E. SEDOV

ENTERTAINING ELECTRONICS

ИЗДАТЕЛЬСТВО
МИР

Е. СЕДОВ • ЗАНИМАТЕЛЬНО ОБ ЭЛЕКТРОНИКЕ

ИЗДАТЕЛЬСТВО «МОЛОДАЯ ГВАРДИЯ» МОСКВА

ENTERTAINING ELECTRONICS

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CONTENTS

What does this book deal with? Radio? Radar? Television? Electronic computers?

Any of the above subjects merits a separate book. What is more, such books have already been written. These include special and popular books, big ones and small ones, books for beginners and students, for pupils and for engineers to suit any level of knowledge and any taste. In addition to radar, television, radio communication and computing techniques, electronic devices are used in a number of other fields. Take, for example, such fields as remote control and measurement, the study of molecules, atoms and nuclei, radio astronomy, modern biology and medicine, electronic technology for processing metals, converting thermal energy into electrical energy with the aid of semiconductors.

And all of this pertains to electronics, because all fields of technology are in need of electronic devices, and the toiler in them, the one that is untiring, mobile and always ready to serve, is the electron.

Is it possible then to tell about all this in a single book on electronics and in such a way that the reader would not only become aware that all this exists in the world (which he, probably, already knows without this book), but would understand the principles and operation of various electronic devices, the essence of the methods and ideas?

We have to admit that it was no easy matter to write a book about electronics covering all the fields of engineering into which it has sunk such deep roots.

We were forced to select only those fields of application, those phenomena and processes, without which further progress would be impossible. The descriptions of the behaviour of electrons had to be translated from the language of equations, curves and formulas into a language comprehensible to all. Yet, despite all that the author and the editors could do, some formulas and curves infiltrated into the book from the pages of treatises and special works. Naturally, everything was done to make them as palatable as possible. For this it was necessary at times to embark on lengthy explanations, at times to seek analogies and examples in everyday life. But all this is a poor excuse for those readers who would have liked to understand electronics without equations and curves.

But would this not oversimplify the picture? After all, curves and equations are the specific language of electronics, and bypassing them is hardly justifiable. It has long been known that it is impossible to learn the customs and the culture of a people without learning their language.

The structure of this book is somewhat unusual. Those conceptions without which it is impossible to understand the essence of electronics are given in the form of drawings and in the text under the general title "This Lies at the Basis". These sections alternate with short stories which tell of the birth of the conceptions, elements, devices, and what came of it all and what led to what. It is our hope that the structure of the book will help the reader making his first acquaintance with electronics to readily understand the fundamentals on the one hand, and on the other, get a well-formed idea of electronics as an independent field of modern science and technology. This field possesses its own inherent logic, its core—a basis for a multitude of practical applications, methods and ideas.

The very word "electronics" is fraught with meaning: not a single electronic device can exist without the electron. So it is with the electron that we shall begin.

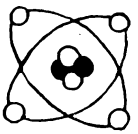
CHAPTER I. ELECTRONS AND ELECTRONICS

IN THIS CHAPTER THE READER WILL LEARN ABOUT THE HISTORY OF THE DISCOVERY OF THE ELECTRON AND ALSO WHY IT WAS THE FATE OF THIS VERY PARTICLE TO BECOME THE MAIN "COMPONENT" OF CERTAIN ELECTRONIC DEVICES, WHICH GAVE THE FIRST IMPETUS TO THE DEVELOPMENT OF ELECTRONICS.

PARTING WITH ITS ATOM THE ELECTRON GAINS ITS FREEDOM

THIS LIES AT THE BASIS

1.1



The basis of the enormous edifice of electronics erected by modern science and technology is a tiny particle known as the *electron.*

The reader, evidently, knows that the atoms of all substances contain electrons that revolve in definite orbits around the nucleus.

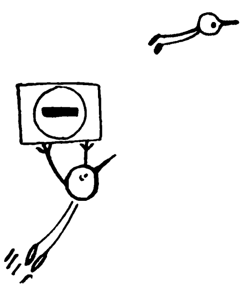
Electrons are so mobile that every second they orbit the atomic nucleus up to five hundred trillion times!

1.2

No one has ever seen an electron. Its radius is 400 000 000 000 *times less than a millimetre. None of the most advanced microscopes known to us can help see such particles.*

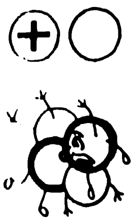
The mass of an electron is 1 000 000 000 000 000 000 000 000 000 *times less than the mass of a gram weight. Clearly, it cannot be weighed on scales.*

1.3



The presence of an electron is detected in a totally different way. The electron has what may be called a "visiting-card"—it carries a tiny portion of electricity, a negative charge, equal to 1.6×10^{-19} coulombs.

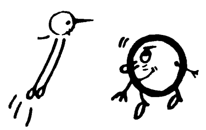
1.4



In addition to electrons each atom contains *protons* and *neutrons*.

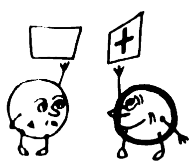
These particles are tightly cemented together by powerful nuclear fields and form a monolithic *atomic nucleus*.

1.5



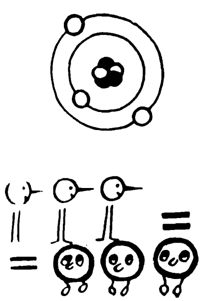
Compared to the electron, the proton and neutron look like veritable giants: the mass of one of them exceeds that of the electron nearly 1840 times...

