THE MASER

It is a quantum-mechanical device which amplifies very short radio waves with extraordinary fidelity. The basic element of the early masers was gaseous ammonia; the latest models make use of crystals

by James P. Gordon

The 50-foot radio telescope at the Naval Research Laboratory in Washington, D.C., recently acquired a strange accessory. Mounted just behind the antenna, at the center of the telescope's parabolic reflector, is an oblong box containing a synthetic ruby and some standard microwave equipment. A bath of liquid helium chills the ruby to the temperatures of the cold reaches of space which the telescope surveys. With the help of this refrigerated gem astronomers hope to extend their range of observation far beyond its present limits, perhaps far enough to clear up once and for all the mysteries of the size and geometry of the universe.

The ruby is part of a new microwave device called the "maser." The letters of this odd word stand for Microwave Amplification by Stimulated Emission of Radiation. The maser represents the ultimate in high-fidelity amplifiers. The best previous amplifiers, using vacuum tubes, put out a mixed signal which combined an amplified version of the input with a wide assortment of oscillations originating in the tubes themselves. If the input signal becomes weaker, the percentage of noise in the output increases, and the resemblance between input and output diminishes. Eventually a point is reached where the input, though still amplified, can no longer be recognized in the output. The great virtue of the maser is that it generates practically no noise. It can detect much weaker signals than other amplifiers can, and hence pick up radio waves from far more distant points in space. As we shall see, it is also finding a number of other important applications in science and technology.

What makes the maser so quiet? It is perhaps helpful to ask first: What makes vacuum tubes so noisy? Vacuum tubes utilize a stream of agitated electrons which are boiled out of a cathode and sent crashing into a collecting plate by an outside voltage. The signal to be amplified imposes its variations on the electron stream. But the particles have their own random variations, which are inevitably part of the output of the tube. It is a tribute to the ingenuity of electrical engineers that, in improvements such as the traveling-wave tube, they have been able to go so far toward muffling the effects of unruly electrons. The least noisy of these tubes, however, leaves a lot to be desired.

The maser dispenses with streams of electrons altogether. Instead it makes use of certain intrinsic oscillations in many types of material particles. These oscillations are basic phenomena of nature. The idea of harnessing them for useful work occurred independently a few years ago to several workers in the field of microwaves, including C. H. Townes of Columbia University, N. G. Basov and A. M. Prokhorov in the U.S.S.R. and J. Weber of the University of Maryland.

To appreciate what led to this notion we should briefly consider the interaction between high-frequency radiation and matter. Every student of elementary physics has witnessed the experiment in which light from a sodium lamp is shined into a container of cool sodium vapor and is completely absorbed. At the same time light of a different frequency—that is, color—from some other source passes through the container undimmed. The classical explanation is that every atom and molecule has certain natural vibrations which occur at sharply defined frequencies. When the oscillations of light or of other electromagnetic waves coincide with one of these frequencies, the radiation gives up energy to the atom or molecule, causing it to vibrate like a pendulum which has been set swinging by a series of properly timed pushes. Conversely, if atoms or molecules can be made to vibrate by some other means, say by thermal agitation, they will emit electromagnetic waves of the same characteristic frequency. In the experiment just mentioned, waves from hot, vibrating sodium molecules are absorbed by the cold molecules. Waves whose frequency does not correspond to the frequency of the sodium vibrations pass through unaffected.

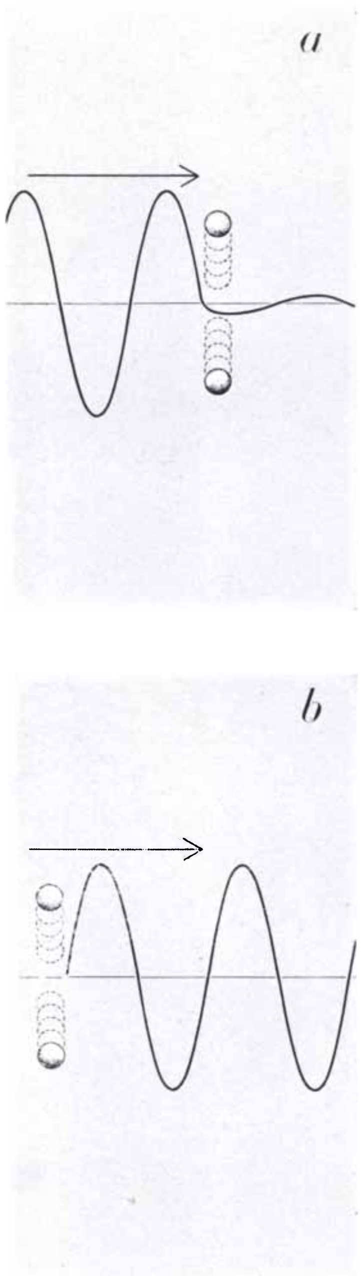
If the reader is wondering how such a mechanism can be made to amplify the energy in a wave, he may as well stop. If the "classical"—that is, pre-quantum mechanical—explanation were completely correct, there would be no maser. (As a matter of fact, there would be no atoms. On the classical theory electrons revolving around atomic nuclei would continuously radiate away their energy and spiral into the nucleus. All of ordinary matter would thus collapse.)

To discover the secret of the maser we must turn to the quantum picture of matter and radiation. In this view atoms and molecules exist most of the time in one of a number of stable, nonradiating states. Each state corresponds to a fixed quantity of energy. Radiation, on the other hand, consists of the particles called photons, carried by a sort of guiding wave. The frequency of the wave is a measure of the energy of the photons, according to Max Planck's famous equation $E = hf$. A particle of radiation is produced when an atom falls from a higher to a lower energy state, and the energy of the photon is exactly equal to the difference in energy between the states. When an atom jumps the other way, from a lower to a higher energy state, it absorbs a photon of the same frequency. Thus

