CHARLES TOWNES

Figure 1. Charles Hard Townes, Nobel Laureate, National Medal of Science winner, recipient of the Morris Liebmann Award of the Institute of Radio Engineers and the Medal of Honor of the Institute of Electrical and Electronics Engineers, and currently professor emeritus at the University of California, Berkeley.

CHAPTER 3

From Radar Bombing Systems to the Maser

Charles Townes as Electrical Engineer

The summer of 1939 found most Americans in an optimistic mood. Signs of economic growth suggested that the Great Depression was finally ending. World's fairs in New York and San Francisco—featuring such marvels as electronically synthesized speech, artificial lightning, and a cigarette-smoking robot—showed millions how new technology might improve transportation, communications, housing, and leisure. Fluorescent lighting, nylon stockings, magnetic tape recording, and television were products of the future displayed that summer. Pan American Airways began regular transatlantic passenger service on June 28 of that year and the first FM radio station (Edwin Howard Armstrong's W2XMN of Alpine, New Jersey) began regular broadcasting on July 18. But events in Europe, long troubling to many, rather suddenly had a sobering effect on everyone: On August 24 Americans learned of the German-Soviet nonaggression pact (seeming to untie Hitler's hands), on September 1 Germany invaded Poland, on September 3 England and France declared war on Germany, and on that same day thirty Americans lost their lives when a

German submarine sank the British passenger ship *Athenia*. On September 5 the US government announced its neutrality, and on September 8 President Roosevelt proclaimed a limited national emergency.

Starting Work at Bell Telephone Laboratories

It was in this somber atmosphere, at the beginning of September 1939, that a group of new employees were welcomed at the Bell Telephone Laboratories at 463 West Street in New York City. A dozen or so newly minted Ph.D.s were given an introduction to the wide-ranging work of the largest and most prestigious industrial research establishment in the world. The new employees were also of the highest quality: Two of them, James B. Fisk and William O. Baker, rose within the organization to serve long terms as President of Bell Laboratories, and a third, Charles Townes, became famous as inventor of the maser and co-inventor of the laser.[1]

Earlier that summer Townes had completed his physics dissertation at the California Institute of Technology and used the first-class train fare sent him by his new employer to travel from California to New York to detour through Guadalajara, Mexico City, and Acapulco by traveling third class. Townes was to continue in an exploratory mode at Bell Labs, as Mervin Kelly, Director of Research, arranged for him to work for a few months in each of several departments, with the idea that this would help Bell Labs and Townes decide what work he was most suited to.

Townes was first assigned to the group of Frederick B. Llewellyn, an engineer who three years before had received the Morris Liebmann Award of the Institute of Radio Engineers for his work on high-frequency electronics and constant frequency oscillators and who, in 1946, became President of the Institute. Llewellyn was then trying to design good generators of microwaves, ultra-high-frequency radio waves with wavelengths below 100 centimeters. At that time, triode vacuum tubes (especially of the Barkhausen-Kurz type), klystrons, and magnetrons were the principal means of generating microwaves, and despite a great deal of work at laboratories in the United States, Europe, and Japan, it was proving extremely difficult to build an oscillator of short wavelength and high power.[2]

Townes undertook to explain theoretically why certain tubes, which were being tested by Llewellyn's group, performed as they did. For this work he had the advantage of an unusually thorough training in electromagnetic theory at Cal Tech from W. R. Smythe, the author of a standard text on the subject. Smythe gave an extremely demanding electromagnetic theory course to all physics graduate students and was proud of the fact that this course "winnowed out everybody who couldn't quite take it at Cal Tech."[3] Townes not only excelled in the course, but ended up helping

Smythe by checking all the derivations and working all the problems in a new book Smythe was writing.[4] Townes, who thus gained a facility with electromagnetic calculations that few engineers had, has commented, "So I knew that field. I think once you know one basic field very thoroughly, that's an enormous help in almost anything you do. . . . you have a very powerful tool. And, yes, that has been very important to me. It was certainly one of the things that gave me a start at Bell Labs."[5]

[Electromagnetic theory] touches on so many fields. I think learning that field as thoroughly as I did has really been quite important to my career.

There's a more general aspect that I would comment on: I think it's very important to learn a subject well enough, to think about it enough, to think about it from all angles, so that you feel at home with it. You feel it's a friend. Something you know intimately. If somebody asks you about it, you can express it back to them in your own way or anybody else's way. You can look at it from any angle and still understand it thoroughly. This gives one a distinctive idea of what happens, and what's going to happen if you're given a certain set of events. You just see it. You visualize what's going on. It's instinctive.

Now I always work out things with equations, too, to be sure it's all correct, to be sure I haven't missed anything. I usually think things through intuitively first, work it out with equations, and then think through the equations: Now, what do these equations really mean? Is that really what's happening? Do these equations really describe the right physical situation? I think the intimacy you have with a given field is very important for quick thinking and also for exploring a problem thoroughly.

Teaching is another way of learning thoroughly, and I have profited from that. I think if you teach a field, then you have to look at it in any ways your students want to look at it. You have to look at all aspects of it. If you just learn it in other ways, you may well skip over certain parts you don't think are too interesting. If you've got to teach it, you have to look at all of those. And I have gotten some very good ideas just having to learn certain parts of a subject which I've otherwise not worried about, and I'll suddenly see something that's there that I'd missed.[6]

In late October 1939 Townes had an idea for a new way to generate high-frequency waves, using nonuniformity of an oscillating electric field to transfer energy from electrons to the field.[7] He thought this invention had promise and had its notebook description witnessed. He later said, "I did not try it out. I'd moved on to another department by then. But Jim Fisk, who was in the tube department, was asked to try it out. Jim tried it out and said it didn't work. So that was the end of that. . . . I'm sure it would have worked in some sense; but if it didn't work . . . more or less right away, then that probably meant that it wasn't all that useful."[8]

Though not in the business of making money from patents, Bell Labs worked hard to protect itself against infringement suits by taking out patents on its inventions. While at the Lab, Townes followed company practice, signing and dating notebook entries that might someday provide evidence in a patent case and informing the Lab's patent office of promising ideas. For work done at the Lab, Townes received a total of ten patents.[9] "Since then I've patented practically nothing."[10] (He did patent the maser, but, as explained below, turned the patent over to Columbia University; he and Arthur Schawlow received a basic patent on the laser, but Bell Laboratories held this patent.)[11]

In early December Townes reported to J. R. Wilson, Director of Vacuum Tube Development, and began work with the engineer G. H. Rockwood to understand cathode sputtering, the gradual disintegration of the cathode (through positive-ion bombardment and through evaporation of atoms) that in many cases determines the lifetime of a vacuum tube. Townes analyzed some data taken by Rockwood and helped collect other data.[12] The work required theoretical insight (for example, into the work-function of a metal surface), engineering expertise (as in knowing that "torque in a quartz fiber = $\frac{\pi Z r^4 \theta}{2L}$"), calculational ability (framing problems in a way that permits calculation and knowing techniques of approximation), and experimental ingenuity (as building "a modification of the Knudsen gauge"). He later commented, "Well, I would say I enjoyed this kind of work. It's the type of engineering which is so close to physics. It's not development of a big system . . . which I later did. Rather it involves trying to understand things."[13] As discussed below, he returned to similar work several months later.

At the beginning of March 1940 Townes moved to his next assignment, the magnetics group headed by the physicist-engineer R. M. Bozorth. Bozorth had come to Bell Labs in 1923, and his work since then had helped make it the world leader in the understanding and exploitation of magnetic materials. According to a 1969 editorial in *IEEE Transactions on Magnetics*, Bozorth did "more to promote the interaction between research and engineering in magnetism than any other person of our time."[14] Townes worked closely with Bozorth and learned much in this period.[15]

In mid-April Townes was asked to report to Dean Wooldridge, who was studying electron physics, such as secondary emission of electrons from surfaces. (Wooldridge too had earned his Ph.D. under Smythe at Cal Tech and had come to Bell Labs in 1936; he went on to become head of TRW, Thomson-Ramo-Wooldridge.) The exploratory period of Townes's employment at Bell Labs here came to an end as he undertook a long-term project. The objective, set by Harvey Fletcher, Director of Physical Research, was to design a gas discharge tube that would operate at 24 volts. The gas discharge tubes then available required considerably higher voltage, which made it impractical to power them by batteries, and there were places in the Bell System where such tubes could be used as switches if they could run on batteries.

So Townes set to work studying the fundamental mechanisms of gas discharges in order to learn how to achieve breakdown at lower voltage.[16]

The work was similar to Townes's earlier work with Rockwood. Indeed, Townes continued the investigation he started there of cathode sputtering; this resulted in a Bell Labs Technical Memorandum in January 1941 and, several years later, in a paper in *Physical Review*.[17]

The work on a 24-volt gas discharge tube was in part theoretical—as in using quantum mechanics to calculate the probability of ion capture of an electron—and in part experimental, involving the testing of new tube designs. The work continued until March 1941, when it was abruptly terminated. Though his notebook testifies to diligent effort and presents both theoretical and experimental results, Townes says, "... I never made very much progress in this discharge tube business."[18]

Figure 2. Charles Townes in 1941.