1.6



The neutron carries no electric charge, it is neutral, and that is why it is called a neutron. The charge of the proton is equal to that of the electron (1.6×10^{-19} coulombs), only it has a positive sign.

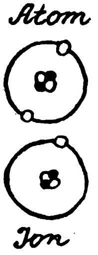
1.7



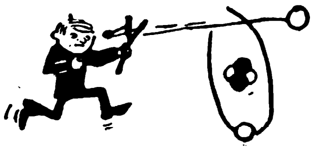
Taken as a whole, *the atom is also neutral*, because the number of electrons in the atom equals the number of protons in its nucleus.

An electron that revolves in one of the atomic orbits is a *bound electron*.

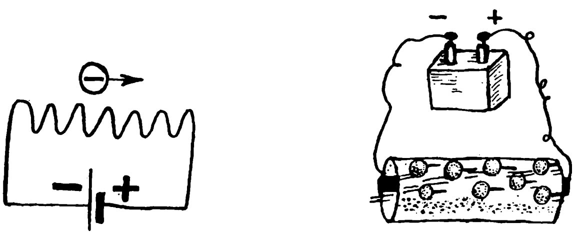
1.8



Often, under the action of external forces electrons gain their freedom: they part with their atoms, flying off their outer orbits. Having lost an electron, an atom is no longer neutral: it turns into a positively charged *ion*.



1.9



The negative charge of electrons forces them to move towards a metal plate connected to the positive terminal of a source of electricity (voltage).

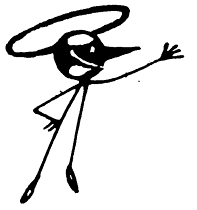
Why The Electron?

How could a particle of matter with a mass 1 000 000 000 000 000 000 000 000 000 times less than that of a gram weight have come to carry such a great weight in our life?

A mere century ago no one had ever heard of an electron. But now there is hardly a person who has not heard something about it. Everyone speaks of the electron with respect.

Books are written in which it is the central character. And it is always the hero and not the villain, despite its being charged negatively.

And all this is due to the fact that the electron has become the main "component" of the electronic devices that play such an important role in all fields of life, science and technology.

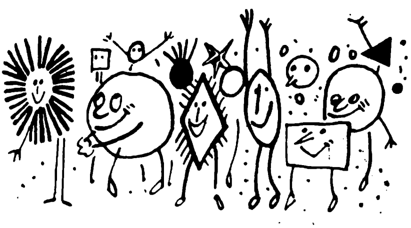


It proved a very convenient "component".

In the first place, it is light and mobile: long before the beginning of the space age physicists, while studying electrons moving in a tube, accelerated them to cosmic velocities.

Secondly, it is a "component" that knows no wear: no one has been able to disintegrate, to "split" the electron.

Thirdly, there is no shortage of the component: until the source of current is exhausted it will continue to discharge a stream of these "components" along a conveyor



(conductor). There will be as many of them as will be required by all the "shops" and "sections" of a complex "production plant", i.e. by all the components and circuits included in a transmitter, receiver or any other electronic device.

This "component" can provide excellent service under widely differing conditions: in vacuum (electronic tubes and valves), in gases (gas-filled tubes) and even in solids (semiconductors).

Need one repeat that the electron has proved very convenient. But just why is it that the electron plays such an important role in modern technology? Its discovery was followed by that of protons, neutrons, photons, mesons and hyperons—a whole family of so-called elementary particles.

So why is it that while we have electronics, there still are no protonics, nor neutronics, nor mesonics? Is it simply because the electron was discovered first? Or is it due to certain exceptional peculiarities not possessed by the other particles?

Why Not Protonics?

Let us take a particle like, say, the neutron. Just what is it like? First of all, this particle has no charge. Secondly, its mass exceeds that of the electron more than 1840 times. Since it has no charge, it is quite indifferent, or neutral, to an external electric field. And, since that is the case, the neutron cannot be controlled with the aid of a field. The electron is totally different. Being charged negatively, it always tends to move towards a plate with a positive potential (see Section I.9). By varying the potential, it is possible to control electrons: to accelerate or retard their movement and change their direction, to increase or decrease the stream of electrons.

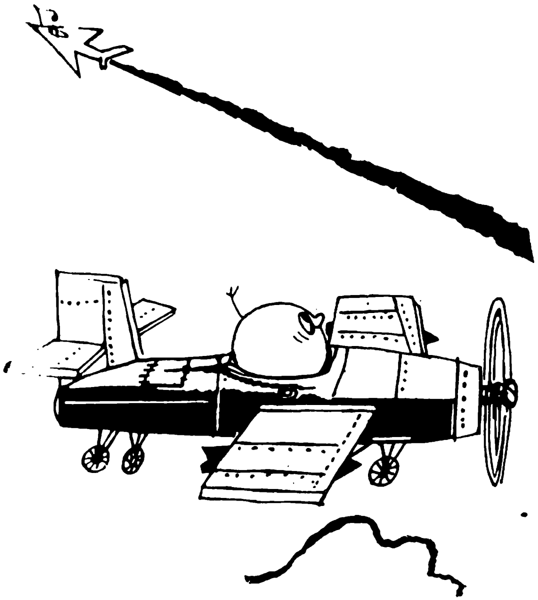
But there are other particles, protons, for instance, that are not indifferent to the action of a field, because they carry a certain positive charge. Why is it then that protonic devices are not used instead of electronic ones?