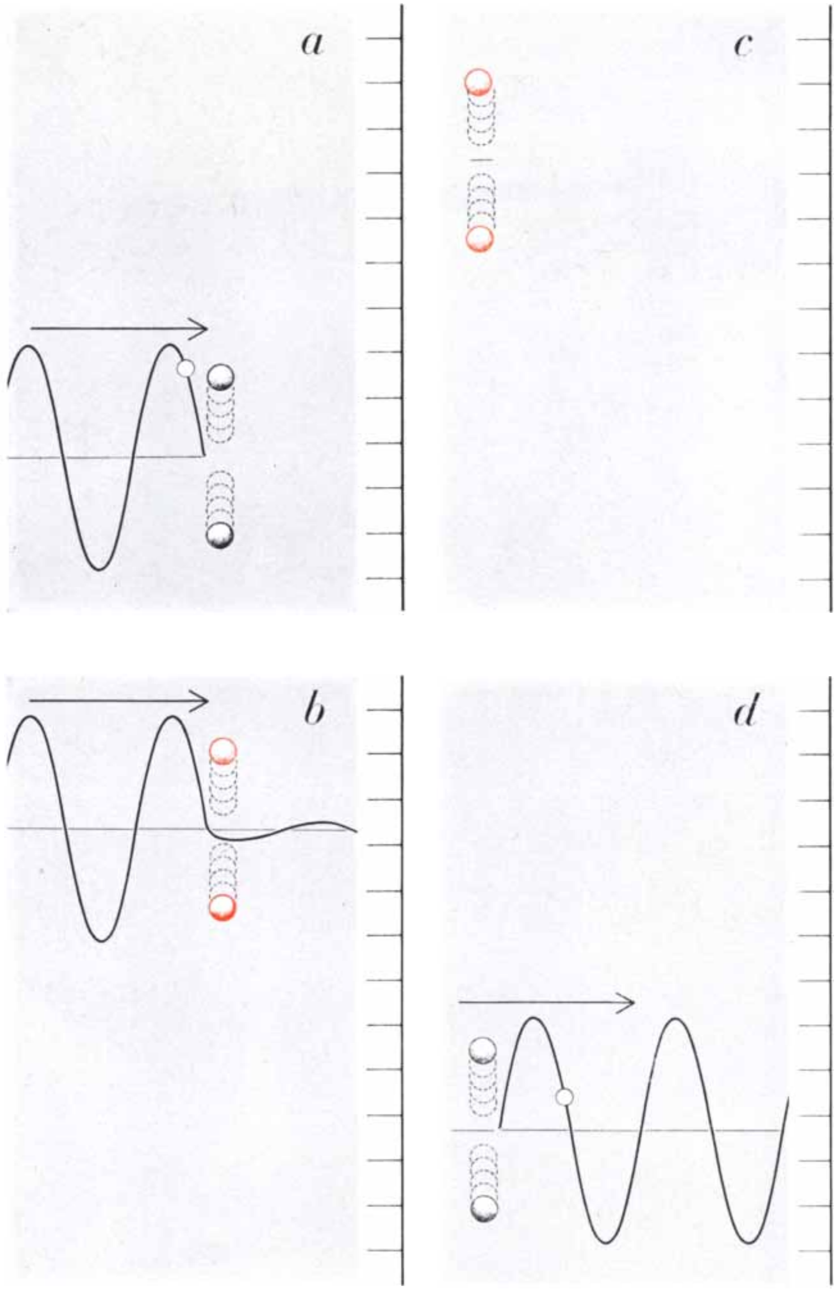
SOLID-STATE MASER is mounted at the focus of the 50-foot radio telescope of the Naval Research Laboratory in Washington, D.C. By largely eliminating the "noise" inherent in conventional amplifiers, the maser enables the telescope to detect very faint signals.

when radiation passes through an assembly of atoms, one of three things can happen. If the energy of the photons does not equal the difference between a pair of energy levels in the atoms, there is no interaction. If the energies match, and a photon collides with an atom in the lower of the two states, the radiation will be absorbed and the atom will be "excited" to the higher state. If the photon collides with an atom in the higher state, it will cause the opposite jump, down to the lower state, and a new photon will be emitted. Thus there will now be two photons where before the collision there was only one.

In any assemblage of atoms there is always some traffic between low- and high-energy states. The atoms keep hopping up and down in their energy states, boosted by energy received in chance collisions and falling because of their natural tendency to seek the lowest energy level. Under ordinary conditions the lower states are always more densely populated than the higher ones. Thus when radiation of the appropriate fre-



CLASSICAL VIEW of the interaction of electromagnetic radiation and matter is depicted. At top an electromagnetic wave (*wavy line*) of the appropriate frequency sets a two-atom molecule (*balls*) to vibrating. The process absorbs energy from the wave. At bottom a molecule spontaneously emits energy (*wavy line*) of characteristic frequency.



QUANTUM-MECHANICAL VIEW of the interaction is similarly depicted. Here the electromagnetic radiation is regarded not as a wave but as a photon (*white dot*) guided by a wave. The frequency of the guiding wave is related to the energy of the photon. The molecule does not vibrate; the broken circles merely indicate that the atoms are regarded as simultaneously occupying a number of positions. At top left the molecule is at a lower energy level. At bottom left the molecule has been "excited" by a photon of the appropriate energy, and raised to a higher energy level. At top right the molecule is at the higher energy level. At bottom right it has fallen to the lower energy level and emitted a photon of characteristic energy. Scale at right of these four illustrations suggests energy levels.

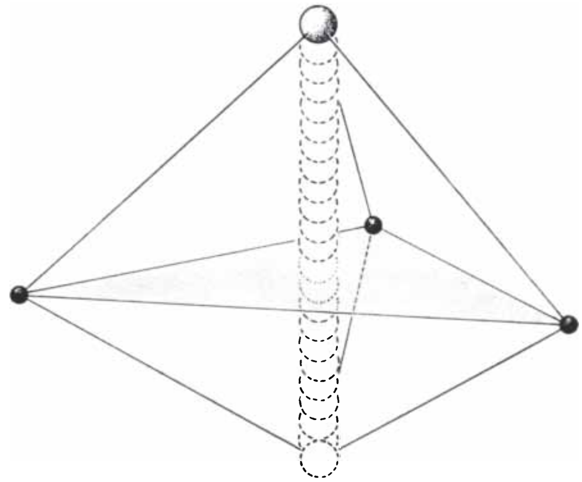
quency passes through the assemblage of atoms, more photons will be absorbed than new ones created, and the outgoing beam will be weaker than the incoming beam.

But suppose it were somehow possible to change the distribution of energy levels so that there were more atoms in the higher of two states than in the lower. Then a beam of photons of the appropriate frequency would produce more downward jumps than upward ones; the net effect would be that more photons would come out than went in. In other words, the output wave would have more energy than the input wave. This is the secret of how the maser amplifies.