Because of the great variety and sophisticated nature of the research going on at Bell Labs, Townes found it a very stimulating environment. He learned, for example, of two different efforts to carry out calculations automatically. In 1937, George Stibitz had begun designing an automatic calculator that would use existing telephone components: relays, sequence switches, and teletypewriter equipment.[19] Townes recalls: "I remember very well his rolling around a relay rack . . . to show people how you could compute with relays. He said, 'Look, you've got to do it digitally. Otherwise you'll never get any precision. You have to do it digitally.' Well, he was doing it with relays." Chuckling, Townes continues: "A rack full of mechanical things. . . . People were not highly impressed with that."[20] Stibitz's work continued, however, and led, before the end of the war, to several digital computers that were used in the design and testing of analog gun directors.[21]

To most people at the time, the work that had recently begun at Bell Labs on electrical analog computing was more impressive. Mechanical analog calculators, such as slide rules, planimeters, and Lord Kelvin's tide predictor, had long been in use, and in the early 1930s Vannevar Bush at MIT had added electrical control to mechanical calculation in his "differential analyzer."

Beginning in 1940, the Bell Labs engineer D. B. Parkinson and his supervisor C. A. Lovell—who were trying to design an automatic gun director—developed what they called "electrical mathematics." By representing variables by voltages, they showed how electrical circuits could add, subtract, multiply, divide, differentiate, integrate, and even make use of tabulated data.[22] A network of resistances could be used to sum voltages, and an amplifier could be used to multiply a voltage by a constant. Specially designed potentiometers became a basic component of their system, as Townes explains: "Lovell had the idea of shaping a potentiometer so that for a given angle you could get a more arbitrary function. You wound the potentiometer on a card of varying height so that the resistance varied, not linearly but with some other kind of functional form."[23] As we will see, Townes came to be very much involved in Lovell's work.

Now one other thing I would have to say about Bell Labs: I think it had a very good atmosphere in not differentiating between physics and engineering in any strong clear-cut way. They had a physics department, and they had various kinds of engineering departments. They had a chemistry department. But there was a lot of interaction. Engineers would work in the physics department a bit, and vice versa. There was a good deal transferred back and forth, and a good deal of interplay. There was not a sharp distinction between the two. . . . [Bell Labs] made a practice of hiring physicists and then transferring them into engineering. During that period engineering schools did not teach a lot of fundamental physics. Cal Tech was one of the few, and Cal Tech did it simply because it didn't have much of an engineering faculty. [Laughs] . . . I was a student there, and the engineering students would take a lot of fundamental physics because they had a small engineering faculty. . . .[24]

It was also at about this time that Mervin Kelly, Director of Research, started a seminar for a small group of employees to keep abreast of the latest developments in physics, engineering, and chemistry. Townes felt privileged to be selected; others were William Shockley and Walter Brattain (later famous as co-inventors of the transistor), James Fisk, Dean Wooldridge, and Stan Morgan (who later headed chemical research at Bell Labs). "... [we] were to meet together once a week and basically have an afternoon off to talk about some aspect of physics or related matters. We could do anything we wanted to. We could read scientific papers, we could invite somebody to come and talk, we could read through important new books or something like this. Whatever we wanted. And the Laboratory provided tea and cookies, which was again quite unheard of at that time."[25]

Townes found his life outside the laboratory stimulating too. He enjoyed New York theater, museums, and restaurants, and, eager to get to know the city, decided to move every three months or so. He lived first in Greenwich Village, then uptown near Columbia University, then in midtown Manhattan. "I would simply put all my stuff in a trunk, get a taxi, move to a new place, and get acquainted with the neighborhood."[26] He took voice and music theory lessons at Juilliard. On a ski trip he met Frances Brown, who was working as activities director at the International House of Columbia University, and the two were married 4 May 1941. (In 1991 they celebrated their golden wedding anniversary along with their four daughters and six grandchildren.) (See Figure 3.)

Figure 3. A 1956 photograph of Charles and Frances Townes with their daughters (from left to right) Linda, Carla, Holly (seated on the floor), and Ellen.

Radar Bombing Systems

In April and May 1940 Germany's blitzkrieg overwhelmed opposition armies on the Continent, and Britain, mortally threatened by German bombers and submarines, stood alone in its fight against Hitler. It appeared more and more likely that the United States would be drawn into the conflict. In May President Roosevelt named a National Defense Advisory Commission to coordinate civilian and military defense, and in June he established the National Defense Research Committee, which was charged with mobilizing the nation's scientists and engineers—whether in industry, academia, or the military—for national defense. In September the United States sent 50 destroyers to England in exchange for air and naval bases in Newfoundland and the West Indies, and the first peacetime draft in US history began.

Bell Labs had not undertaken military R & D until 1937 when the Navy asked the laboratory to investigate the use of radar for an automatic gun director. Over the next several years the number and range of military projects increased, including work on radar systems, specialized communications systems, sonar, the proximity fuse, the acoustic torpedo, and magnetic detection of submarines. In 1940, military projects accounted for 2.5 percent of the Bell Labs' budget; this grew to almost 85 percent in the following two years.[27] Nearly all research work not related to the war effort had to be set aside.

Townes remembers being called into a meeting with Mervin Kelly at the end of February 1941. There he was told that on the following Monday he would start work on a radar bombing system, as part of a group headed by Dean Wooldridge and including Sidney Darlington and one or two others. Townes had received no warning that a change of assignment was to be made: "... that was pretty sudden and unexpected, and I wasn't accustomed to being treated that way."[28] Nevertheless, he did not resent the action, believing that US involvement in the war was imminent and that to contribute to national defense was everyone's duty.[29]

So on Friday, 28 February Townes closed out Notebook 17015 with a page headed "This work discontinued for national defense job," which listed all of the apparatus that was put into storage.[30] The following Monday he made the first entry in Notebook 17870, which was a diagram and analysis of a servomechanism. The assignment of Wooldridge's group was to design, build, and test a bombing system that would make use of radar and the analog computing techniques being developed by Lovell.

Bombing played a large part in the Allied victory in World War II, and its effectiveness was highly dependent upon the techniques used to drop the bombs accurately. The Norden optical bombsight (itself a mechanical analog computer) gave satisfactory results under certain conditions: daylight, clear weather, and little danger from antiaircraft fire or enemy fighter-aircraft (in order to permit a straight run at constant speed to the release point). To achieve accuracy under other conditions, military planners turned to electronic bombing systems, consisting of electrical analog computers and radar devices.

Most of the bombing radars worked as follows: the bombadier identified the image of the target on the cathode-ray screen of the radar set, moved a set of cross-hairs to cover the image, and then kept the cross-hairs on the image as the plane approached the target; an analog computer took as input such things as altitude of the airplane, ground speed, winds, and ballistics of the bomb, and gave output in the form of a needle showing the pilot which way to turn and an indication to the bombadier when to release the bomb.

Such a bombing system was a combination of two new technical devices: an airborne radar set and an electrical analog computer. Bell Labs, as we have already seen, was the leader in electrical analog computing, and it had already established its expertise in radar. (In the United States the design of almost all World War II radar systems was done either at Bell Labs or at the MIT Radiation Laboratory.) The previous September a group at the Bell Laboratories in Whippany, New Jersey, had begun work on a bombing system that combined an S-band radar (that is, one producing 10-centimeter microwaves) with a version of the analog computer developed for directing antiaircraft fire.[31] Wooldridge's group was to design and build the computer for a new system, while the radar set would be designed and built by a group in Whippany.

Townes took part in the conceptual design of the system, such as what variables were to be used as input and how they were to be measured. The wind speed, for example, was read from a more or less standard pitot tube and corrected by taking into account air density and temperature. Townes took part also in the hardware design. The basic calculating device was the custom wound potentiometer, and in the design of each of these one had to consider accuracy and the amount of current drawn. He had to be concerned also with the design of phase-shifting devices, of circuits for controlling motor speed, and of servomechanisms (as for automatically keeping the radar antenna aimed at the target as the plane maneuvered). His training in mechanics was invaluable in calculating such things as torque required to move a worm gear, efficiency of transmission of torque, and the condition's needed to avoid the binding of worm gears. Townes took part also in the testing of components and of the system as a whole.[32] There were many subjects, such as amplifiers and servomechanisms, that he learned thoroughly for the first time in doing this work.

The group worked rapidly designing, building, and testing a prototype system. (The circuit shown in Figure 4 was designed in the first six weeks of the project.) The following winter, shortly after the Japanese attack on Pearl Harbor had compelled US entry into the war, a unit had been built and was ready for in-flight testing. In February and March, Wooldridge and Townes attended the unit on some fifty trial bombing runs out of Boca Raton, Florida.[33] Though the system was designed to require little human intervention, Wooldridge and Townes needed to be present to adjust and repair the system and to observe its operation.