The proton has a mass 1840 times that of the electron. Take an ordinary cannon ball and place beside it a ball that is 1840 times heavier. If the first should happen to weigh 30 kilograms, then the second could prove heavier than ten spaceships!

The heavy and inert protons can never hope to compete with the agile electrons—heavy bombers will never be as manoeuvrable as light fighter planes. All pilots know that the lighter an aircraft, the less its inertia. Turn the controls the tiniest bit, and the fighter changes course sharply. But even with the highest manoeuvrability, inertia must be taken into account, otherwise the fighter would fly past the target by inertia, without scoring a hit.

But to return to the subject, it must be stated that the electron possesses an insignificant mass and insignificant inertia compared to the proton and neutron. This means that external forces can instantly cause it to accelerate and fly along the most complex of paths. No sooner is voltage applied, than the electron gathers enormous speed. The sign of the voltage is reversed and immediately the electron flies back.

This is probably one of its most important properties. Without it, it would be impossible to "draw" an image 25 times a second on television screens; to produce oscillations with the current in a circuit changing its direction and magnitude as often as 10 000 000 000 times a second; to



control high-speed rockets and to perform within an hour calculations with an electronic computer that would take a human being several years.

A Bit About Photonics

In addition to the electron, proton and neutron, modern physics is now aware of about 200 varieties of elementary particles. Are there none among them as light, mobile and accessible as the electron? Of course, there are. For example, the photon.

Speaking of mobility, this is a particle that knows no rest at all, being always "on the go". At rest, it disappears:

the scientists assert that *the rest mass of the photon is zero*. It is even easier to get a glimpse of the photon than the electron. Physics has established that all visible light consists of photons. And it is no accident that in recent years it is precisely this particle that has begun competing successfully with the electron in quite a number of fields of technology.

Whereas until recently such fields of engineering as radio communication and radar were monopolized by electronics, now a new field has appeared, which may well be called photonics. What we have in mind are the quantum oscillators (or so-called lasers), which have undergone rapid development in recent years. Of course, here we also have to reckon with the solution of complex problems. Photons carry no charge and therefore cannot be controlled by an electric field, and it is much harder to make them oscillate at a given frequency than in the case of electrons. But these difficulties are being overcome and soon, in addition to electronic radio communication, there will appear photon communication.

May it happen that after this there will be no more need of electronics? No, photonic techniques will not oust electronics. Firstly, in addition to radio communication, electronics has other problems to solve. Secondly, it is impossible to develop photonic devices without the aid of electronics. Photons are born of electrons: when an electron in an atom changes its state, say it jumps from an orbit remote from the nucleus to a closer one, the atom emits a photon.

But all this will have to be dealt with separately. In the meantime, one thing should be noted: the electron is not struggling to maintain its monopoly, and whenever there is a need to exceed its possibilities, it gladly presents people with a photon.

Will there be other fields of engineering developing along with photonics and electronics, utilizing the properties of still other particles? Who knows. There are already hypotheses about the possibility of communication by means of neutrino or gravitational waves. But science has not studied such waves as yet. That is why all modern means of radio communication are based on the interaction of electrons and electromagnetic waves.

But Who Has Seen It?

Anything we cannot explain we call a wonder. Wonders are worked by spirits, magicians and gods. Electronics was created by man. Man tamed the electron, studied its properties, made it solve a multitude of various problems. While designing an electronic device, an engineer considers the electron: it will behave thus and thus, do this and that, fly here or there.

But who has seen the way all these things happen? No one. At best it is possible to see the trace of a beam on a screen or to measure the total charge of all the electrons flowing every second along a conductor—in other words, the electric current. Both the current and beam are streams of electrons—an enormous quantity of moving particles. A solitary electron is too small a particle to be seen under any microscope.

Everyone has seen the outside of a television set. The more inquisitive have even looked inside. What did they find? Nothing of special interest. A multitude of components, an intricate network of wires. Dully glowing valves, but no motion. A kingdom of death. Only the screen is alive.

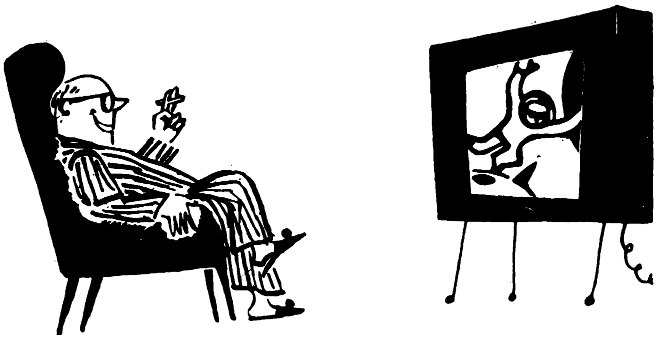
How are moving images born of the motionless components and wires? Who doubles the live actors of a play, how does a sports game come to life on the screen? The leading role here is played by the electron.

While the action is taking place on the screen, an invisible but highly intense "backstage life" is in progress in all the elements inside the television set. The engineer has studied it in great detail. He can tell you just how many electrons will pass through each wire during each second and how they will behave in various circuits, though he has never laid his eyes on an electron either.