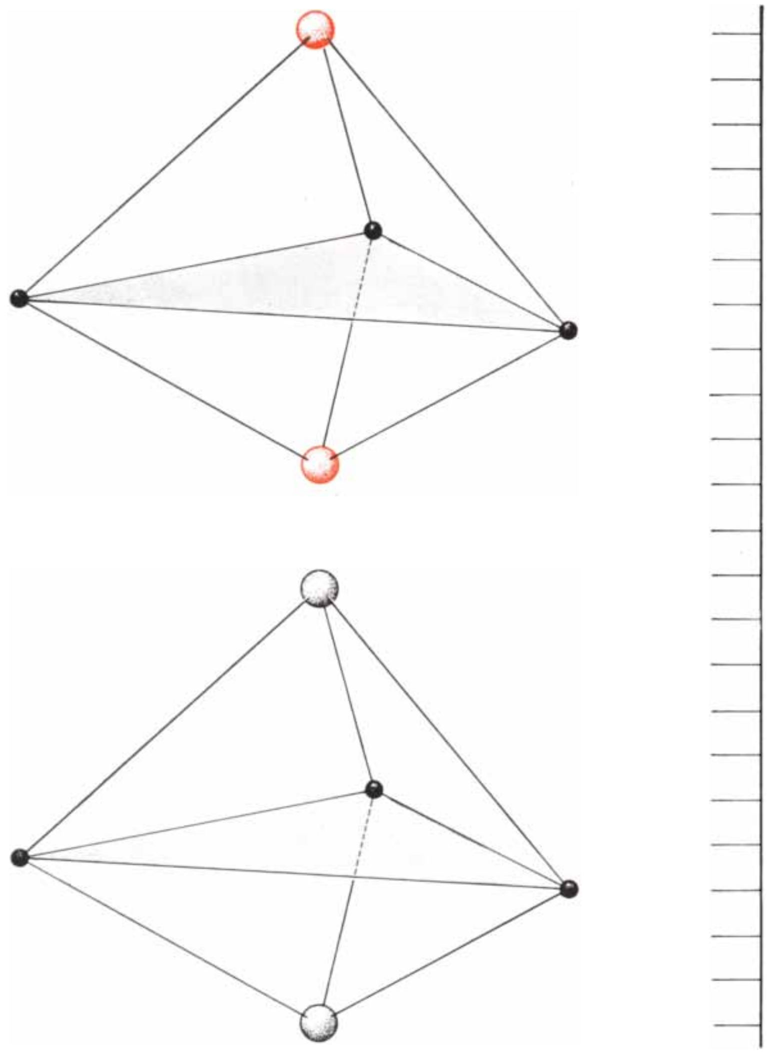
The first of the masers to be developed is based on the molecule of ammonia. For reasons we shall mention in a moment, the ammonia maser is more useful as an oscillator and a timekeeper than as an amplifier. It is in any case a remarkable device: a simple metal chamber, into which only a little ammonia gas is admitted, which yields a weak microwave signal of almost unbelievable purity. Its output wave falls short of a mathematically perfect sine curve by less than one part in 100 billion!

The molecule which produces this perfect monotone has the shape of a pyramid. At the apex of the pyramid is a nitrogen atom; at the base, three hydrogen atoms [*see illustrations at right*]. The nitrogen atom is able to move through the plane of the hydrogen atoms. thus turning the pyramid inside out. On the classical theory we picture the nitrogen atom flipping back and forth at a characteristic frequency of about 24,000 million vibrations per second, or 24,000 megacycles per second. At any given instant the nitrogen atom is on one side of the hydrogens or on the other. From the quantum point of view the nitrogen has at a given time a certain probability of being on either side—in a sense it is partly on both sides. Moreover, the molecule as a whole has two distinct energy states. The difference in energy between the states equals the energy of a photon with a frequency of 24,000 megacycles per second.

Now it happens that ammonia molecules in the higher state are repelled by strong electrostatic fields, whereas those in the lower state are attracted. Thus we have a method for segregating the high-energy molecules and getting maser action. The separator is a cylinder of charged rods [*see illustration at top of page 48*]. In the vicinity of the rods the field is strong; along the axis of the cylinder the field is weak. When a beam of



CLASSICAL VIEW OF THE AMMONIA MOLECULE is that its single nitrogen atom (*large ball*) vibrates back and forth across the plane of its three hydrogen atoms (*small balls*).



QUANTUM-MECHANICAL VIEW OF THE MOLECULE is that, in a sense, the nitrogen atom is simultaneously on both sides of the plane of the hydrogen atoms. The molecule may occupy either a higher energy level (*top illustration*) or a lower energy level (*bottom*).

ammonia molecules is sent through the separator, those in the upper state are attracted to the axis, while those in the lower state are pulled toward the electrodes and dispersed. Out of the far end comes a stream of molecules, virtually all of which are in the upper energy-state. If these molecules are irradiated with 24,000-megacycle microwaves, only downward transitions will be induced. Energy will be given up by the molecules to the microwave field, and the incoming wave will be amplified.

In the actual instrument ammonia gas at low pressure escapes from a nozzle into an evacuated chamber containing the separator and a resonant cavity. After passing through the separator, molecules in the upper state enter the cavity, into which the microwave signal is fed through a waveguide.

The resonant cavity is simply a metal box with highly reflecting walls. Each incoming photon can bounce back and forth across the chamber thousands of times before it escapes again, greatly increasing its chance of interacting with a molecule in the beam.

Whenever there is a collision, a new photon is born. It too is trapped in the chamber for a time and may collide with another molecule, producing a second new photon, and so on. If there are enough molecules in the cavity, this chain reaction becomes self-sustaining; the amplifier turns into an oscillator, generating its own wave without any input signal.

The ammonia maser is an extraordinarily stable oscillator. Its virtually unvarying sine waves can be used as a "pendulum" to regulate an almost perfect clock [see "Atomic Clocks," by Harold Lyons; SCIENTIFIC AMERICAN, February, 1957]. Although such timepieces have not yet been fully tested, it has been demonstrated that two ammonia masers will maintain their frequencies with respect to each other for at least a year with an accuracy of one part in 10 billion. A maser-regulated clock should gain or lose no more than one second in a few hundred years.

As an amplifier the ammonia maser has a remarkably narrow band-width: it will not amplify waves which depart from its central frequency by more than 3,000 to 5,000 cycles. The ammonia maser is not readily tunable; the central frequency cannot easily be changed. This means that it is not really a practical amplifier. If it were used in a communications channel, it could transmit only one voice at a time; it could not come close to receiving a television station. The ammonia maser was, however, the instrument which first demonstrated the great potentialities of maser amplifiers. Moreover, studies of its resonance curve have contributed important information about the magnetic fields within the ammonia molecule.

It was not until the invention of masers that utilize solids rather than gases that practical low-noise microwave amplifiers became a reality. Solid-state masers have a noise level even lower than that of the ammonia maser. Furthermore they are tunable, they have much broader band-widths and they put out much more power. The fact that their frequencies can be varied makes them unsuitable as standards of frequency or of time, but it adds considerably to their general usefulness as amplifiers.

The action of the solid-state maser also depends on quantum jumps, but they are jumps of electrons within individual atoms rather than energy transitions of whole molecules. It is by now a familiar fact that every electron is in effect a small spinning magnet. In most atoms, which are nonmagnetic, the electrons are paired off with their poles opposed to each other so that their magnetism is canceled out. There are a few substances, however, in whose atoms the cancellation is incomplete; some electrons are unpaired and the material as a whole is magnetic, or, in technical terms, paramagnetic.