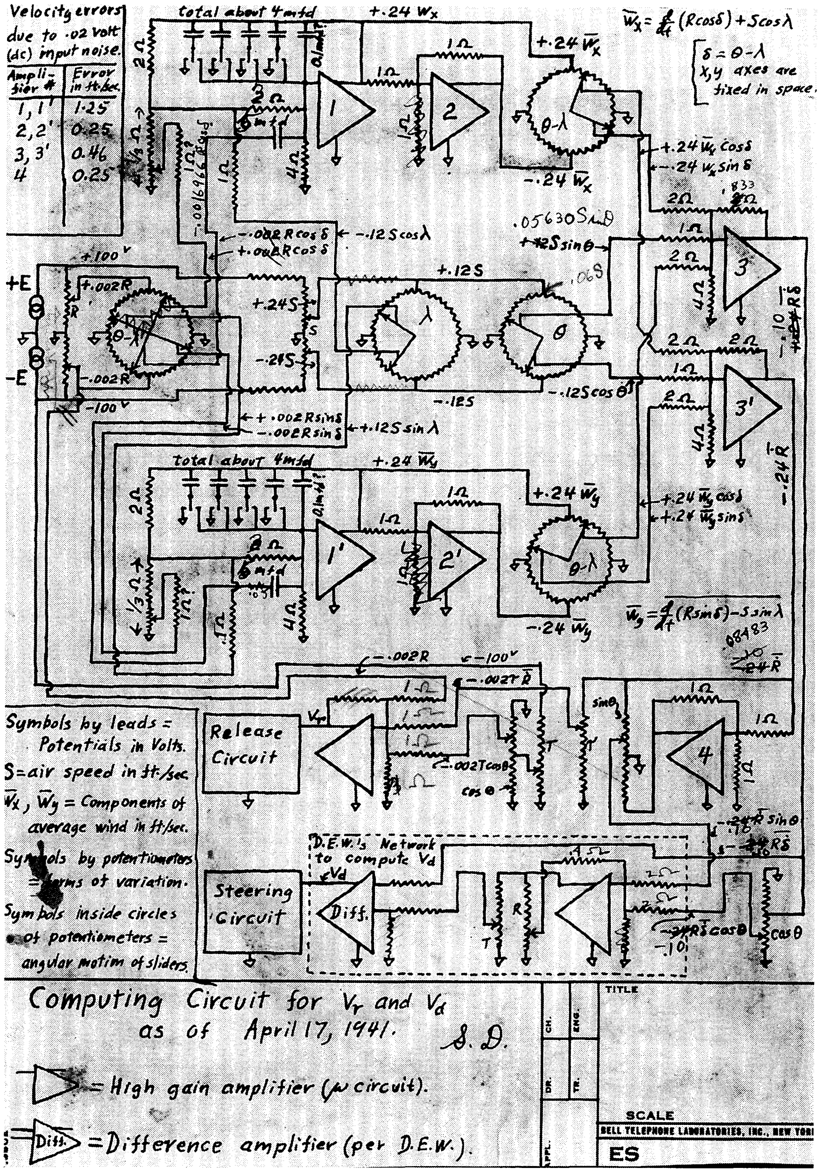


Figure 4. A diagram, drawn by Sidney Darlington, from Townes's notebook showing the computing circuit for two of the variables used in the bombing system.

We did our first bombing exercise, bombing a ship that was anchored offshore. One of the curious things is that the Norden bombsight was so highly thought-of at that time—and that made it so secret—that even though we were supposed to be designing a bombing system they would not tell us anything about the Norden bombsight. We couldn't see it, we couldn't know what it did. We asked our Air Force representatives, "What kind of precision do you get? What kind of precision do you need?" They would just say, "Just do the best you can." People talk about the Norden bombsight dropping bombs in pickle barrels, and they had great stories about it. But the actual accuracy was not all that good. . . .

The very first run we had, we had a colonel who was a very nice person. . . . [He] flew us, and the first bomb we dropped we had a run at an altitude of five-thousand feet. Five-thousand feet was a reasonably high altitude at that point. We dropped the bomb, and I quickly dashed up to the cabin to see what happened. It missed by about a hundred feet. And this colonel, who wouldn't tell us anything about the Norden bombsight—yes, sure, he'd used it. He couldn't say a thing about it. So then he said, "That's a damned good shot, if you ask me." That boosted our morale a great deal, and gave us our first real information on the accuracy then.[34]

TOWNES: *. . . [the Army Air Corps] would send people from time to time to fly with us and see how it was coming out. That was not so unusual. One time we had a load of fairly high-level people—some Bell Labs people and some people from Washington—fly in our plane. The radar antenna housing got stuck. That is, you let the antenna down out of the body of the plane so the antenna could see out, and then you'd raise it back up where the antenna couldn't see, in order to land. Well, it was let down, and we couldn't get it up. Everybody thought that all these bigwigs were going to have to jump. [Laughs] Oh, dear, what had we done now. All these older men, distinguished people, we were going to make them jump out of there.*

NEBEKER: *Couldn't you land the plane anyway?*

TOWNES: *No, they said it was too dangerous. Too dangerous. So I managed to climb down in there with some wrenches and screwdrivers and get it fixed. It was generally motor-driven, you see, and it had gotten jammed, and they couldn't do a thing with it. It was a heck of a job. Did it by hand and got it back up again.*[35]

Over the next four years Townes divided his time between the New York area (at about this time he moved from the Bell Labs offices on West Street to the new campus in Murray Hill, New Jersey) and Florida. The testing of a bombing system usually took a month or two. Most flights were from a base at Boca Raton; others were from a base near Pensacola. As the quotation above suggests, this was a dangerous business. Though Townes was not involved in any serious accidents, three of the four Air Corps pilots he flew with died in noncombat airplane accidents before the end of the war.

In the spring of 1942 Wooldridge and Townes began work on a new system (designated the D-150550 bombsight radar), whose radar used 3-centimeter microwaves. During the war there was a continued move toward shorter wavelengths: from 23 centimeters (L band) to 10 centimeters (S band) to 3 centimeters (X band) to 1.25 centimeters (K band). Shorter wavelengths allowed improved resolution and reduced size of components (notably the antennas). Wooldridge's group had first worked with S-band radar; now they were responsible for the overall system design ("marrying the radar and the computer"[36]), as well as the computer design, of a bombing system using X-band radar. (The radar itself was designed by another Bell Labs group.)

While ships and coastlines were readily discernible with S-band radar, bombing over land usually required higher resolutions for target identification. The new system promised improvement in this respect by employing X-band radar. The other main advantage of the new system was that it would not require level flight, so the pilot could change elevation as he approached the target.[37] In addition, Wooldridge and Townes designed a version of this system for use in torpedo bombing.[38]

Other refinements were made to this and later bombing systems: allowing optical as well as radar guiding (so that a break in the cloud cover could be used to advantage), making input of certain variables automatic, taking into account new variables, and allowing for "offset bombing" (where the target is different from the ground site used for tracking, since not all targets show up well on radar).

For certain functions, the accuracy achievable with the custom-designed potentiometers was not sufficient. Townes worked, for example, on a circuit to provide a better approximation of $x \sin (y + z)$.[39] He also devised a novel way to get a better approximation of the cosine function: He modified a potentiometer output by using vacuum tubes to switch the circuit, when it was in a particular voltage range, to an appropriate subcircuit.[40] Colleagues were surprised when Townes showed that this fairly complicated way of calculating the cosine actually worked.

All of the systems Townes worked on were quite complicated, incorporating many tubes, potentiometers, motors, and mechanical relays. The tubes, because they were being used in calculations, had to have a linear and accurate response, and on at least one occasion the group had a special tube manufactured to its specifications. With such components, there were frequent problems: "... by the end of the war I felt we had as many [tubes and relays] as we could afford. Otherwise, the troubles with them would be too frequent."[41]

In this work Townes learned systems engineering. His notebooks include long lists of aspects of a system to be checked or problems to be solved, such as "Tilt motor did not quite have sufficient power to run drive,"

"... amp[lifier] #10 is off balance," "Antenna azimuth drive has been jittery and oscillating on occasion—usually just during warm up."[42] (See Figure 5.) Some pages of the notebooks consist entirely of lists of problems or of adjustments and corrections or of tests to be done. Looking at one of these pages in 1992, Townes remarked, "Well, I'm still doing that kind of thing with our telescopes that I'm currently working with."[43] (After a period in which he had been working only on relatively small laboratory instruments, Townes submitted a proposal to the National Science Foundation for a large and complex telescope system. In Townes's words, "One of the reviews came back saying, 'Well, can Townes build anything like that?' [Laughs] I guess he didn't know about my war work. There was a good deal of similarity."[44])

~~SECRET~~ SEP 1 194

Matching Resistance of Cards 646642 and 646643 - Case 23665-1

File

September 1, 1943-1115-CHT-GM

GROUP 4
Downgraded at 3-year intervals;
declassified after 12 years

MR. L. N. HAMPTON:

Subsequent to your letter to Mr. D. E. Wooldridge of August 14th questioning requirements on the resistance ratio of α_1 to α_2 cards of the D-164558 potentiometer, these requirements have been reviewed and recalculated. This situation was discussed with Mr. W. W. Werring when the circuits for α_1 and α_2 were designed so that we were aware that a close tolerance on the resistance ratio of these two cards is a difficult manufacturing problem. However, the circuit simplification afforded by this design seemed to justify its difficulty.