The first impression is that this is very short of wonder. The electron has begun to play every conceivable role. It doubles actors in a TV play and performs as the "singer backstage", making the speaker reproduce the accompanying sound. It controls rockets, machines, aircraft, makes complex calculations and translations, processes metals and provides an opportunity for studying the microstructure of substances.

No one has seen it at work. Like an invisible, fabulous gnome it works more and more new wonders. But knowledge and the power of imagination of researchers throws light on all the aspects of how the agile electrons behave in various devices developed by man.

In an attempt to stress this property of elec ronics, the well-known American science-fiction writer Arthur Clark has described the following imaginary episode.



Picture to yourself that great thinkers of the past, say Newton and Leonardo da Vinci, were given an electronic valve and a modern car to study. By the appearance of the car they could, doubtlessly, draw some conclusions as

to its purpose and design. But in the case of a diode or a triode, they could say nothing. Absolutely nothing! Because the appearance of an electronic valve or of any of its parts throws no light whatsoever on the electronic processes that take place within it. Neither Newton nor Leonardo da Vinci, for all the wealth of their scientific imagination, could conceive either the electron or its role and behaviour inside these devices which were totally unintelligible to them.

It required hundreds of brilliant guesses and many thousands of experiments conducted by the scientists of the centuries that followed for science to obtain a clear picture of the unseen processes in which the electron takes part.

But what is the electron itself like? What is it made of? Is it solid or hollow? Is it homogeneous or made up of parts of some kind?

So far nothing is known about this. Today the electron is something like a threshold which science cannot cross. Will it ever?

Yes it will! Just as it was able to proceed from the molecule to the atom and from the atom to the investigation of smaller particles. Matter in the hands of science is like a nested doll in the hands of an inquisitive child who wants to know what there is inside.

Molecule. Atom. Nucleus. Proton. Neutron. Electron. The thirst for knowledge has no bounds and neither has matter, either in extent or depth. Probably, an integral electron does not exist in nature, there being instead a cluster of waves or a system of even smaller particles. And then one fine day the electron as such will disappear from science. That will be something!

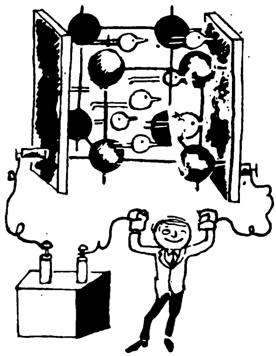
What will become of electronics then? Why, nothing! It will not be affected in the least. This will be a real wonder: no electrons will exist but there will be electronics! Actually, there is nothing strange about this. The devices developed by electronics will continue to serve man and, after all, it is not so important whether the main element in them is a bunch of waves, a homogeneous integral particle, or a system of particles bound into one. The main thing is that our ideas should not run counter to the results of experiments, and that each new development in electronics is an experimental confirmation of the validity of the ideas forming its basis. So in the meantime let there be a particle, no one has ever seen it anyway.

The whole enormous edifice of electronics was erected mentally through the efforts of many inventive and inquisitive minds, beginning from the moment when the electron was discovered, when the physicist Helmholtz did not feel, hear or see an electron but *guessed* that it must take part in electrolysis.

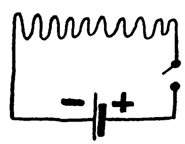
CURRENT CAN FLOW NOT ONLY IN A METAL BUT ALSO IN A GAS, LIQUID OR VACUUM

THIS LIES AT THE BASIS

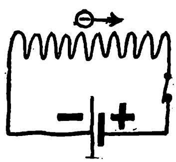
I.10



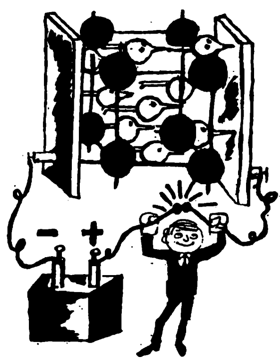
Atoms of a metal form a *crystal lattice*, and in the spaces between the lattice points free electrons move chaotically, wandering aimlessly here and there.



I.11

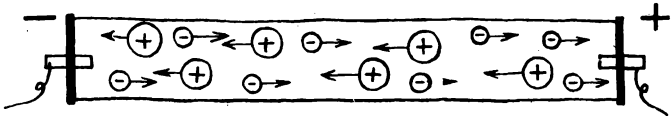


But it is enough to connect a metal plate to the two poles of a voltage source for the electrons immediately to acquire an aim. They will move towards the positive pole of the battery, and an *electric current* will begin to flow in the metal.

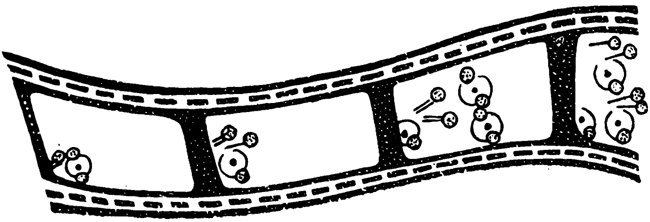


I.12

An electric current can also flow in a gas. A voltage applied across a gas-filled tube causes ionization of the gas: free electrons stream towards the plate with the positive potential, colliding with the atoms in their way and detaching electrons from their orbits. The positive ions (atoms deprived of their electrons) move toward the opposite

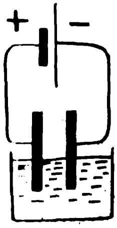


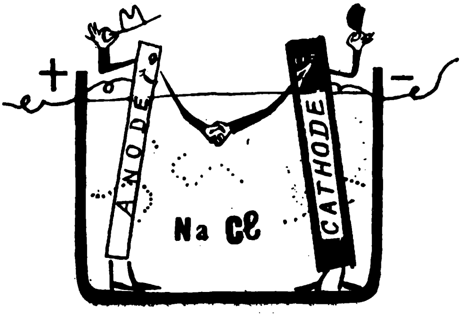
end of the tube. The characteristic glow of the gas in the tube bears witness to the fact that ions and electrons are moving towards each other in the tube—that an electric current is flowing.