It is the behavior of unpaired electrons placed in an external magnetic field that makes the solid-state maser possible. As usual, there are two ways to describe this behavior: the classical way, which has the advantage of being easy to visualize but the drawback of being incomplete; and the quantum way, which is implausible but correct. Classically we imagine that the spin axis of the electron wobbles, or precesses like a top around the direction of the field [*see diagram at left in illustration at top of opposite page*]. In quantum terms we say that the spinning electron can have just two positions: one in which its axis points in the same direction as that of the field; the other in which it points in the opposite direction. The two positions constitute different quantum states, the higher of which is represented by the electron whose axis points in the direction of the field. As in the case of molecules, the difference between the levels corresponds to the energy of a photon whose frequency equals that of the classical vibration. Also as in the case of molecules, there are normally more electrons at lower levels than at higher.

To make a maser we simply need to find a way of reversing the normal distribution and putting the majority of electrons in the upper state. Then if they are irradiated with photons of the correct frequency, they will jump down, amplifying the incoming beam.

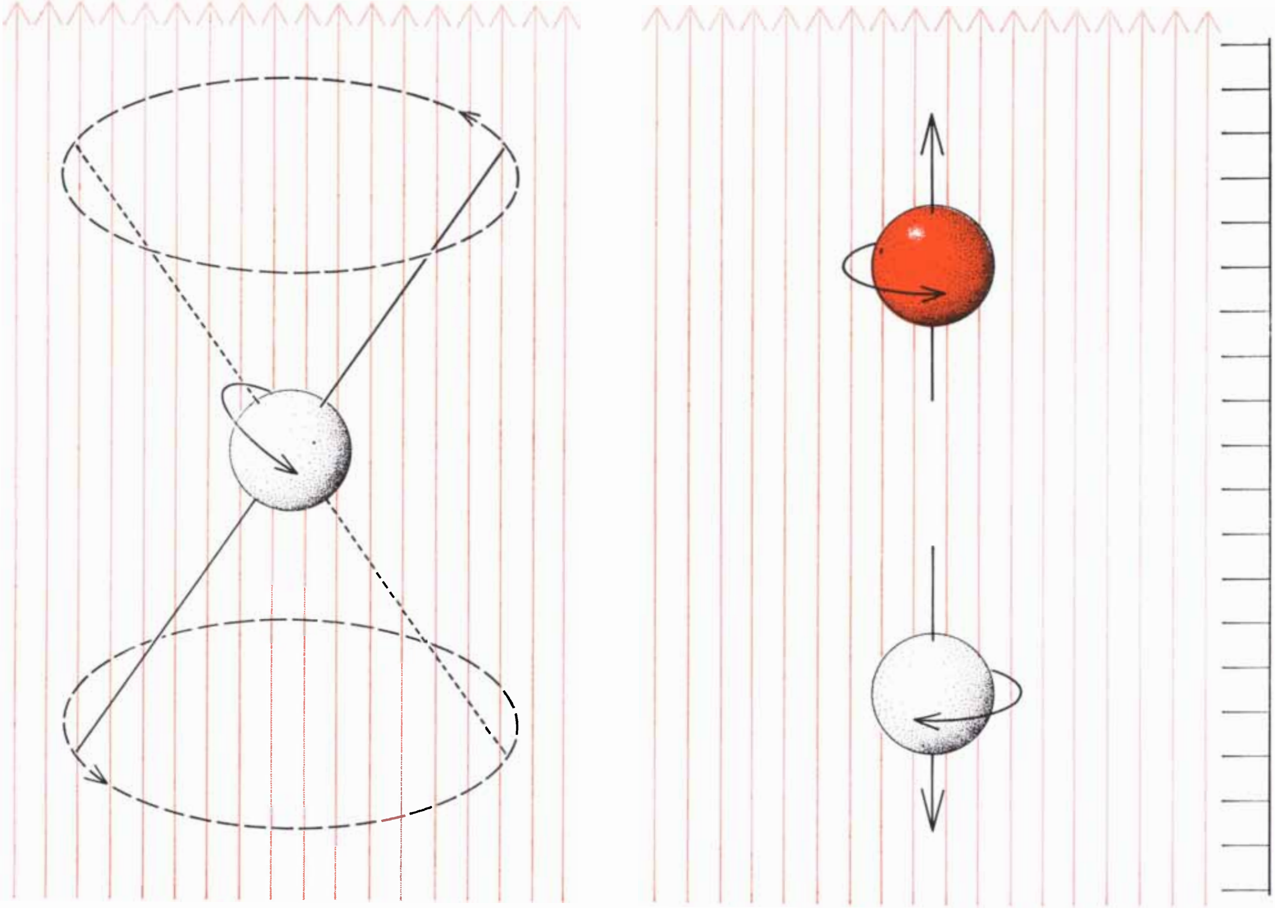
The first type of solid-state maser that was developed is known as the two-level paramagnetic maser. In some versions the paramagnetic material is a silicon crystal containing some impurity atoms, such as those of phosphorus, which have one more electron than they need to satisfy their role in the crystal lattice. In other versions it is a quartz crystal which has been subjected to neutron bombardment to release unpaired electrons. The crystal is placed between the poles of a strong magnet and cooled to a temperature a few degrees above absolute zero in a bath of liquid helium, so that most of its unpaired electrons fall into the lower of their two possible energy states. Then it is subjected to a fairly high-powered microwave pulse, which briefly raises the majority of the electrons to the higher state. While this "inverted population" of electrons lasts, it can act as an amplifier for a weak microwave signal. In silicon the amplifying period lasts about a minute after each "pumping" pulse; in quartz, only a few thousandths of a second.

The difference between the energy of the upper and lower levels depends upon the strength of the magnetic field. Hence by adjusting the strength of the magnet, the maser can be tuned over a wide range of frequencies. With very strong fields it may be possible to reach the never-never land of waves a fraction of a millimeter long.