Since the original specification of these cards, it has become possible to broaden the tolerance on the resistance ratio of any pair from ± 1% to ± 3% of nominal value and still obtain the desired accuracy. It is hoped that this will facilitate manufacture and that further increase in tolerance with consequent decrease in accuracy will not be necessary.

C. H. TOWNES

Copies to
Messrs. E. T. Mottram
W. W. Werring
D. E. Wooldridge

W. J. Fritz advised 9/2 by W.W.W.

Figure 5. One type of problem Townes had to deal with is illustrated by this letter from Townes to L. N. Hampton, who was in charge of manufacturing the potentiometers used in the system Wooldridge's group was building.

Throughout the war, work proceeded at an intense level at Bell Labs. According to a history of the laboratory, "Early in 1942, the normal 48-hour work week was increased by nearly 40 percent, and the actual hours worked often went far beyond. . . ."[45] Though corroborating this, Townes reports that he often found himself with short intervals of leisure because there were frequent delays in testing the bombing systems, as when the weather was unsuitable for flying or the plane had mechanical problems. In many of these intervals, he worked at solving a scientific puzzle he had set himself.

In 1930 Karl Jansky of Bell Labs was asked to investigate "atmospherics," disturbances to radio transmission believed to be caused by electrical phenomena in the atmosphere. In a 1933 paper Jansky argued that some of the electrical disturbances were of extraterrestrial origin.[46] Already as an undergraduate Townes had read of Jansky's discoveries and wondered how radio waves might be generated in space. He finally succeeded in finding a plausible mechanism for the generation of these waves and soon thereafter published his theory of the so-called free–free electron transitions, which was the first to explain correctly how radio waves were emitted by galactic ionized gas.[47] This work may have owed something to his efforts, in his first assignment at Bell Labs, to devise a way to generate microwaves.

None of the systems Townes worked on were used during the war, and this bothered Townes. (Quite a few other groups at Bell Labs developed bombing radar systems, and a number of these went into production before war's end.[48]) He would rather have seen one of the systems rushed into production and put to use, whereas it seemed that the completion of one design led only to requests for still more complicated systems operating at shorter wavelength with improved performance and new capabilities.[49] He considered leaving Bell Labs. "I was thinking . . . of going over and joining [General Joseph W.] Stilwell in China as some kind of technical assistant there. . . . My bosses then got wind of this, and they worked on me very hard to stay. I didn't quite see the right kind of an opening there, so I said, 'Well, okay. I'll just keep on doing this.' "[50]

Townes's next assignment was, not surprisingly, a still more advanced bombing system, one incorporating the new K-band radar. On the one hand, this assignment proved even more frustrating: Townes could see that it would not work effectively, but was unable to convince his supervisors of that. On the other hand, this assignment led directly to his path-breaking work in molecular spectroscopy and from there to the invention of the maser and laser.

In September 1944—when Allied armies, just three months after D-Day, reached German soil and it appeared the war in Europe might be over by Christmas—Wooldridge and Townes were asked to begin work immediately on a system (the AN/APQ-34 high-altitude bombing radar) that had already been designed at the MIT Radiation Laboratory. According to Townes, "That was a little bit of a blow . . . because they had suddenly tried to jump ahead of us and do something still more advanced than we were doing, and had sold it to the military, and the military had said, 'Well, of course, if we're going to have it manufactured, that ought to be AT&T. . . .' "[51] Bell Labs was to redesign the system for manufacture and build a prototype.

Substantial redesigning was required, and as part of the process Townes did a theoretical analysis of the total error of the system. He obtained estimates of the error for each variable of each component (which took five pages to tabulate), calculated the error in output of each component (expressed as milliradians error at an elevation of 2000 feet), and (assuming each error distribution to be Gaussian and independent) calculated total error as the root mean square of component errors.[52] Today this is standard practice, but at the time Townes felt he was being quite innovative. (In test flights the actual errors in range and deviation were each typically one or two hundred feet; this compared favorably with what the Norden bombsight could achieve in daylight with good visibility, conditions not of course required for the radar systems.)

While it was easy to allow bombadiers the choice between visual and radar bombing—by providing both a Norden bombsight and a radar system—it was difficult to design a single system that could take advantage of both visual and radar input. This was one of the objectives of the new system, and Townes considered various ways of integrating visual sighting and radar sighting.[53]

Townes, however, soon came to have doubts about whether the radar system would work. The new K-band radar seemed to offer improved resolution, but it was untried. A memorandum written by the physicist John Van Vleck alerted Townes to the possibility that water vapor might absorb strongly in exactly that frequency range.[54] After further calculations, he decided that the absorption would be so strong that the radar would be unusable in applications, such as bombing radars, requiring much range. Townes explained his doubts to others at Bell Labs, to I. I. Rabi at the MIT Radiation Laboratory, and to the Pentagon, but without result. "I tried to persuade people that it wasn't going to work, but I was too young and the decision had been made. Well, they went ahead and put it in the field, and it had no range because of water-vapor absorption. So all the equipment was junked."[55]

One thing I remember is that when the first atomic bomb was dropped [6 August 1945]. . . . I was working [late] in a little hut in Whippany checking out some radar. I've forgotten what. But I remember this little hut, and I had a radio, and I heard that this bomb had been dropped. And it was an unknown kind of bomb that did a very powerful job. Well, I knew precisely what it was. A number of friends I had who had been working on the system were indiscreet enough to keep me posted on what was happening. I remember very well. And I said, "Well, I don't have to keep working today." So I shut down and went home.[56]

Microwave Spectroscopy, the Maser, and the Laser

When the war ended, Townes was eager to return to more fundamental research. Like many physicists, he believed that his wartime engineering experience would be of great benefit in scientific research. He considered investigating the radio waves coming from space, but was advised by knowledgeable people that one could never get much information from those waves.[57] Townes might have pursued that possibility nevertheless—and in the next few years a new field of radio astronomy did emerge, which was pioneered mainly by people who had worked on radar during the war[58]—had he not seen another promising avenue of research.

His work on the K-band radar system got Townes thinking about the interaction of microwaves and molecules. With the generators of microwaves and the sensitive detectors that were developed for radar, one could, Townes thought, do a powerful new type of spectroscopy, one that would determine molecular properties with much greater accuracy than any method available at the time. He had calculated that as the density of a gas decreased, the width of the absorption line would decrease but—contrary to what spectroscopists expected—the intensity would not. Townes recognized that the ability to record the sharp absorption lines would give one precise information about molecular structure, such as bond distances and bond angles.

Townes saw also that microwave spectroscopy, as he called it, might be of value to a communications company such as AT&T. In a memo he wrote to his supervisors arguing for such a research program, he stressed the possible applications while admitting that, "So little work has been done in microwave spectroscopy . . . that the course of its future development and application is difficult to predict."[59] His general argument ran as follows: "Microwave radio has now been extended to such short wavelengths that it overlaps a region rich in molecular resonances, where quantum mechanical theory and spectroscopic techniques can provide aids to radio engineering. Resonant molecules may furnish a number of the circuit elements of future systems using electromagnetic waves shorter than 1 cm." In the memo Townes listed possible applications of the knowledge of molecular resonances, including chemical analysis, detection of radio waves (using molecules as detectors of the frequencies corresponding to their resonances), establishment of frequency standards, and generation of high-frequency waves. In a laboratory notebook he was more specific about what circuit elements might be based upon molecular absorption and emission: frequency discriminators, band absorption filters, band pass filters (by re-emission), time delays (by absorption and re-emission), and oscillators.[60]

The memo was well received, and as soon as Townes found someone to take his place on the radar project—this did not happen until early January 1946—he was allowed to begin work on microwave spectroscopy (and was provided with two technical assistants). He first studied the absorption, at various pressures, of water vapor and ammonia. This rapidly led to other fruitful investigations, and over the next decade he published an average of ten articles per year. For this work and for a classic text, *Microwave Spectroscopy*, he is recognized as one of the founders of the field. *Microwave Spectroscopy*, coauthored with Arthur Schawlow, was first published in 1955 and is still in print.[61]

Townes has pointed out the dependence of this new field on electronics generally: "Electronic techniques are characteristic of microwave spectroscopy, being involved in the production, detection, and amplification of microwaves. In some cases very sensitive electronic circuits are needed for proper detection and amplification, since the fractional power decrease may be quite small—as small as one part in 10^8 in an absorption path of 1 meter."[62]

