The key to using this property to make an atomic clock was to design a resonating cavity with the characteristics of providing a controlling feedback mechanism that would stabilize the frequency at its peak. Townes inspired Harold Lyons at the American Bureau of Standards to produce a working molecular clock based on ammonia; announced to the public in 1948. In use it proved little better than astronomical time-keepers, but the basic principle was established.

By 1950, the Naval Office of Research requested Townes to investigate how to use microwaves of millimeter lengths. This was a huge technical challenge. At wavelengths measured in centimeters the engineering problems of forming metal exactly to get the microwaves to resonate were difficult but just manageable. Resonant cavities of diameters of a few millimeters were another level of problem altogether. It seemed worse than an engineering problem. Standard thinking on the problem indicated it would contravene the second law of thermodynamics. Some radical lateral thinking was required and Townes was the man already pursuing a separate parallel path. In a flash of inspiration he saw a resonator of molecular dimensions: his oscillating ammonia molecule!

A tiny, simple tool that he could manipulate in the sort of molecular beam machine popular at Columbia University. It was nanotechnology before that term was coined. Townes produced an inverted population of high energy molecules then separated them magnetically from the mass of low energy molecules. Then he could channel the high energy molecules into a resonant cavity and energize them with microwaves for stimulated emission of more microwaves. In other words, the incoming microwave radiation would be amplified. In May 1951 Townes wrote in his laboratory notebook a simple description of the complete: ‘Apparatus for obtaining short microwaves from excited atomic or molecular system.’ A diagram included a label to a ‘small hole for obtaining useful radiation’. Early next year his doctoral student Arthur L. Schawlow witnessed and signed the entry.

At Columbia Townes had two new workers: James P. Gordon wanting a doctoral project and Herbert J. Zieger who had just completed a doctorate on molecular beams. Zieger had a scholarship from the Union Carbide chemical company for studies on how to produce intense beams of infrared radiation to stimulate chemical reactions. The pair was set to work on the production of microwaves from ammonia beams. They soon diverted away from the seemingly impossible demands of millimeter waves and reverted to microwaves at 1.25 centimeters for which they had ample equipment and experience. Nevertheless, this was an extraordinarily ambitious project to ask of a doctoral student, even by the standards of those bold times. Townes ignored his head of department and colleagues who insisted it was bound to prove a waste of time and money. Townes had both a tenured position and confidence in his inspiration.

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Townes's confidence stemmed from both Einstein's proposition of stimulated emission, and the recent experiments on inverted populations of atoms and molecules. Not only that, but the quantum mechanical essence of the system he hoped his workers would build had already been publicly discussed at a conference in Ottowa by Joseph Weber of the University of Maryland in 1952. The method for obtaining stimulated emission of radiation proposed by Weber was never put into practice but the concept of making a working device was already in the public domain in America.

The concept was also exciting to workers far separated by distance, culture and the cold war. At the powerful Lebedev Physics Institute of the Soviet Academy of Sciences in Moscow were Aleksandr M. Prokhorov and Nicolay G. Basov. Both had endured active military service during the second world war before gaining posts at the Institute. There they used spectroscopy to study microwave radiation and the phenomenon of the different energy levels of molecules and their behavior as oscillators. First, the pair published, in 1945, a concept of how to manipulate molecules to amplify microwave radiation. Then they consolidated this with cesium fluoride as a molecule that oscillated between its energy states in response to microwaves.

Because of the frigid relations between the Russia and America at that time, publications of potential strategic interest in the open literature were scanned by both parties. During the late 1940s and early 1950s, the Lebedev group and the groups in America working on induction of molecular oscillations by microwaves would have been independent from each other in approach and day-to-day exchanges. Nevertheless, inchoate concepts and propositions were available to anyone with institutional access to translated versions of intriguing papers. There were plenty of American translators of Russian, and the reverse, in those days. Furthermore, Prokhorov spoke English well, having been born and raised in Australia by his Russian parents.