1.13

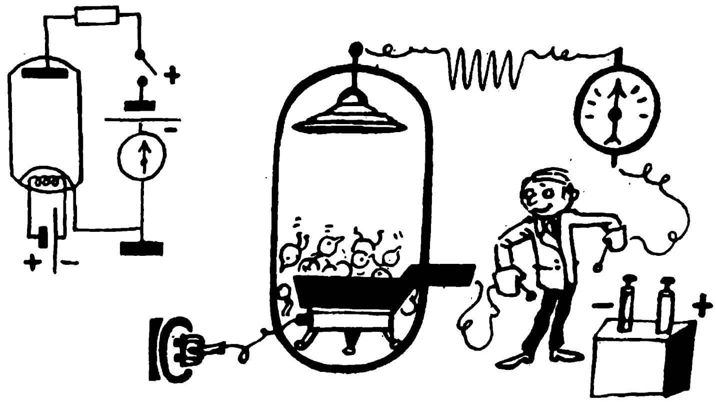
To set up an *electric current in a liquid* (for instance, a solution of table-salt), it is necessary to immerse two metal rods in it and connect them to a voltage source. Now the rods have become *electrodes*: the one connected to the positive terminal of the source serves as the *anode*, and the one connected to the negative terminal is the *cathode*.





1.14

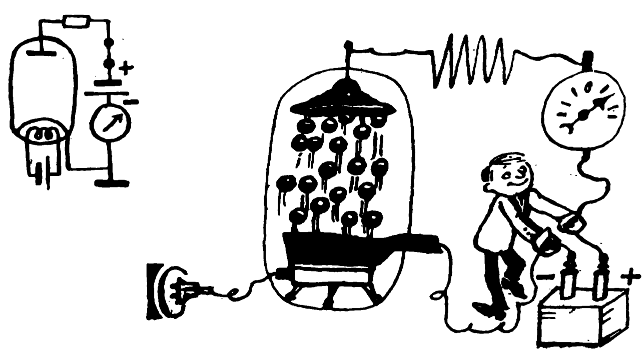
In electronic valves the electrons move in a *vacuum* or, in other words, in a void. An example of such a device is the *diode.*



The envelope of a diode houses two main parts which are also called the anode and the cathode.

Near the cathode there is a filament or miniature electric heater which heats the cathode. In this case an "electron liquid", consisting of electrons that move chaotically within the very body of the cathode, between its atoms, begins to "boil". This phenomenon is known as *electronic emission.* As a result of this emission, a cloud of "electron gas" is formed round the cathode.

1.15



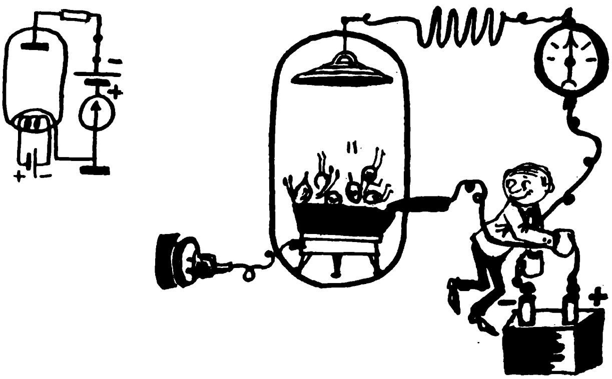
If the cathode is now connected to the negative terminal of a voltage source and the anode, to the positive terminal, the anode will begin attracting electrons from the cloud, "drawing" them away from the cathode, and a current will flow inside the diode.

Freedom for the electron proves very short-lived: no sooner does it escape from the cathode than it is immediately attracted by the anode.

I.16

The diode is often employed in circuits as a rectifier, as a device which may be compared to a one-way valve.

In the Figures in Section I.15 the "valve" is open. In order to close it the poles of the voltage source must be interchanged so that the negative terminal is connected to the anode and the positive terminal, to the cathode.



Now it is harder for the electrons to escape from the cathode, because it attracts them. But even those that do escape have nowhere to fly in particular: previously they were attracted by the anode, now it forces them back to the cathode.

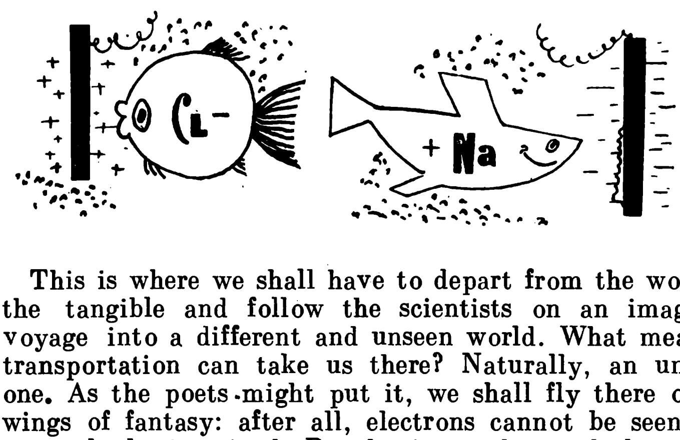
With such a connection no current flows through the diode. The "valve" has broken the electric circuit that the diode is connected in.