The K-band radar system was important to this development in two ways. Though Townes had some earlier experience with visual spectroscopy, it was the K-band system that directed his attention to molecular spectroscopy. Secondly, the K-band equipment was just what was needed for the new field, and because the military was no longer interested, the equipment was sold as surplus. Townes recalls, "there was suddenly abundantly available lots of Klystrons and wave guides and equipment and detectors at this wavelength.... In fact, I remember buying a few Klystrons down on the sidewalk in lower New York City. . . ."[63]

Townes was delighted to be doing scientific research again, but he had not abandoned engineering. Besides doing the engineering required for the spectroscopic apparatus, he was still alert to technological possibilities: In August 1947—in the midst of this flurry of work on molecular spectroscopy—he took time to pursue an idea he had for a new type of television picture tube (based on the phenomenon of bombardment-induced conductivity) and even obtained a patent on the scheme.[64]

Though Townes was happy at Bell Labs and was not seeking another job, when I. I. Rabi offered him an associate professorship at Columbia University, he accepted, beginning work there in January 1948. He preferred a university setting: ". . . I like teaching, I like interaction with the students. I also like the breadth of the university, having people in the humanities and other fields that you can interact with."[65] He was also disappointed that Bell Labs had declined his request that an additional researcher in molecular spectroscopy be hired.[66]

At Columbia Townes continued using microwave spectroscopy to determine properties of molecules, atoms, and nuclei. But he began to search for ways to expand the field. "After about 1948 . . . the backlog of wartime techniques was beginning to run out. I felt the need for still shorter wavelengths—generated coherently by oscillators. So from time to time I tried to think of ways one might generate shorter and shorter waves, by harmonic generation and new types of tubes and so forth. This got me back into applied work but for the purpose of producing tools for basic research."[67] The method that seemed to him most promising, and to which he gave most of his attention, used Cerenkov radiation to generate the short wavelengths.[68] But in 1951 he had an idea for a new type of oscillator that would succeed beyond everyone's expectations.

In 1950 the Navy had asked Townes to head a committee to examine the possibilities of new techniques for generating millimeter waves, and in April 1951 he was in Washington D.C. to chair a meeting of this committee. Waking up early that Sunday morning, he went for a walk, and while sitting on a bench in Franklin Park he had the idea for a new way to generate millimeter waves. If a gas could be produced in which most of the molecules were in an excited state, then electromagnetic waves of just the right wavelength would be amplified by stimulating the molecules to emit energy at that wavelength.

Townes, working with graduate student James P. Gordon and post-doctoral student Herbert J. Zeiger, finally succeeded in getting such a device to work in April 1954. Called the maser (**m**icrowave **a**mplification by **s**timulated **e**mission of **r**adiation), it was soon being used as an amplifier (about one hundred times more sensitive than preexisting techniques) and as an oscillator (of such constancy that a maser clock could be accurate to 1 second in 300,000 years).

After remarking that the physics literature already contained mention of the possibility of obtaining amplification by stimulated emission, Townes pointed to two essential contributions of his group: recognizing the coherence of the resulting radiation (more readily conceived with the engineer's view of radiation as consisting of waves than with the physicist's view of radiation as photons) and the adding of an external resonator for feedback.[69] Townes and other physicists had considered the possibility of getting stimulated emission from an inverted population, but the weakness of that effect made any practical application seem highly unlikely; feedback in a resonant cavity is what made masers practical.

In his years at Columbia, Townes's engineering skills were called upon constantly: "I personally [assembled] the apparatus mostly. . . . I was the one who knew all the parts of the apparatus and how it would go together, and I fixed the leaks and did everything with the electronics, with the students helping me. That's rather different from the way I have to work now. Mostly they are the ones who know the apparatus. . . ."[70]

Townes, along with many others, sought ways to extend the frequency range of the maser. He believed that what was needed was a high-Q resonator having only a few modes of oscillation (Q is a ratio of energy stored to energy dissipated), and believed that this could be done more easily by jumping over the intermediate frequencies and working with light waves.[71]

At this time Townes was working as a consultant to Bell Labs (one day every other week), and there he often talked with Arthur Schawlow, who had been his postdoctoral student at Columbia. Schawlow was also thinking about ways to extend masers to the infrared or even visible range. Working together, they wrote a landmark paper on the conditions required to make masers operate in the infrared, visible, and ultraviolet regions.[72] This paper stimulated a great deal of work, particularly at industrial laboratories, and within three years there were several working lasers (the first being Ted Maiman's at Hughes Research Laboratories).

The maser opened up a new field, which the invention of the laser greatly expanded. In 1959, for the first international conference devoted to the subject, Townes suggested the name 'quantum electronics,' and he edited two books with that name in title.[73] The first issue (January 1963) of the *Proceedings* of the newly formed Institute of Electrical and Electronics Engineers (IEEE) was a 400-page special issue on quantum electronics. From its inception to the present, quantum electronics has been a hybrid field, both physics and engineering. Townes points out that ". . . from the early 1950s to the early 1960s, essentially everyone who contributed to this growing field of masers and lasers . . . were those who had been occupied with the basic science of radio and microwave spectroscopy."[74]

In his years at Columbia University, Townes came to know the radio pioneer Edwin Howard Armstrong, inventor of the regenerative circuit, the superheterodyne receiver, and the super-regenerative circuit. His 1933 patents on frequency modulation (FM) as a way of avoiding static in radio broadcasting were eventually upheld by the courts, but only after his death in 1954.

TOWNES: *I used to see him [Armstrong] at lunch fairly frequently. He was a nice person, interesting. . . . He, at that time, was right in the middle of a patent suit and used to talk a lot about that. He was very annoyed at RCA and other people who wouldn't recognize his patents. Particularly frequency modulation. RCA was claiming that frequency modulation occurs in nature, which then rules out the patentability. Armstrong was arguing it never occurs in nature. That didn't seem quite right to me, but it is not so common in nature. He felt very strongly about this, but he was not too unreasonable. I enjoyed having lunch with him.*

NEBEKER: *He could talk about other things than his patent suits?*

TOWNES: *Yes, he could.*

NEBEKER: *I know that became his main occupation in later years.*

TOWNES: *That's right. He had a lot of patents to fight. By then he'd spent a whale of a lot of money fighting, and he still wasn't winning. But we talked also about general things. He frequently ate lunch with the physicists at the Faculty Club. We'd meet over there. So I would see him with moderate regularity.*

NEBEKER: *He was interested in what was going on in physics generally?*

TOWNES: *I guess he was probably more interested in my work than in others because it had something to do with electronics. He didn't particularly talk about high-energy physics or nuclear physics, but he talked about electronics. . . .*

He may have influenced me some in the following respect. He eventually jumped off a building and killed himself, and I think some of it was family problems. But I'm sure he was very depressed about this RCA situation, and he'd spent much of his fortune on it.

When the maser came along, I was supposed to submit the patent case to people in the university so they could patent it, which I did. They didn't have any patent policy, so they called together a committee to decide what to do. Major Armstrong had always been just patenting his own things without going through Columbia at all, and he had set a precedent. According to the agreement that I had signed for the support of my lab work, the patent belonged to Columbia University and I was obliged to turn it over to them. They finally decided that they really didn't have any policy, and that if I'd like to patent it to go ahead and patent it myself. Columbia wouldn't bother about it.

So I did that. But knowing Armstrong's problems and how difficult these things could be probably was part of my reasoning. I don't remember it that clearly. In any case, I decided that I didn't want to get locked up in a lot of patent problems and spend my life that way. The Research Corporation was handling patents and giving the resultant money to universities, and they'd given substantial amounts to the physics department. So I gave the maser patent to the Research Corporation and let them take it over and worry about it and give me a certain fraction back. Then I didn't have responsibility for it, and I could forget about it. So that's what I did.[75]

Townes remained at Columbia until 1961, though the last two years he spent almost entirely in Washington as vice president and director of research of the Institute for Defense Analysis (a nonprofit think tank that advised the government on weapons systems and on arms control measures). In 1961 he accepted the position of provost and professor of physics at MIT, and in 1967 he moved to the University of California at Berkeley as university professor of physics. From 1967 to the present he has given most of his time to research in astronomy.

As we have seen, Townes long had an interest in astronomy. Though he chose not to pursue radio astronomy after the war, he returned to that field in the late 1950s when he and Columbia associates J. A. Giordmaine and

L. E. Alsop installed a maser on the Naval Research Laboratory's radio telescope in Washington D.C. in 1959 (see Figure 6).[76] (This was the first use of a maser as an amplifier, but maser amplifiers soon found many other applications, notably for satellite transmissions, beginning with Echo in 1960, and in the discovery of the cosmic background radiation by Arno Penzias and Robert W. Wilson in 1965.)