On 8 April 1954, Jim Gordon interrupted an afternoon departmental seminar: 'It works!' After convincing his supervisor and colleagues that it did what he claimed, they searched for a name. How about microwave amplification of stimulated emission? A suitably long name for a rectangular metal tube about one meter long: the maser. By May 1954 Gordon and colleagues submitted for publication a brief note announcing their invention and this was published in July of the same year. The next year Townes applied for a patent and it was issued to him in 1959 for a deliberately broad range of stimulated emission procedures for: 'Production of electromagnetic energy.'

Meanwhile Basov and Prokhorov had submitted in December 1953 a proposition of what they called a molecular generator, which should have been able to amplify microwave radiation. It was based on their earlier theoretical publication. After some more work to correct their paper in proof stage it was published in October 1954. But the concept of Townes had been converted by Gordon and Zieger, and later on with the help of Tien Chuan Wang, into the first working maser. The team consolidated this with a very detailed description of its theory and operation in a paper published in July 1955. In that paper Gordon acknowledged the earlier papers of Basov and Prokhorov with the comment: 'An independent proposal for a system of this general type has also been published.' Townes, Prokhorov and Basov were awarded the Nobel Prize in 1964 for their discoveries leading to the maser, and as shall be seen, toward the laser.

Maser: it was a strange sort of invention to announce to the world. What was it for? Was there anything useful that could be done with it? Could the military agencies that had spent so much money on this area of research put it directly to use, like Randall's cavity magnetron? Not at all: as some skeptics joked, the maser could have signified a 'means of acquiring support for expensive research'. Townes and Gordon continued to develop the use of the maser for spectroscopy studies. That was what interested them, and in the culture of the department at Columbia such fundamental studies were what they did best and were famous for.

Other groups saw the potential for making better atomic clocks and started research to make masers that operated with other materials such as hydrogen. University researchers soon took up the idea of masers as a hot new topic of fundamental research. Military funders appreciated the potential for amplification of radiation in the form of weak radio signals, and some with more lurid imaginations wondered if this could work as that prize-winning death ray at last. No way: the power available from the original maser was a miniscule fraction of one watt. Bell Laboratories were prepared to put some funds into this work, despite some research managers being reluctant. They considered that as a telecommunications company it was peripheral to their business strategy.

Creation of laser light

Attitudes to scientific and technological research vary hugely from individual to individual. There are some who see themselves as able to 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. America has been for long been the best place to do this, but bear in mind that Valentin Fabrikant in Moscow more than a decade previously had proposed a system that could potentially amplify radiation. The patent for Fabrikant's idea was eventually granted in 1959, but by then it was superseded by developments elsewhere. Property rights were of low priority in the Soviet Union. Nevertheless, Einstein's theory of stimulated emission and demonstrations of how to produce inverted populations of molecules 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 for atomic bombs and then taught undergraduate students in physics. Already he had started life as an inventor with an idea for a type of soft contact lens. Gould was allotted a project to study the fine structure of the metallic element thallium. He needed to use a molecular beam machine – a chunky metal tube several meters 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 found it all a struggle.

One day Rabi came to Gould's lab and told of his recent visit to Kastler in Paris, of how Kastler was using optical pumping successfully. As a technical novelty that news excited Gould's talents as an inventor – it would be the first use of optical pumping in America. Moreover, the energy radiated from an oscillating 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 energy into a beam of light than a beam of microwaves. He also knew the corollary, that to achieve higher frequency, somehow much more energy needs to be pumped into the system in the first place.

Instead of a molecule of appropriate structure to oscillate 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 oscillators, 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 soft and highly reactive metal, but can be manipulated as a vapor in a transparent tube. Most importantly, Gould considered its simple structure should permit 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 electrons 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 dropped from the metastable to the ground state 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. Like most inventions, it was 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 vapor, would provide the positive feedback of the light. This would entrain the light into a narrow, coherent and intense beam. That would be fed out through one of the mirrors that would be partially reflective. The mirrors formed a space in which the light would oscillate back and forth; a resonant cavity (the term oscillate in this sense is on a vastly larger scale than atomic or molecular oscillation). As more and more pairs of electrons travelling together came to be 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 extremely intense energy from the device. To supply plenty of power to maintain the inverted population, the medium would be optically pumped.