Voyage In A Bath

Even schoolchildren know about electrolysis. If two metal rods are immersed in a bath containing molten table-salt, and connected to the different poles of an electric battery, an electric current will flow through the melt and along the external wires.

On one of the rods pure sodium will be deposited from the table-salt melt and at the other chlorine gas will be liberated. The sodium will be deposited on the cathode, that is on the rod connected to the negative pole of the battery. Bubbles of chlorine gas will form round the other rod, the anode.

So far we have been talking of tangible and visible things. The rods can be touched. The molten salt can be analyzed. Traces of pure sodium can be seen on the cathode, and one can observe the bubbling of chlorine gas at the anode. But what has produced all this? Why has the current suddenly caused the liquid to turn into a gas and a solid? The chlorine makes its way towards the anode, and the sodium is deposited on the cathode. Why not the other way round?



This is where we shall have to depart from the world of the tangible and follow the scientists on an imaginary voyage into a different and unseen world. What means of transportation can take us there? Naturally, an unusual one. As the poets might put it, we shall fly there on the wings of fantasy: after all, electrons cannot be seen, they can only be imagined. But having understood the role of electrons in this process, we can understand all of its internal mechanism.

What does take place? For those acquainted with the structure of the atom it is easy to understand the process of electrolysis. The thing is that the sodium atoms very willingly surrender the only electron circuiting in their outer orbit.

Having given up an electron, the atom is no longer neutral: the number of electrons is now less than the number of protons in the nucleus. Now it is positively charged and, therefore, no longer an ordinary atom but a traveller-atom. The Greek for traveller is "ion". And this traveller does not like to remain long in one place. If there is a plate nearby connected to the negative terminal of a voltage source, it will set out immediately.

Chlorine atoms, on the contrary, willingly accept electrons. Their outer electron shell contains only seven electrons. Eight electrons in the outer shell of an atom make up a "full set".

There is a general law of nature: if the outer shell of an atom lacks one or several electrons, the atom strives to take them from without to make up a "full set".

That is why, observing this law, the chlorine atom takes the eighth missing electron from the sodium atom.

Having received a travel pass in the form of the eighth electron, the chlorine atom acquires a negative charge and also becomes an ion—it travels towards the positive electrode. After reaching its destination (i.e. the anode), the ion hands in its travel pass—the eighth electron.

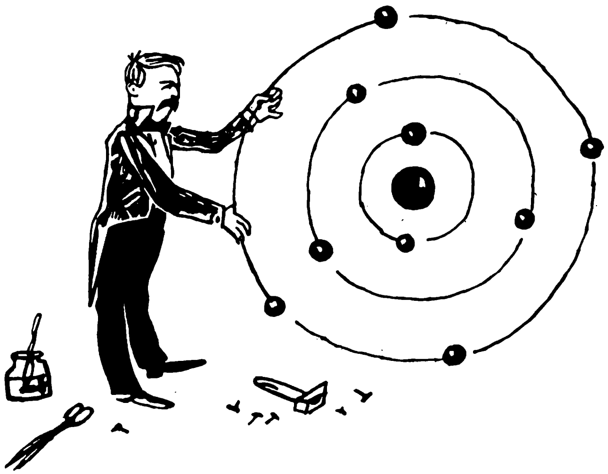
The electron will run along the external wire, and since more and more "tourists with passes" continue to arrive, electrons run continually along the wire, forming an electric current. The current inside the bath is of a different nature: here the "voyagers" continuously flow in opposite streams—the negative chlorine ions move towards the anode, while the positive sodium ions hasten to get to the cathode.

On reaching the cathode, the sodium ions deprive it of the electrons they lack and, having become neutral atoms of pure sodium, are deposited on the cathode.

A Portion Of Electricity

It is easy enough to talk about electrons in the electron shells for those who know about them. But imagine what it was like for Helmholtz. He studied electrolysis at a time when the atom was still considered a real atom—the smallest and indivisible particle of matter. (In Greek the word atom means indivisible.)

No one knew anything about electrons. By the weight of the sodium deposited on the cathode one could tell how many sodium atoms had arrived there. By measuring the current flowing along the external wire, the charge carried by these atoms was determined. It was found that a certain number of sodium atoms always carried the selfsame charge.



But if instead of table-salt, molten calcium chloride salt was contained in the bath, then the same number of atoms of calcium carried a charge twice as large.

That, in essence, was all the information Helmholtz had at his disposal. But it proved enough for a brilliant guess: in nature there must exist an ultimate indivisible portion of electricity, a sort of an electric atom. Each ion of sodium carries one portion of electricity, each ion of calcium, two. Not 1.75, nor 1.5 but precisely two—two "electric atoms".