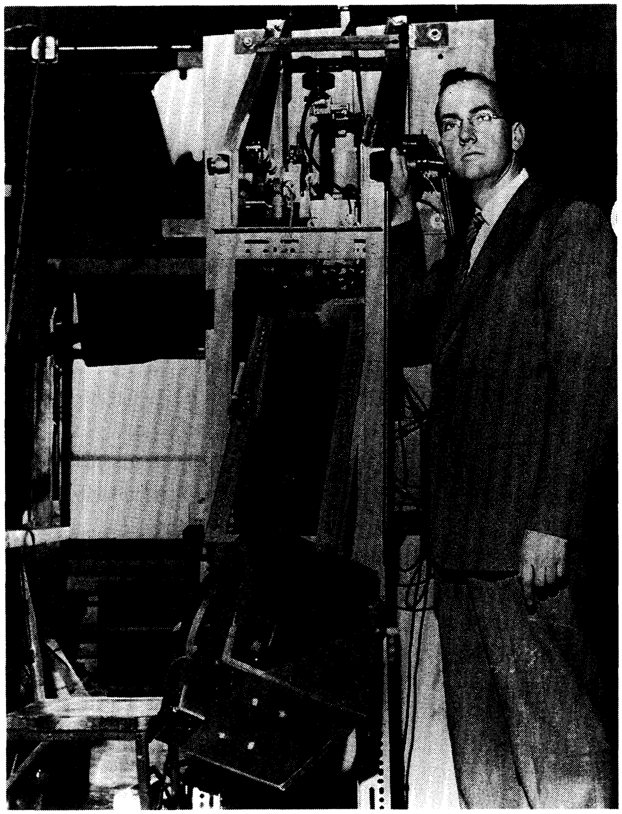


Figure 6. Towns in his laboratory at Columbia University with the first maser amplifier used for radio astronomy.

Townes pioneered the new field of molecular astronomy. In 1955 he had suggested that astronomers look for molecules in interstellar space.[77] Several quite simple free radicals had been discovered much earlier with optical astronomy. Townes's former student, Alan Barrett, made the important discovery of the hydroxyl radical (OH) in 1963. But most astronomers doubted that there were others and that there were any stable molecules, and no one had made the effort to search for them. So when Townes turned to astronomy in 1967, he attempted this and, together with several colleagues, discovered the first stable molecules in interstellar space.[78] Townes wrote recently, "About a hundred different molecules have now been found, including all those thought to be the most important in initiating life, floating in interstellar space and waiting to condense into stars and planets. . . . this new astronomy had its roots in my somewhat arbitrary assignment during the war."[79] (It is interesting that masers have been found in interstellar space, in gas clouds where molecular populations are inverted naturally and amplify microwaves.)

Other areas of astronomy to which Townes has made important contributions are infrared astronomy and, in recent years, infrared interferometry. Borrowing a technique from radio receivers, he introduced heterodyne detection to astronomy by proposing, building, and using an infrared heterodyne detector.[80] The technique was valuable in astronomical spectroscopy because of its high resolution and was especially valuable in astronomical interferometry, the modern form of which depends strongly on the use of lasers in still other ways.

Though the subject of this chapter is the engineering work of Charles Townes, it should be remembered that he has made his greatest contributions as a research physicist and later as an astrophysicist, authoring some 300 papers. In addition, he has been extremely active as a teacher, a university administrator, and a government advisor. At Columbia, MIT, and Berkeley he has directed the work of more than 60 Ph.D. students (including Arno Penzias, Ali Javan, and Elsa Garmire) and almost as many postdoctoral students (including Arthur Schawlow, Reinhart Genzel, and Koichi Shimoda). He was chairman of the physics department at Columbia and provost of MIT. He has been a science advisor to Presidents Eisenhower, Kennedy, Johnson, and Nixon and served on numerous advisory committees for the military, NASA, and the National Academy of Sciences. He has also been active in professional organizations, serving as an editor of half a dozen journals and as president of the American Physical Society.

Townes and Engineering

Yet engineering has been an important element of Townes's career from its inception to the present. Born in Greenville, South Carolina, on 28 July 1915, he regards his engineering experience as beginning with his upbringing on a farm (his father, though, was an attorney): "I think a farm is a good place for both experimental physics and engineering. People have to make do with what's there. They invent things and make things and fix things."[81] As a youth Townes was, by his own report, more interested in nature than in man-made things.[82] He collected leaves, insects, rocks, and bird sightings. He was close to his older brother Henry, who became a biologist, and he went to college expecting to become a scientist, probably a biologist. Nevertheless, he took an interest in gadgets. (See Figure 7.)

A favorite cousin, Frank Dargan, was chairman of the electrical engineering department at Clemson University. He gave Charles and his brother a crystal radio set, which they experimented with. Later, when Charles was in high school, he built his own crystal radio, but never got it working properly. He also had an interest in old clocks and watches, which he used to take apart and reassemble to make them work.

Figure 7. Charles Townes at about age 12.

Charles's interest in gadgets—and in making inventions—is shown in a letter he wrote, as a 10-year-old, to his older sister Mary Townes, then attending Winthrop College in Rock Hill, South Carolina. (See Figure 8.)

After earning a B.A. and B.S. from Furman University (a small Baptist college) in Greenville in 1935, Townes enrolled at Duke University. The physics department there owned two Van de Graaff generators, but they

Dec. 14, 1925

Dear Mary,

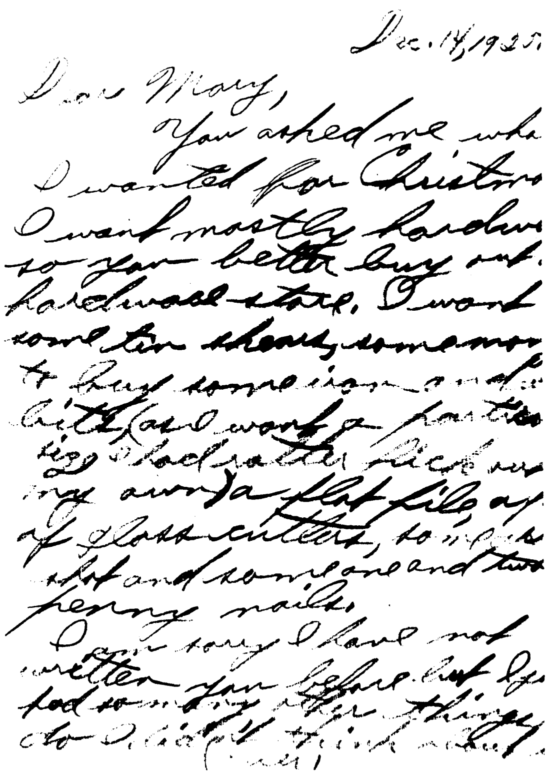
You asked me what I wanted for Christmas. I want mostly hardware so you better buy out a hardware store. I want some tin shears, some money to buy some iron and wood bits, (as I want a particular size I had rather pick out my own) a flat file, a pair of glass cutters, some rifle shot and some one and two penny nails.

I am sorry I have not written you before but I just had so many other things to do I didn't think about it.

Daddy has got a patten [*that is*, patent] thing up that costs a nickel to patten anything. He did it because Henry [Charles's older brother] fusses so much saying I copy him in every thing…

Your brother,

Charlie



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I am sorry I have not written you before but I just had so many other things to do I didn't think about it.

Figure 8. First page of a letter that Townes wrote to his sister Mary on 14 December 1925.

had never functioned very well. Townes undertook to bring them up to a high level of performance by making modifications to the machinery and belts and the way charges were picked off the belts. His master's thesis, which he completed in early 1937, was an analysis of these machines. "I never did any physics with them," he says, so all of this may be regarded as engineering experience.[83]

Townes then moved to the California Institute of Technology as a Ph.D. candidate in physics, but again his thesis work involved a great deal of engineering. He chose W. R. Smythe as thesis advisor: "He was tough, and he didn't have any other students. I felt I would get a lot of attention."[84] There he worked on a gas-diffusion apparatus for isotope separation, one that Dean Wooldridge had built several years earlier, but was not then being used: ". . . some of the pumps were cracked, and there were other leaks in the vacuum system. A lot of things needed fixing up and improving."[85] (See Figure 9.) He used the apparatus to separate particular isotopes—oxygen 18, nitrogen 15, and carbon 13—and then did spectroscopy on them to determine nuclear spins.[86] Townes's first publication came out of this thesis work; it was not, as one might suppose, a physics paper, but rather a contribution to engineering ("Greaseless vacuum valves").[87]

We have already seen that Townes worked at Bell Labs for more than eight years. His connection with the laboratory, however, began before that day in September 1939, when he first reported for work, going back in fact to his college days in Greenville. He was becoming increasingly interested in physics, but neither his college nor the local library received any physics journals. The local library did, however, receive *Bell System Technical Journal* (AT&T sent the journal gratis), and Townes read it with great interest. A Bell Labs scientist, Carl Darrow, wrote quite a few articles summarizing advances in particular scientific areas. Townes recalls, "To have a summary of a new field of physics written there in a journal was a great opportunity. So I studied those hard."[88] In the 1940s Townes came to be good friends with Darrow.