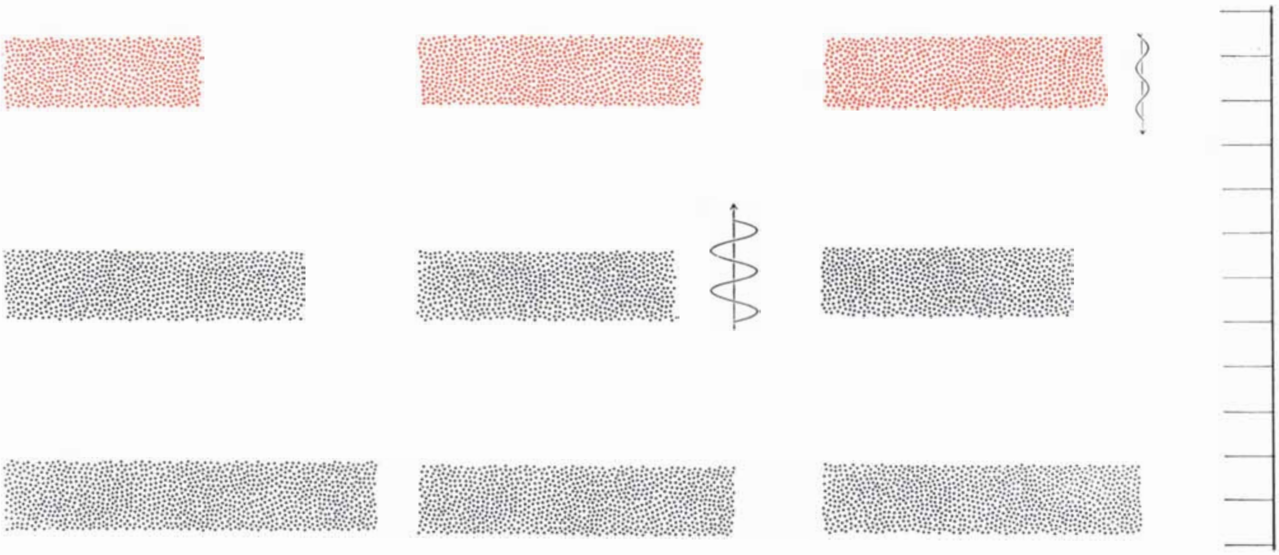
In a solid crystal the outside field is not the only one to act on unpaired electrons. The electrons are also influenced by the magnetism of neighboring atoms. The internal magnetic effect varies from point to point in the crystal, so that not all the electrons are subjected to exactly the same field. Thus they respond to slightly different frequencies, and this is the reason for the wider band-width of the solid-state devices.

The chief disadvantage of the two-level maser is that it can be operated only in bursts; its amplifying action stops each time its electrons drop down again to the lower level. This problem has been overcome with the development of the newest member of the maser family: the three-level paramagnetic maser.

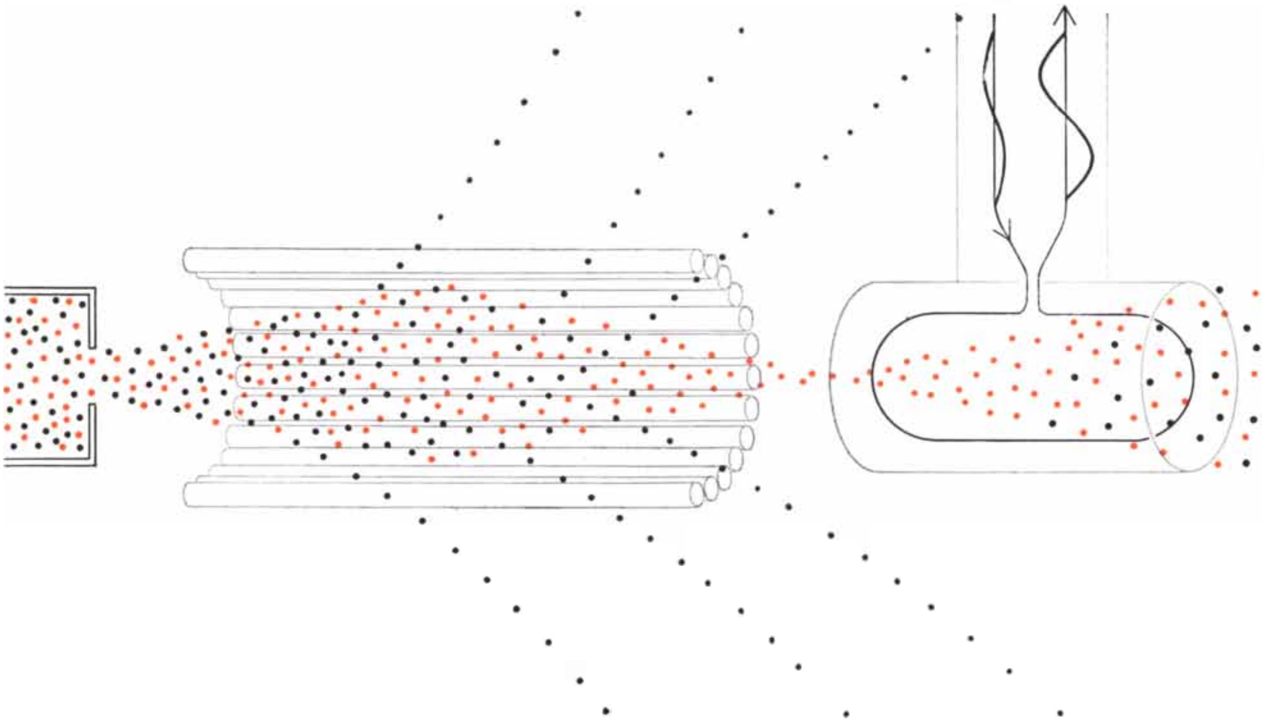
Conceived by Nicolaas Bloembergen of Harvard University, the three-level paramagnetic maser has a basic element



ELECTRON IN A MAGNETIC FIELD *(colored arrows)* is depicted from the classical standpoint *(left)* and from the quantum-mechanical *(right)*. In the classical view the axis of the electron's spin precesses, or wobbles, around the direction of the magnetic field at a frequency related to the strength of the field. In the quantum-mechanical view the electron has a higher energy state *(top right)* in which its "south" magnetic pole is pointed in the direction of the field, and a lower energy state *(bottom right)* in which the pole is pointed in the opposite direction. The difference in the energy levels is related to the strength of the field.