However, this was not the first time that a Fabry-Pérot system had been proposed to produce a positive feedback for radiation. Robert H. Dicke of Princeton University had applied, in 1955 and 1956, for patents on 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. Gould knew he needed to work fast.

In November of 1957, Gould described his idea in this notebook: ‘Some rough calculations on the feasibility of a LASER: Light Amplification by Stimulated Emission of Radiation’. He had the nine pages of description officially notarized 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 brushed it off as trivial pedantry. He stated clear ambitions about what his laser would be used for: communications, radar, television, astronomical spectroscopy, chemical reactions, nuclear fusion.

Life in the stimulated emission business was getting tense, especially for Gould. Through bizarre misfortune for a budding inventor, he was somehow under the impression that to patent his idea he needed a working device. The US Patent Office 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’ potentially could make the device; that is, ‘reduce it to practice’ as patent examiners say. Hoping to work up his patent idea, he abandoned his doctorate studies in exchange for 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.

But a few doors along the same corridor where Gould had attempted his doctoral studies was the office of Charles Townes. Gould and Townes had discussed with each other 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 vapor as the gain medium, with optical pumping and a silvered reflective glass box of about one centimeter 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.

Townes was also 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 phrase 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 vapor and other engineering difficulties. Nor were practical applications described beyond suggesting spectroscopy studies and frequency standards. They filed for a patent in July 1958 and it was granted in 1960.

The state of interest and funding for lasers about 1957 was strangely at 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 focused on sending signals as electricity down wires or as radar through the air. Similarly inclined were the military agencies. Then one day early in October a strange bleeping signal appeared from space: Sputnik! It had been launched on huge 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. Gould soon found himself in a ludicrous situation where he 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 stirred up by Senator Joseph McCarthy were waning, the bureaucratic momentum of the national security business bulldozered 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 on 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 when 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, especially 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.

Eventually, however, Gould 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 seventeen 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.

This patenting saga was confounded throughout by the vaguely 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 at a specific time. If the people and the context change then the revered precision of science wobbles on shaky communications; particularly if using words rather than mathematical symbols. Patent disputes in America are now held before judges only, not juries.

Not only did Gordon Gould celebrate a rueful vindication as inventor, he had already enjoyed one of the early and very personal benefits of lasers. After a cataract operation in 1985 one of his retinas became detached. A surgeon fixed it back in place using an argon laser made specifically for eye surgery. That use had originated in 1960 when some ophthalmologists at a hospital near the TRG lab asked to borrow one of the 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 but 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, by accident and keen observation, was the ability of the beam to cut and weld deep within the eye without damaging intervening transparent tissue. A laser physicist at the Northrop Corporation in Los Angeles, Mani L. Bhaumik, took up that astonishing news and in 1973 was able to unveil the first effective equipment for laser eye surgery. Not even Gould’s fertile imagination anticipated that in his original list of potential uses.

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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 programs. 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, Javan proposed a mixture of two elements. Gases were considered suitable because they are highly homogenous. The gas mixture should readily absorb light and spontaneously emit it, in other words be fluorescent. Neon was the obvious gas for this property 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 in the ceaseless movements of the mixture. 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.

Javan accepted a post with Bell Labs at their facility in Murray Hill, New Jersey, in 1958. Theoretically, the four-level system he proposed would be more efficient and more likely to produce a continuous beam than three-level systems. The technical difficulties were daunting but at least he could start from the position of ordinary neon fluorescent tubes that were powered by electricity. The critical step was to produce an inverted population in the gas in which stimulated emission would occur, followed by increasing that population using a pair of Fabry-Pérot mirrors.