Townes's connection with Bell Labs did not end when he moved to Columbia in January 1948. For most of his years at Columbia, he was a consultant to Bell Labs, and he has maintained personal relationships with many Bell Labs scientists and engineers to the present. He said recently, "I continue to get help by calling those people. They also, I hope, get a little help and a few suggestions from me from time to time."[89] As testimony to the value of being part of a large scientific and technical community, Townes said, "Frequently, the efficiency of sorting out unfruitful routes for solution of a problem depends on easy access to a friend who has relevant knowledge. Hence, being closely surrounded by other scientific and technical activity is often important to new and exploratory work."[90] His own work shows the fruitfulness of combining ideas from different scientific and technical areas, and he has commented, "What I think really delayed the development of quantum electronics was a lack of the piecing together of ideas from a variety of fields."[91]

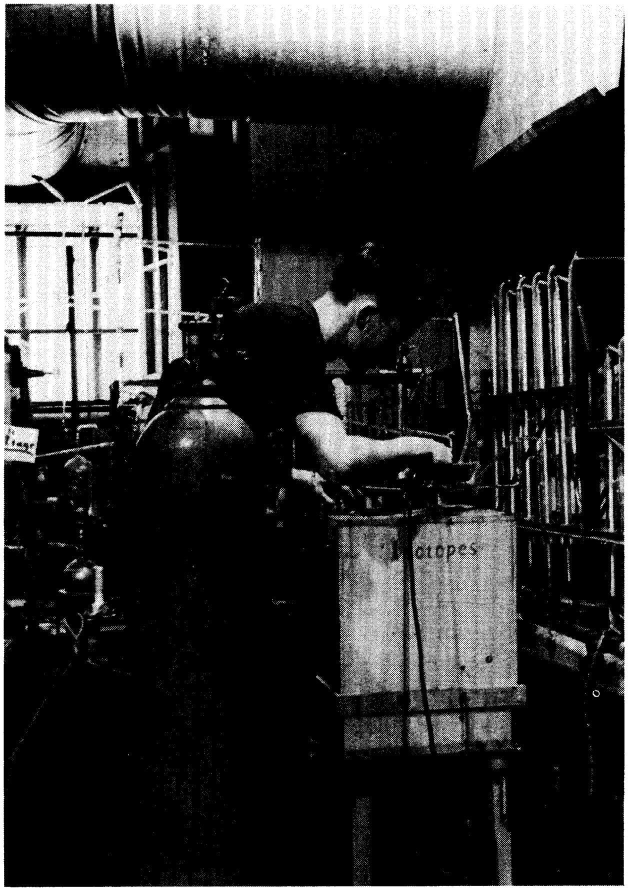

Figure 9. Townes in his lab (and office) at Cal Tech in the academic year 1937/38 working on his isotope separation system. On the back of the photo are the words "Looking for leaks—a large portion of most research."

Townes has also maintained contacts with the engineering community in general. Early in his career he joined the Institute of Radio Engineers (one of the predecessor societies of the IEEE) because he valued its journal, *Proceedings of the IRE*. (It is indicative of the origins of radio astronomy that many of the seminal papers in that field, including Townes's 1959 article on the maser amplifier for radio astronomy, appeared in *Proceedings of the IRE*.)[92] In 1958 Townes was awarded the Morris N. Liebmann award of the IRE, and in 1961 the David Sarnoff Award of the American Institute of Electrical Engineers (the other predecessor society of the IEEE). In 1967 he received the highest award of the IEEE, the Medal of Honor, and in 1988 he was named an IEEE Life Fellow.

The traditional view is that technology is derivative of science: Scientists make discoveries and gain understanding of how things work, and engineers later apply scientific knowledge to practical problems. Historians of technology have emphasized the influence in the other direction: Technology both permits scientists to answer questions and raises new questions.[93] Townes has, in numerous writings, expounded on the symbiosis of science and technology: "While scientists are rather familiar with the flow of contributions from basic to applied work, and the phenomenon is recognized in generality by the broader public, I do not believe adequate recognition is given to the reverse flow—the contribution of technology to basic science. Convenient and sophisticated instrumentation is but one example. More broadly, such contributions encompass important scientific discoveries produced by applied research, the development of industrial and commercial products on which much basic research depends, and new technical possibilities that emerge from applied work in industry and in military and space programs."[94] He has also commented that, "Science and technology really have to develop together. That's a great disadvantage for countries that don't have a good technological base. Their scientists are at a considerable disadvantage."[95]

As shorthand one may say that wartime radar systems led to microwave spectroscopy, and that microwave spectroscopy led to masers and lasers. This is shorthand because it was, of course, not technology spawning technology but people discovering and inventing, people with particular talents, motivations, and knowledge. The story of Charles Townes shows how fruitful a combination of scientific and engineering knowledge can be, and it reveals also several important aspects of the modern relationship between science and technology: the scientist's ability to contribute to the advance of technology, the engineer's ability to contribute to the advance of science, and the personal and institutional connections between industrial R & D and academic science.

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[1] The information about Charles Townes contained in this article comes mainly from the following sources: (1) an extensive oral history interview of Townes conducted by the author 14 and 15 September 1992 (available at the Center for the History of Electrical Engineering); (2) the laboratory notebooks kept by Townes in his years at Bell Labs and papers from the files of the projects on which he worked (available at the AT&T Archives); (3) interviews of Townes by William V. Smith (18 to 20 June 1979), Joan Lisa Bromberg (28 and 31 January 1984), and Finn Aaserud (20 and 21 May 1987), all of which are available at the archives of the Center for History of Physics of the American Institute of Physics; (4) a 35-hour oral history interview conducted by Suzanne B. Riess, 5 November 1991 to 3 July 1992, for the Regional Oral History Office (ROHO), The Bancroft Library, University of California, Berkeley (the interview will be available in final manuscript form in 1994); and (5) published writings by Townes and others.

[2] See "The early history of microwaves," Chapter 8 of Henry E. Guerlac's

Radar in World War II (Tomash Publishers and American Institute of Physics, 1987), pp. 185–240; and "The background to the development of the cavity magnetron" by R. W. Burns in a book he edited called *Radar Development to 1945* (Exeter: Peter Peregrinus, 1988).

[3] Interview 1992, p. 10

[4] The final sentence of the preface to the book, *Static and Dynamic Electricity* (New York: McGraw-Hill, 1939), reads, "In particular, he [the author] wishes to thank Dr. Charles H. Townes for checking all the derivations in the final manuscript and the answers to those problems not appearing in the preliminary edition."

[5] Interview 1992, p. 116.

[6] Interview 1992, pp. 116–117.

[7] Bell Labs Notebook 17015 (1939–1941), p. 7. The device is further described in the six following pages. Townes wrote up some of this work as a Bells Labs Technical Memorandum, "Energy relations in electron flow through non-uniform high frequency fields," 2 January 1940.

[8] Interview 1992, pp. 8, 11–12.

[9] Patents 2,438,954 (electronic oscillator of the cavity resonator type); 2,439,381 (computing bombsight, with Darlington and Wooldridge); 2,457,287 (air-speed indicating system); 2,488,448 (computing circuit for determining bomb release points, with Wooldridge); 2,511,197 (averaging device, with Darlington and Wooldridge); 2,544,754 (electron camera tube); 2,701,098 (concealed ground target computer); 2,707,231 (frequency stabilization of oscillators); 2,707,235 (frequency selective systems); and 2,819,450 (molecular resonance modulators and demodulators).

[10] Interview 1992, p. 9.

[11] The basic maser-laser patent is number 2,879,439 (issued 24 March 1959), and the basic laser patent (with Schawlow) is 2,929,922 (issued 22 March 1960). The only patent Townes has since received is number 3,469,107 for stimulated Brillouin parametric devices (with Stoicheff, Garmire, and Chiao), issued 23 September 1969.

[12] Bell Labs Notebook 17015 (1939–1941), pp. 21–46.

[13] Interview 1992, pp. 17–18.

[14] *IEEE Transactions on Magnetics*, December 1969.

[15] Townes did not make many notebook entries in the month and a half he was in Bozorth's group [Bell Labs Notebook 17015 (1939–1941), pp. 48–56]; he reports that in this time he was "mainly learning" (Interview 1992, p. 21).

[16] Bell Labs Notebook 17015 (1939–1941), pp. 57–127. Work recorded on pages 57 to 120 is classified as Case 35887; work on pages 121 to 127 as Case 37641.

[17] Bell Labs Technical Memorandum 6 January 1941, "Theory of cathode sputtering in low voltage glow discharges"; Townes, "Theory of cathode sputtering in low voltage gaseous discharges," *Physical Review*, vol. 65 (1944), pp. 319–327.

[18] Interview 1992, p. 28.