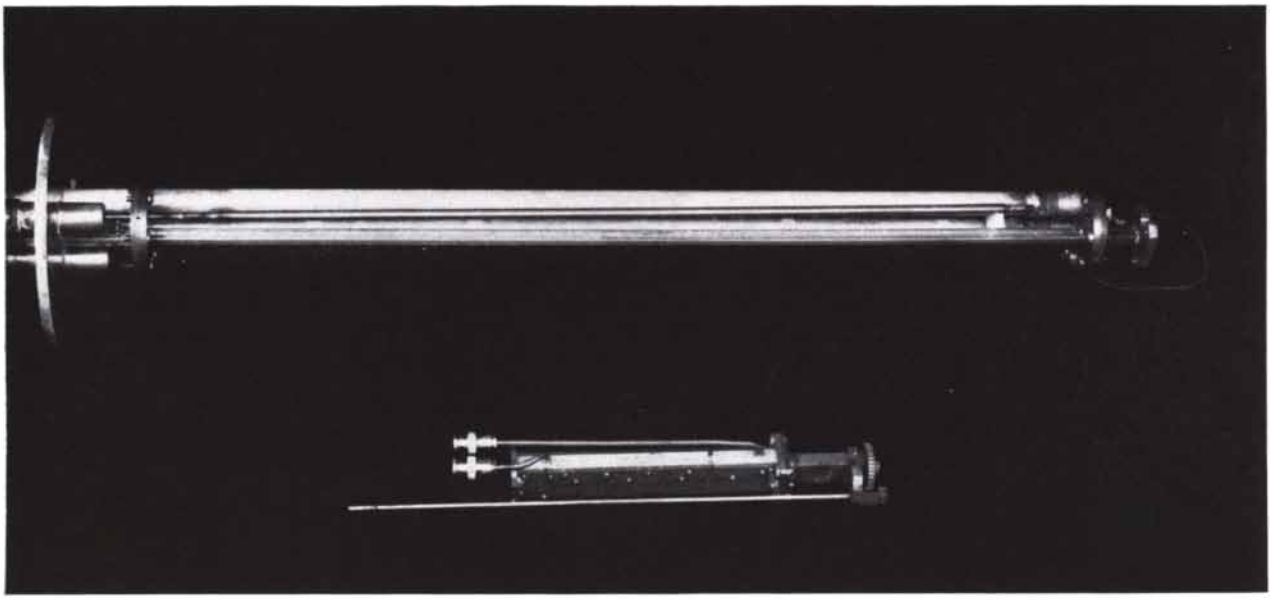
THREE-LEVEL SOLID-STATE MASER is considered. At left are electrons in three energy states; the largest number of electrons is in the lowest state, the smallest number is in the highest state. In the middle electrons are "pumped" from the lowest state to the highest by microwave energy of the appropriate frequency. At right electrons drop from the highest state to the middle state, emitting microwave energy of a lower frequency. Thus energy put into the maser at the latter frequency can be amplified.



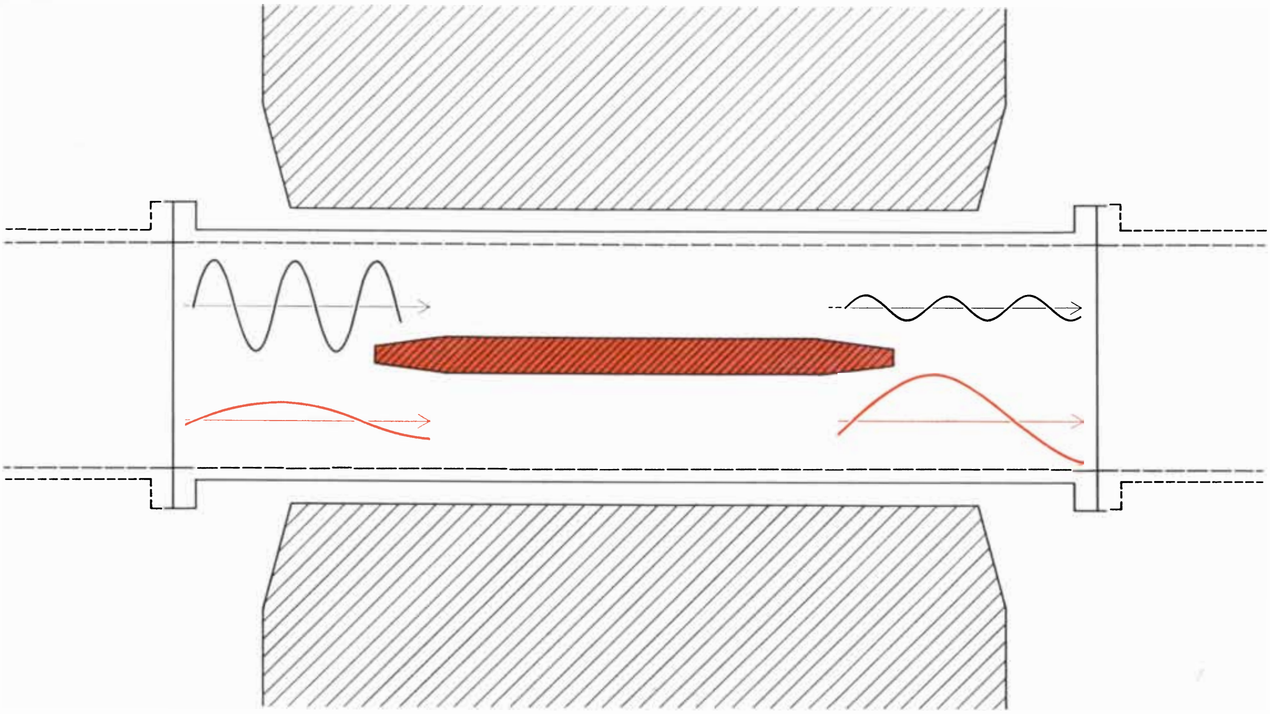
AMMONIA MASER sends ammonia molecules in two energy states through a cylinder of electrically charged rods. The molecules in the lower state (*black dots*) are pulled toward the rods; the molecules in the higher state (*colored*) are attracted to the axis of the cylinder. The molecules in the higher state then enter a resonant cavity (*right*), where they may be used to amplify a microwave signal.

consisting of atoms with more than one unpaired electron apiece. Atoms of this kind are found in the naturally paramagnetic elements such as iron and chromium, in which one of the interior shells of electrons is not filled. Quantum mechanics tells us that in many such atoms there is one more energy level than the number of unpaired electrons. For example, chromium atoms, which make up part of the ruby crystal, possess three unpaired electrons and thus have four energy levels.

Any three of the available levels can be used. When the crystal is cooled to very low temperatures, the atoms distribute themselves among the energy states in the usual way, each higher level containing fewer atoms than the one below it [*see illustration at bottom of preceding page*]. Now we irradiate the solid with microwaves of the proper frequency, causing a jump from the lowest of our three levels to the highest. By this pumping action the top level is kept fuller than the middle one. Therefore a weak signal whose frequency corre-



COMPONENTS OF A THREE-LEVEL MASER appear in the photographs on these two pages. The object at top in the photograph at left is essentially a waveguide through which microwaves are conducted to the maser cell. The object at bottom in the same