The correct ratio and pressure of the neon and helium was found by exceedingly difficult calculations of the possible behaviors of the atoms at their respective energy levels, coupled to endless experimental testing of the calculated predictions. The mirrors were equally difficult because the gain of stimulated emission expected from the system was only about 1.5 percent. The mirrors had to be aligned as accurately as possible, along a tube needing be one meter long to obtain sufficient gain in light. Of course, they needed a laser measuring tool for this.

Instead, they fiddled with micrometer screws to move the mirrors mounted at the ends of the quartz tube.

Trial and error, in both the gas and mirror systems was their standby; insufficient 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 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 journey of faith way into the realms of increasing your chance of luck by throwing the dice more often.

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Howard Hughes, the highly entrepreneurial but eccentric founder of the Hughes Aircraft Company, took his company to prosperity by manufacturing military aircraft. Later the company diversified into electronics. In support of their research they built the Hughes Research Laboratories, at Malibu, just west of Los Angeles. Included on the site was 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. He wanted to get out into what he called the 'real world'; although he soon found himself acknowledging the debt he owed to Lamb for his understanding of quantum phenomena.

Maiman's first job was with Lockheed Aerospace at Van Nuys, California, but he soon moved to the Hughes's Atomic Physics Department. There he found his boss was Harold Lyons. So with his background in microwave spectroscopy coupled with Lyons's understanding of masers, Maiman naturally applied for funds to continue work on microwave phenomena. The Air Force provided a grant, but Maiman soon found himself also dealing with a project funded by the Army Signal Corps. They required a maser using a solid medium to amplify microwaves, based on the principles described by Schawlow and Townes.

The apparatus then in use to amplify microwaves used a large artificial crystal of ruby powered by huge strong magnets. To maintain an inverted population in the ruby it was cooled in liquid helium, which in turn had to be insulated in a jacket of liquid nitrogen. A cumbersome piece of kit weighing over two tonnes: not the sort of specialist consumer electronics product that Hughes needed to develop its business. Maiman soon revealed his creative flair by placing a small permanent magnet directly around the ruby and put both into a small container full of liquid helium. A neat device of about ten kilos, that could fit at to the focus of a radar receiving dish. The Signal Corps used it as a research tool.

Maiman became hooked on the business of amplifying radiation but vowed his invention would produce light, be small, work at room temperature and have a solid amplifying medium. Powerful, easy to fit into ancillary equipment, and easy to use: the essentials of something for sale in large numbers to ordinary customers. Maiman intended to make his living as an inventor.

All the determination he could muster soon became essential. The Hughes Research Laboratory is in a romantic and balmy location at Malibu, but scenery and fresh air 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. Maiman was not only isolated but the lab at Malibu was at first uncongenial for such work. His managers considered masers and lasers a research sideline. However, they did have a General Research Fund and Maiman's success with the maser for the Signal Corps gave him sufficient prestige to obtain $50,000 from the fund.

What solid medium then? Rubies and sapphires are gemstones consisting of corundum, a crystalline form of aluminum oxide. Ruby owes its beautiful red glow to a small proportion of chromium oxide; other metal impurities give the blue to sapphire. These hard crystals can be grown in the laboratory for use as 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 energized to higher levels by ultraviolet radiation.

When Maiman was researching few manufacturers could produce ruby to sufficiently high quality. The precise shape of the ruby to be used was a crucial problem for Maiman to solve. At first he used a one centimeter 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 important. In contrast to the gaseous media being tested by Javan and others, where the mixture of gases is without significant structural inconsistency, tiny flaws in the crystal lattice of a solid-state medium sent light bouncing all over the place. Furthermore, Maiman needed to energize his crystals sufficiently to produce a large inverted population of chromium ions. These would stimulate emission of light in a three-level system.