Of course, Helmholtz didn't even suspect that he was the first to have a mental look into that very atom which up till then had been considered indivisible. For the portion of electricity is that very electron. Revolving in the outer shell of the calcium atom, there is not one electron, as in the case of sodium, but two electrons. Giving up these two electrons to two chlorine atoms, it becomes an ion carrying a double portion of electricity. That is why the same number of calcium atoms carry twice as large a charge.

All this became known much later, after Rutherford had created his model of a planetary atom, in which the nucleus replaced the Sun, while the electrons revolved in their orbits like our planets (see I.1).

But it was the portion of electricity detected by Helmholtz that brought science to these discoveries, that allowed it to make the first and, perhaps, the most decisive step.

Space Within An Envelope

Helmholtz' idea gave rise to many questions. What is this portion of electricity? What carries it? What is it like? What does it consist of?

Experiments conducted soon after Helmholtz' discovery confirmed that in all phenomena involving electricity, tiny negative electric charges really did take part: they were given the name of electrons. But still, just what are these electrons? An incorporeal portion of electricity or a bit of substance of some kind?

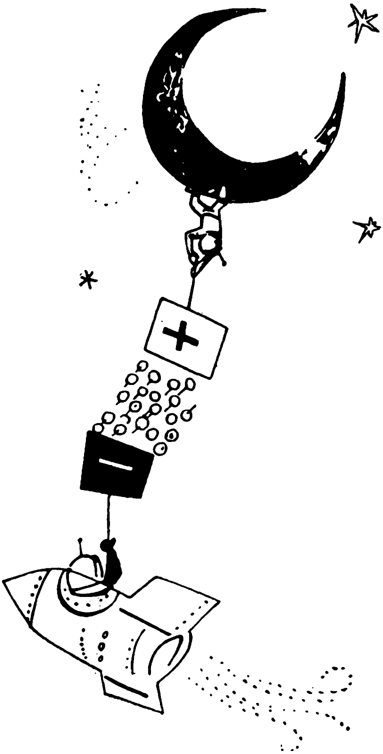
It proved to be neither the one nor the other. Though an electron possesses mass, it is not a substance. It is a particle of matter that is contained in all substances existing in nature.

In the history of physics the electron has occupied a place of honour: it was the particle that marked the beginning of the study of a large family of elementary particles.

From the moment of its discovery, physicists began devoting great interest to the electron. It was established that free electrons exist in all metals, something like a liquid poured into the empty space between the atoms of the metal (see I.10). How were physicists able to look inside the metal and see the invisible electrons there?

By may of experiments, of course. Experiments form the very basis of electronics, the source of its achievements, the supreme judge in evaluating its ideas. So let us enter the world of electronics just as the scientists have entered it: not empty-handed, but holding an electric battery and a piece of metal—a metal plate.

We connect the plate to the positive and negative terminals of the battery, and immediately all the electrons that have been roaming about aimlessly within the plate, acquire an aim (see I.11). Now let us disconnect the plate from the battery and begin heating it. Emission of electrons will begin. A cloud of "electron gas" will form around the heated plate (see I.14).



No one yet has seen an electron nor an electron cloud either. Nevertheless, modern physics handles electrons with nearly the same confidence as a cook does potatoes. To paraphrase a Russian proverb, for every "electronic dish" there is a ready recipe.

Do you wish to speed up the "boiling" of the "electron liquid"? Take nickel or tungsten. They provide the greatest "vaporization" of electrons and, besides, are highly refractory — they can be heated to very high temperatures. And it is still better to coat the nickel or tungsten plate with an oxide film—an oxide of an alkaline-earth metal. The "vaporization" will be still more effective. The specialist would say that the emission has increased.

Everyone knows that before a radio set can start receiving, it must warm up for 2-3 minutes. However, not everyone knows that this is the time required for the invisible clouds of electrons to form and grow round the cathodes of all the valves.

The movement of electrons in the cloud is chaotic, the only thing capable of making all the electrons move in the same direction being a metal plate at a positive potential. Well, this is easy enough to achieve. We have the battery.

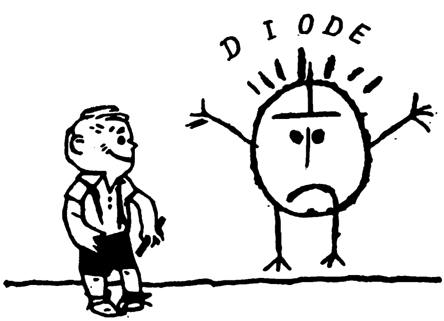
Let us connect the plate surrounded by the cloud of "electron gas" to the negative terminal and place next to it another plate connected to the positive terminal. Will current be set up in such a device?

Yes, but only under one condition: the experiment must be conducted in an empty space. On the Earth this would be prevented by the air, which would keep the electrons escaping from the cathode from flying to the anode. To overcome this effect of the air Edison did a very simple thing: he created "space in miniature"—he placed both plates inside a glass envelope from which the air was exhausted. And he was the first to see how under these conditions electric current flowed between plates not connected by a wire.

If you wish to repeat the experiment, you do not have to create "space in an envelope"; you can buy in any shop selling radio parts a two-electrode valve—a diode (see I.14).

The diode was invented by the English scientist Fleming in 1904. But its principle has remained almost unchanged to our days. It is mainly the design that changes. In Fleming's diode and in a number of other subsequent diode designs, the heater current was fed directly to the cathode. A substantial improvement was the introduction of the filament, which was first suggested by the Russian scientist Chernyshov.