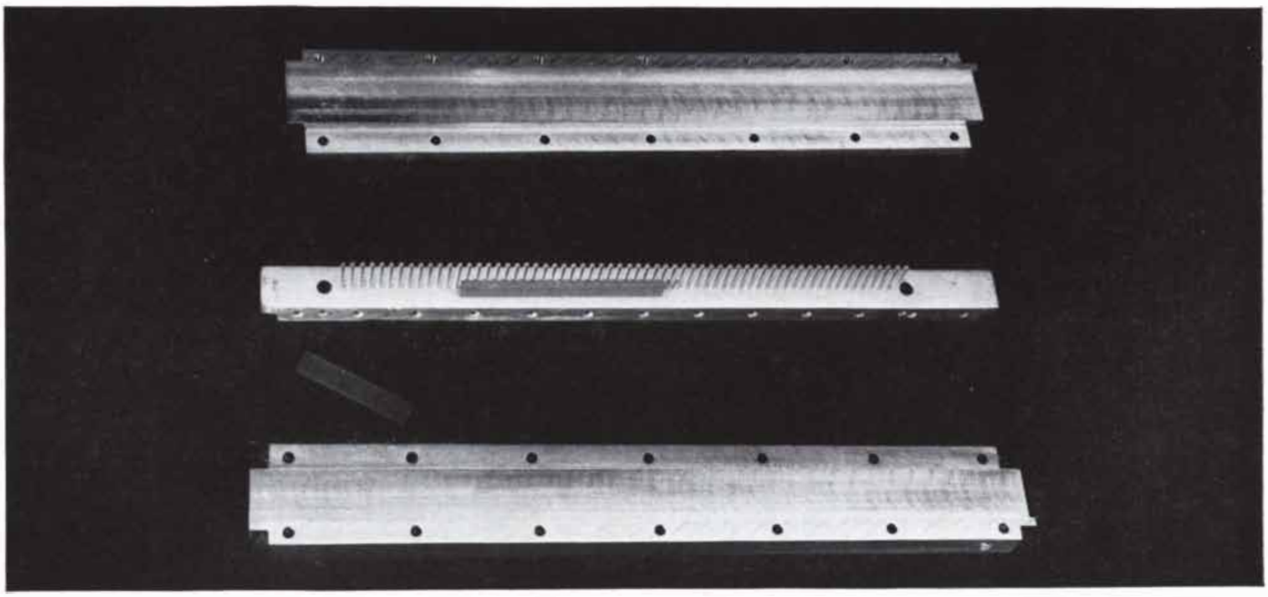


SOLID-STATE MASER consists essentially of a crystal (*center*) between the poles of a magnet (*top and bottom*). Microwave energy of an appropriate frequency (*black curve at left*) pumps electrons in the crystal to a higher state. An input signal (*colored curve at left*) of lower frequency is amplified (*colored curve at right*) at the expense of the pumping energy (*black curve at right*).

sponds to the energy gap between the top and middle levels will cause more downward than upward transitions, and the signal will be amplified. Pumping and amplification can go on at the same time, and so the maser operates continuously.

The first three-level maser was built at Bell Telephone Laboratories. Since then numerous masers of this kind, incorporating a variety of different crystals, have gone into operation at many other laboratories. One of them, as we have indicated, is already attached to a radio telescope. Soon they will be appearing in other applications.

There are jobs to be done by all the members of the maser family. In addition to simply telling time, ammonia and other gas-maser clocks will help explore some of the basic questions of physics. One plan is to recheck the celebrated Michelson-Morley experiment, which demonstrated that the speed of light is constant. Turning the maser's beam of molecules in two directions—along the path of the earth's travel and against it—



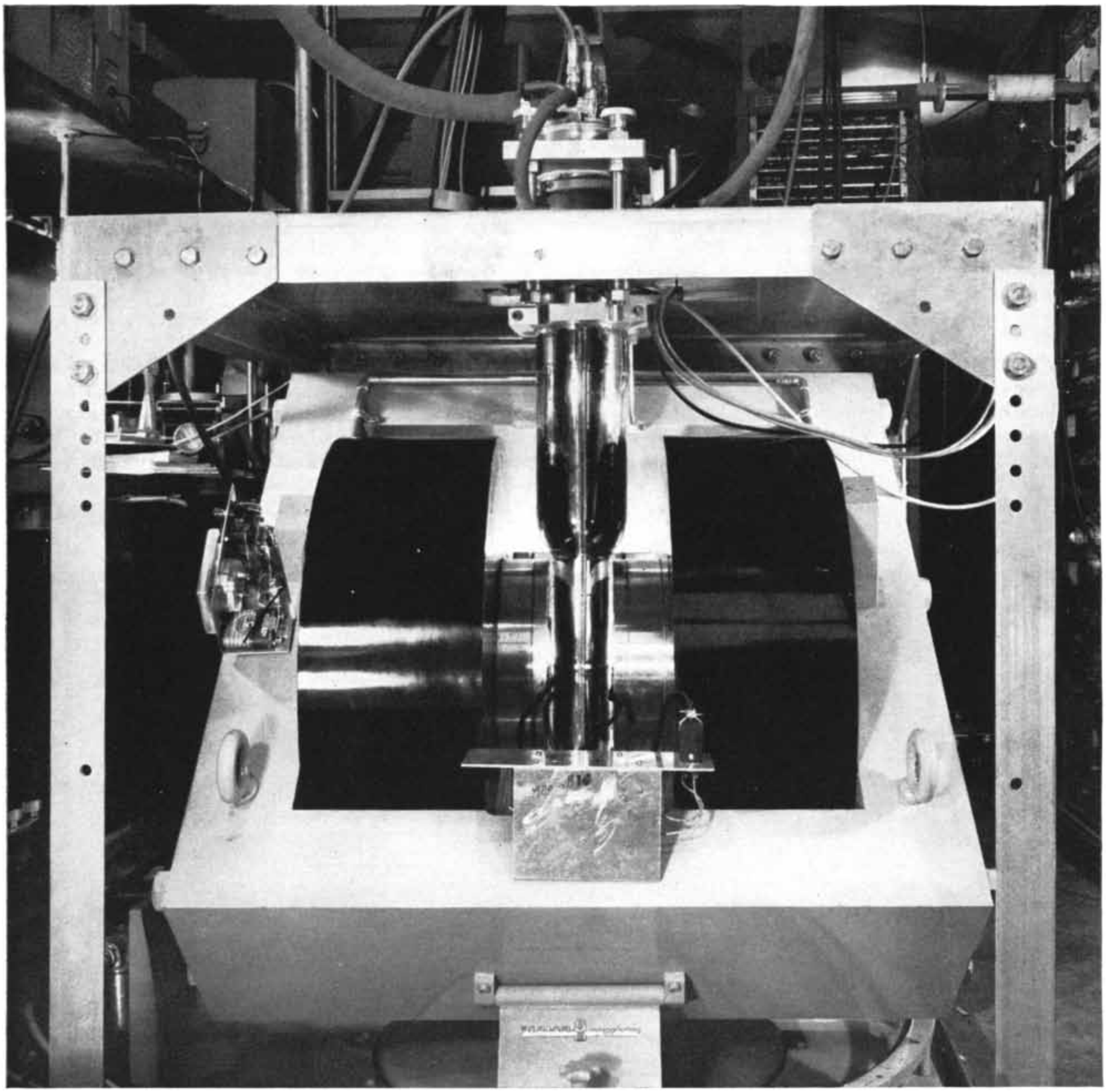
photograph is the maser cell, which is mounted at the right end of the waveguide. In the photograph at right the maser cell is dissected. One section of the large synthetic ruby of the maser stands against the row of pins in the middle; another one is to the left.

should result in no change of the output frequency, if light travels at a constant rate regardless of the motion of the observer. If there is a difference, it is too small to show up on Michelson's light interferometer. But the maser may be able to detect it. [As this issue of SCIENTIFIC AMERICAN went to press, it was announced that the experiment had been performed by Townes, working with J. P. Cedarholm, G. F. Bland and B. L. Havens of the International Business Machines Watson Laboratory at Columbia University. No difference was detected.]