An intense source of light? Maiman scanned the commercial catalogues for the largest conventional lamp available, a monster at 1000 watts from General Electric, using a mercury vapor arc. Special cooling was needed and to get the light onto the relatively small ruby it had to be focused. Handling these bulbs was inconsistent with Maiman's concept of a consumer device. He searched both his brain and more catalogues for an alternative. A glowing light bulb to represent an inventor inventing is iconic. Probably it derives from Thomas Edison, but it suits Maiman's flash of inspiration. He tried what at that time was a novel and 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 color 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.

More good fortune: the highest intensities were available from lamps in the form of short tight spirals. This was getting good – the ruby, as a cylindrical rod, could be fitted inside the spiral. The ruby would be mirror coated at both ends and when the lamp was fired then high intensity light would surge and pump along its length. Rising like a phoenix on the laboratory bench in Malibu was a device remarkably convergent with Gould's proposition as a notebook sketch for a laser. There was just one snag: a big one. These bulbs were designed 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. The working principle would be demonstrated, and surely pulses would be ideal for some applications. Maiman understood the significance of the fact that laser light had never been created before.

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. A pragmatic pair with one objective: beat the competition from all the big players to produce the first working laser. To achieve that they had 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. As far as anyone knew then, and now, this does not occur naturally anywhere in the known Universe. Could such photons reveal themselves as a tiny spot of bright pure light projected onto the far wall of his laboratory?

By the time D'Haenans set up a test run on 16 May 1960 the team 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 ruby rod were finely polished and mirrored. Robust flash lamps available from commercial manufacturers provided the energy for optical pumping. Everything was housed in a small polished aluminum container whose form pleasingly matched its function.

After many trials of increasing power, the oscilloscope recording from the device suddenly shot up to a tight high peak totally unlike the previous traces. This was it! For the first time incoherent light had had been converted into laser light.

Before, stimulated emission of radiation was an obscure idea of Einstein in a dusty old paper, weird equations of early quantum physics. A thought experiment. Now laser light shot out from little box of tricks at the flick of a switch. The deceptive simplicity of this device was a mark of daring talent at engineering design. Nevertheless, 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.

Hughes Research Laboratories became interested. Harold Lyons rallied round and made sure Maiman obtained good publicity and a supply of ruby crystals of favorable dimensions and purity, specially grown at the Linde company, part of Union Carbide and the only US manufacturer. Finally, the team was able 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.

However, all was not sweetness and light. Maiman had entered the Hughes company with a determinedly independent attitude: he refused to sign their standard form on patent rights. Full credit for his discovery and invention was his requirement, both as a research paper, to be followed by a patent application within the year allowed after publication of a paper. Thereafter the problems that he encountered resembled those of Gordon Gould. 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. But by then the journal was so deluged with papers about fashionable masers that the editor had imposed a moratorium on any more. In frustrated shock Maiman submitted a substitute paper of only 260 words to the journal *Nature*, who promptly published it in August 1960. Priority was duly claimed, but with embarrassingly few details to impress his competitors.

Worse still, to Maiman's horror he found a pre-print version of the original 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 electronics trade publication. 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 battle through the jungle of publication in academic journals.

Could it get any worse? Hughes initially declined to proceed with patenting. Maybe his laser was, as someone at a conference in the early 1960s said, merely 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, however, thought otherwise; Javan and team had both demonstrated a working device and filed for a patent to their gas laser in December 1960. Although death-rays were not on Maiman's list some newspapers soon promoted such desolation. Neither did it help that 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 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. Impossible!

After much politicking within the company a patent 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. Hughes made a lot of money on that patent. 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, possibly because of it, he acknowledged in reply to his question that Valentin Fabrikant originated the concept of lasers, but no one else.

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 system delayed them. The mirrors in the apparatus operated at such fine tolerances that small vibrations in the lab would misalign them. At last Javan and his team achieved genuine laser light on 12 December 1960.

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 of direct use as a practical commercial product.

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 union 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. 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.’

Characteristically, Ted Maiman was more succinct in his autobiography:

‘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.’