[19] S. Millman, ed., *A History of Engineering and Science in the Bell System: Communications Sciences (1925–1980)* (AT&T Bell Laboratories, 1984), pp. 356–359.

[20] Interview 1992, pp. 34–35.

[21] M. D. Fagen, ed., *A History of Engineering and Science in the Bell System: National Service in War and Peace (1925–1975)* (Bell Telephone Laboratories, 1978), pp. 163–170.

[22] Ibid., pp. 134–136.

[23] Interview 1992, p. 35.

[24] Interview 1992, pp. 35–36.

[25] Interview 1992, p. 29. Another of Kelly's initiatives was directed toward all Bell Labs employees: Communications Development Training, usually called Kelly College, was a large in-house training program for the continuing education of company employees.

[26] ROHO Interview, p. 247.

[27] See the first two chapters of Fagen, *A History of Engineering and Science.* After the war, the number of military projects decreased rapidly; in 1947 they accounted for 15 percent of the Bell Labs budget.

[28] Interview 1992, p. 38.

[29] Interview 1987, p. 27.

[30] Bell Labs Notebook 17015 (1939–1941), p. 125.

[31] This was the SCR-519 radar combined with a version of the M-9 computer. See Fagen, *A History of Engineering and Science*, pp. 91–93.

[32] Bell Labs Notebook 17870 (1941–1942), pp. 1–200.

[33] Bell Labs Notebook 17870 (1941–1942), pp. 118–119.

[34] Interview 1992, pp. 41–43.

[35] Interview 1992, pp. 63–64.

[36] Interview 1992, p. 71.

[37] See "Proposed Bomb Sight: Memorandum for file," 28 March 1942, Bell Labs Archives, Case 23665.

[38] See "Conference Notes —Case 23665: Memorandum for file," 29 October 1942, Bell Labs Archives, Case 23665, and Bell Labs Notebook 17870 (1941–1942), pp. 138–156.

[39] Bell Labs Notebook 19729 (1944–1946), p. 7.

[40] Bell Labs Notebook 19729 (1944–1946), pp. 12–13, and Interview 1992, p. 84.

[41] Interview 1992, p. 50.

[42] Bell Labs Notebook 18774 (1942–1943), p. 101.

[43] Interview 1992, p. 86.

[44] Interview 1992, p. 86.

[45] Fagen, *A History of Engineering and Science*, p. 9.

[46] Karl Jansky, "Electrical disturbances apparently of extraterrestrial origin," *Proceedings of the IRE*, vol. 21, 1933, pp. 1387–1398.

[47] Townes, "Interpretation of radio radiation from the Milky Way," *Astrophysics Journal*, vol. 105, 1946, pp. 235–240.

[48] Fagen, *A History of Engineering and Science*, pp. 89–113.

[49] ROHO Interview, p. 169.

[50] Interview 1992, p. 58.

[51] Interview 1992, p. 75.

[52] Bell Labs Notebook 19729 (1944–1946), pp. 96–101.

[53] Bell Labs Notebook 19729 (1944–1946), pp. 106–108.

[54] [Harvard] Radiation Laboratory Report No. 43-2, "The atmospheric absorption of microwaves," 27 April 1942.

[55] Interview of Townes, *Laser Pioneer Interviews* (Torrance, CA: High Tech Publications, 1985), pp. 35–47.

[56] Interview 1992, pp. 57–58.

[57] See ROHO Interview, pp. 207–209, and Interview 1992, pp. 108–110.

[58] See chapter 2 of J. S. Hey's *The Evolution of Radio Astronomy* (New York: Science History Publications, 1973).

[59] Memorandum by Townes entitled "Applications of microwave spectroscopy" (undated, probably May 1945), Bell Labs Archives.

[60] Bell Labs Notebook 20464 (1945–1946), p. 2.

[61] New York: McGraw-Hill, 1955.

[62] C. H. Townes and A. L. Schawlow, *Microwave Spectroscopy* (New York: McGraw-Hill, 1955), p. 1.

[63] ROHO Interview, p. 268.

[64] Bell Labs Notebook 21268 (1946–1947), pp. 142–144, and Patent 2,544,754 (electron camera tube).

[65] Interview 1992, p. 118.

[66] Four people in industrial research labs with experience in radar technology (besides Townes, they were W. E. Goode at Westinghouse, A. H. Sharbaugh at GE, and W. D. Hershberger at RCA) began to explore the new field of molecular spectroscopy after the war. All were permitted to do so for some time (showing the freedom scientists in industry had), but because the field seemed not to have much application, they were not given much support nor, in some cases, allowed to continue work in that area.

[67] Interview of Townes in *The Way of the Scientist: New Views from the World of Science and Technology* (New York: Simon and Schuster, 1966), p. 61.

[68] Paul Forman, "Inventing the maser in postwar America," *Osiris*, 2nd series, vol. 7, 1992, pp. 105–134.

[69] Townes, "The laser's roots: Townes recalls the early days," *Laser Focus*, August 1978, pp. 52–58.

[70] Interview 1979, p. 62.

[71] Townes, "The laser's roots: Townes recalls the early days," *Laser Focus*, August 1978, pp. 52–58.

[72] Townes and Schawlow, "Infrared and optical masers," *Physical Review*, vol. 112, 1958, pp. 1940–1949.

[73] *Quantum Electronics* (1960) and *Quantum Electronics and Coherent Light* (1965).

[74] Townes, "The laser's roots: Townes recalls the early days," *Laser Focus*, August 1978, pp. 52–58.

[75] Interview 1992, pp. 126–128.

[76] J. A. Giordmaine, L. E. Alsop, C. H. Mayer, and C. H. Townes, "A maser amplifier for radio astronomy at X-band," *Proceedings of the IRE*, vol. 47, 1959, pp. 1062–1070.

[77] Townes, "Microwave and radio-frequency resonance lines of interest in radio astronomy," in H. S. van de Hulst, ed., *IAU Symposium No. 4: Radio Astronomy* (Cambridge UK: Cambridge University Press, 1957), p. 92 [the talk was given in August 1955].

[78] Townes, A. C. Cheung, D. M. Rank, D. D. Thornton, and W. J. Welch, "Detection of NH_3 molecules in the interstellar medium by their microwave emission," *Physical Review Letters*, vol. 21, 1968, pp. 1701–1705.

[79] Townes, "Reflections on my life as a physicist," *Bulletin of the Center for Theology and the Natural Sciences*, vol. 12, no. 3, 1992, pp. 1–7.

[80] The idea was initially advanced in Townes and H. A. Smith, "Frequency conversion and detection of infrared radiation," *Polarisation matière et rayonnement* (Presses Universitaires de France), pp. 467–483. The first paper giving results obtained using the heterodyne detector was Townes, M. A. Johnson, and A. L. Betz, "10-mm heterodyne stellar interferometer," *Physical Review Letters*, vol. 33, 1974, pp. 1617–1620. Townes reports that he seldom writes an instrumentation paper, waiting to describe the instrument until he has obtained scientific results with it.

[81] Interview 1992, p. 114.

[82] Townes, "Reflections on my life as a physicist."

[83] Interview 1992, p. 113.

[84] Interview 1992, p. 114.

[85] Interview 1992, p. 114.

[86] ROHO Interview, p. 117.

[87] *Review of Scientific Instruments*, vol. 9, 1938, pp. 428–429.

[88] Interview 1992, p. 108.

[89] Interview 1992, p. 101.

[90] Townes, "Science, technology, and invention: Their progress and interactions," *Proceedings of the National Academy of Sciences of the USA*, vol. 80, 1983, pp. 7679–7683.

[91] Townes, "Quantum electronics at Columbia University," *Proceedings of the Fortieth Anniversary Symposium of the Joint Services Electronics Program (JSEP)* (U.S. Army Research Office, 1987), pp. 71–88. In this paper Townes tells of adapting an idea he got from a biologist colleague at Columbia to understanding noise in a maser amplifier.

[92] See the list of papers on pages 190 to 204 of Hey, *The Evolution of Radio Astronomy*.

[93] For example, Thomas Kuhn, in "Energy conservation as an example of simultaneous discovery" (in Marshall Clagett, ed., *Critical Problems in the History of Science* (Madison: University of Wisconsin Press, 1959), pp. 321–356), shows how important knowledge of the steam engine was in the formulation of the principle of conservation of energy.

[94] Townes, "Science, technology, and invention: Their progress and interactions," *Proceedings of the National Academy of Sciences of the USA*, vol. 80, 1983, pp. 7679–7683. More than a hundred years earlier, in 1874, another

physicist who was much involved with engineering, William Thomson (later Lord Kelvin), made a similar point: " . . . I have more to say respecting the reflected benefits which electrical science gains from its practical applications in the electric telegraph than of the value of theory in directing, and aiding, and interesting the operators in every department of the work of the electric telegraph," *Popular Lectures and Addresses*, Vol. II (London: Macmillan, 1894), p. 211.

[95] Interview 1992, p. 104.