Another project is a check on the general theory of relativity, which predicts that clocks are slowed up by gravitational fields. Artificial satellites will soon be circling the earth at distances where its gravity is noticeably weaker than at the surface. An atomic clock mounted in one of these vehicles could demonstrate the effect, if it exists.

Maser amplifiers may greatly simplify long-distance radio and television communication. As an example of what may be in the cards, suppose a ring of balloon satellites were made to circle endlessly around the earth. They would be permanent reflectors, from which signals could be bounced from any point on the earth's surface to any other. The received signals would be very weak. But the cold and lonely satellites would not contaminate them with much noise. Thus the sensitive, almost noiseless maser amplifiers could pick them up and boost them to useful levels without degrading them beyond recognition.

French workers have applied the maser principle to build a super-sensitive magnetometer for measuring the earth's field. In other laboratories people are thinking of using masers to produce beams of infrared radiation with an extremely narrow band of frequencies. The list is not exhaustive, and there are probably important applications that no one has thought of as yet. Quantum mechanics is adding a new dimension to "classical" electronics.



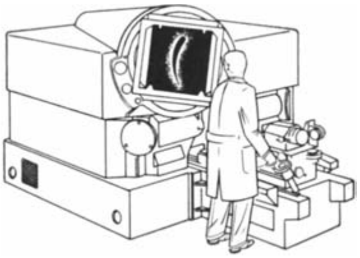
COMPLETE THREE-LEVEL MASER is photographed at Bell Telephone Laboratories. In center, between the poles of a large electromagnet, is a silvered flask which is filled with liquid helium. The maser cell is inside the flask between the two magnet poles.

Kodak reports on:

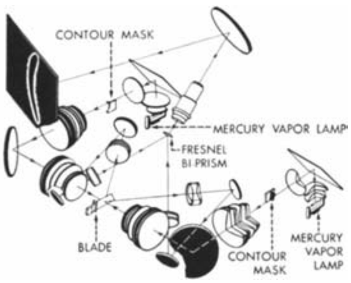
a large optical device . . . how sometimes they don't listen the first time . . . beating our heads against the spectrophotometers

For blades (also vanes and buckets)

This is a blade from a jet engine. Many mathematical minds, mighty mathematical machines, and much aerodynamical experimentation have created its shape. Violation of the plan to the extent of a few thousandths of an inch in a single cross-section of a single blade sucks at efficiency like a little leech. And there are so many blades in a single compressor or turbine that the total number of them made in the brief span of air-breathing non-reciprocating history must compare with all the wooden spokes in all the wagon wheels of all the supply trains in all armies since Alexander the Great. Tolerances on wooden spokes have always been broad.



Therefore we have been busy lately building this large optical device. It works as follows:



Not long before this periodical reached its subscribers, the two mercury lamps were turned on and the first cross-section of the first blade was seen in magnification against its tolerance envelope scribed on the screen. Inspection from now on should go well.

The device has been named Kodak Section-Profile Projector. *It is enough to restore faith in the future of geometrical optics. Inquiries go to Eastman Kodak Company, Military and Special Products Sales, Rochester 4, N. Y.*

Freezing here

In manufacturing *Kodak Frozen Section Stripping Film* we are attempting to perform a public service for and through pathologists. They are paying scant attention. Unless an upturn sets in soon, we shall give up.

This product is the ultimate in slow films, being endowed with no light sensitivity whatsoever. Its sole known function is to support a CO_2-frozen tissue section being microtomed. A description of the technique, stated to be quick and easy, may be found in *American Journal of Pathology*, *28*, 863-873 (1952). This paper depicts a 10μ section of adenocarcinoma of the rectum showing invasion of the wall, bronchogenic squamous cell carcinoma cut at 5μ, lung tissue cut at 5μ showing edema secondary to cardiac failure, and other examples of tissues said to be otherwise difficult to handle.

The product consists of a 10μ gelatine layer atop a 30μ cellulose ester layer atop a heavier carrier base from which it is separated before use. If the gelatine layer is pre-stained, the stain transfers in seconds to the specimen. The film is supplied in unperforated 35mm rolls 25 feet long for $15 (list) by arrangement through Eastman Kodak Company, Special Sensitized Products Division, Rochester 4, N. Y. This is not the way great industrial empires are built.

Self criticism

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At a certain point in a column where we distill a lot of mesityl oxide for intramural reasons, a peculiar substance was found to accumulate. Infrared spectroscopy showed it to be 4-methyl-4-penten-2-one, an unconjugated isomer of properly conjugated mesityl oxide. A busybody among us who is quick on the draw with his gas chromatography outfit then opened a bottle of our Eastman Grade *Mesityl Oxide*, numbered Eastman 582. Sure enough, a separable fraction was present, and sure enough, it was this very same isomer. Should we take the position that it is the nature of mesityl oxide to isomerize spontaneously? We decided we should not. Up went the "P" to make it Eastman P582, and down came the price to $2.30 a kilo. Even as a Practical Grade solvent, we plan to keep its isomer content below 0.5% when packed.

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We are co-operating in a splendid project to measure and catalog the infrared absorption spectrum of every organic compound that can be rounded up. One observation from this experience has impressed itself: how often the infrared spectrum shows a carbonyl linkage in compounds that are not supposed to have any. "You are seeing carbonyls in your sleep," the boss chid our normally genial chief control chemist when he came in all worried and upset about finding a carbonyl dip in the spectrum of bis-(3-chloro-n-propyl) ether. But gas chromatography went on to demonstrate two fractions present to the extent of 2% and 4% respectively, and these were found by I-R to be carbonyl compounds. That is why we have shorn this ether of its capitals, italics, and Eastman number.

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Our ultraviolet spectrophotometers are another thorn in our side. U-V is very good at showing isoquinoline bands, and it showed them in *1,2,3,4-Tetrahydroisoquinoline* (Eastman 7065), where there shouldn't be any. We have rehydrogenated our complete stock thereof, redistilled it, and resolved not to let it happen again. At least it was our spectrophotometer that discovered the impurity, not somebody else's.

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All this is for the benefit of Eastman Organic Chemicals. Our current List No. 41 catalogs some 3700 of them—a large number of battlegrounds for the war against impurity. Chemists who have the List find it a handy way to make sure they don't waste time making something they can buy. For a copy, write Distillation Products Industries, Eastman Organic Chemicals Department, Rochester 3, N. Y. (Division of Eastman Kodak Company).

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