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Science journalist who relate the invention of the laser, relish the drama of the wartime origins, conflict of personalities, patent disputes, and debate over who actually did the deed. Scientists arguing for better funding of pure research promote the story as a classic example of how their activities can lead directly to highly successful new technologies.

So far so interesting, but as always, the story is more complicated and carries a deeper message. The story of the laser peels back some of the mystery around the problem of prediction in science and technology. This problem arises at different levels and the first level is the hypothetico-deductive approach to research. A prediction is the essential next step after formulating a hypothesis; if a prediction cannot be formulated then you do not have a hypothesis, just some vague idea about what might explain your observational facts. Thus, standing next to a working magnetron is liable to melt the candy in your pocket: well isn’t that interesting, maybe it is due to the power of the rays, so we predict that microwaves are powerful. That is no use: get some more facts. Water molecules absorb microwaves. Because there is good evidence for that statement, we predict that the water will rise in temperature. Furthermore, if our experiments on that fail to falsify our null hypothesis, then we make the technological prediction that a plateful of cold food, containing water, can be heated up and cooked by exposing it to microwaves.

Such day-to-day prediction in the science lab and the technological R&D department can induce a sense of omnipotent power, a faith in a method that will, if applied correctly and persistently, lead inevitably toward understanding, innovation and progress in general. This, unfortunately, is too close to mistaking the trivial prediction of a method of investigation for the ability to see into the future. Scientists are as unpredictably bad as technologists at predicting the future. Occasionally they get it right, without obvious reason, whilst too many of them make fools of themselves by confidently predicting the future, usually what will not happen. To name names would be invidious, few notorious examples will do: heavier than air flight is impossible; the atom will never be split; these atoms that we recently have split will never yield worthwhile power; X-rays are a hoax; the world market for electronic computers will be five machines; television – nobody needs that . . . Thus it was natural for several laser physicists to pose the question, in books of the 1980s and 90s telling of masers and lasers from their personal experience: could the laser have been invented 50 years ago? Unequivocal answers were not obvious from their examinations of much historical data on the theories of light, electromagnetic radiation, and stimulated emission.

I propose the answer to their question is a simple No. Consider the definition. ‘Invention (Patent law): the discovery or production of some new or improved process or machine that is both useful and is not obvious to persons skilled in the particular field.' The laser as a useful machine was not obvious to anyone researching on the significance of Einstein's brief mention in 1916 of a possible quirk of quantum theory to which he gave the name stimulated emission of radiation. The scientists in their university laboratories were asking questions about the quantum world, about the fine structure of hydrogen and ammonia. What really is meant by oscillator? What is the true nature of this resonating electron of Einstein?

Few of them were asking such questions, probably not enough to form a research collective like the invisible colleges we met in Chapter 1. Furthermore, they were working through tough times for science. Only technology was thriving financially during key periods of the lives of these researchers, most of it military. Thus an enormous resurgence in faith in big technology, aided by big science, to deliver all manner of goods became the driver of one particular technical competence to manipulate microwaves.

However, there were a few disparate researchers who proposed that if coherent radiation could be produced by this possible quantum phenomenon, if such a thing unknown in the natural world could be actually created in the laboratory, then possibly something useful could be done with it. If nothing useful, then surely it would be a major intellectual coup, the stuff of international fame and prizes. One or two of them at least documented the idea that if the radiation was light rather than microwaves, then the energy of any coherent beam would be surely be useful; maybe a new means of communication or an aid to chemical synthesis.

In contrast, to grasp that theory and the first experimental evidence for its validity, then fly off with it into the unknown was mainly the initiative of several outsiders: students, non-academics, self-styled inventors. True inventors, as distinct from innovators, are much rarer than scientists for the simple reason that discovering the facts of nature can yield to the persistent plod at its most mundane, through to potent mixes of intense curiosity and high intelligence. Inventors need something rarer: imagination to create a new machine. In this case a design of a machine totally without precedent to produce a postulated phenomenon totally unknown in the natural world. How could that have been predicted?

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