When the diode is connected to a battery, you can observe the development of current with an ammeter—an instrument for measuring electric current—connected into the diode circuit. Deflection of the ammeter pointer is the only visible result of all the phenomena we have described. All the other processes are invisible. But none the less precisely those processes we have been talking about are taking place inside the envelope: the electrons which escape from the cathode form an electron cloud around it, the anode attracts the electrons, and an electric current flows inside the envelope.



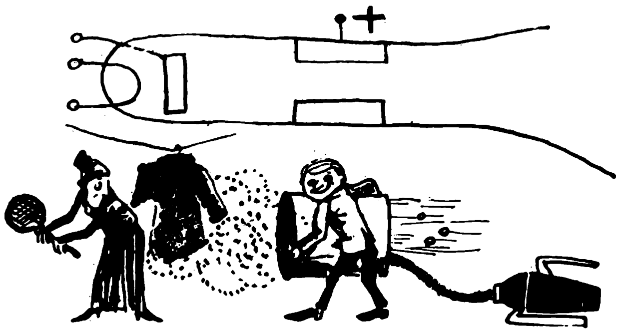
THIS LIES AT THE BASIS

1.17

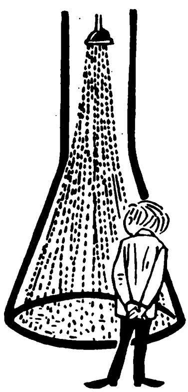
Among the many parts housed inside the cathode-ray tube you will also find a heater, cathode and anode.

The anode of the tube bears no resemblance to that of the diode: it is made in the form of a cylinder.

The electrons fly from the cathode to the anode and, after passing through it, strike a screen. The screen is coated with a special compound which begins to glow at the place where an electron strikes it.



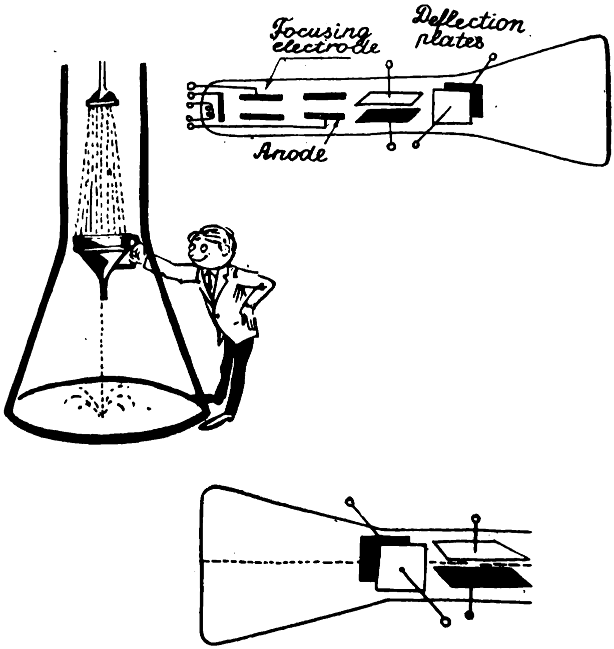
1.18



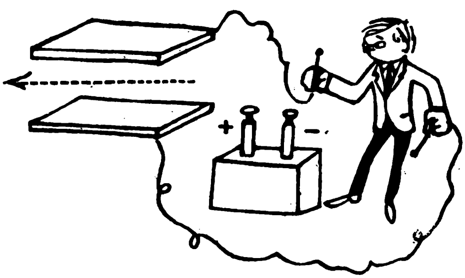
In order to direct all the electrons flying out of the cathode to a certain point on the screen, they have to be gathered into a narrow beam. The electrons resist this and repulse one another because they all carry a charge of the same sign (negative). As a result the beam "swells" and, were it to strike the screen in such a form, a large blurred spot would form on the screen.

1.19

The focusing electrode has helped to curb the "recalcitrance" of electrons. It is also made in the form of a hollow cylinder which is connected to the negative terminal of a voltage source and, therefore, its walls repulse the scattering electrons, gathering them into a narrow beam which is directed along the longitudinal axis of the cylinder.

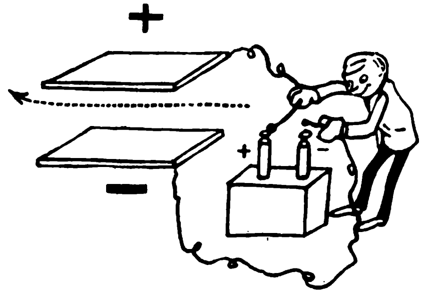


1.20



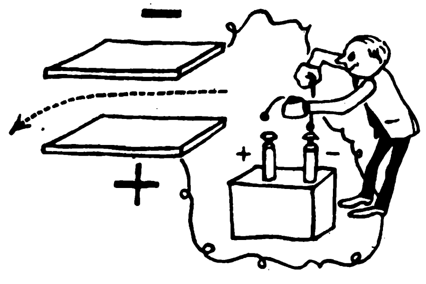
On its way from the cathode to the screen, an electron passes plates. If no voltage is applied across them, the electron pays them no heed and flies straight to the centre of the screen. It is accompanied by all the other electrons, causing a bright spot to glow in the middle of the screen.

1.21



But what will happen if a voltage is applied across one pair of the plates? All the electrons will be deflected towards the positive plate, and the spot will shift upwards from the centre of the screen.

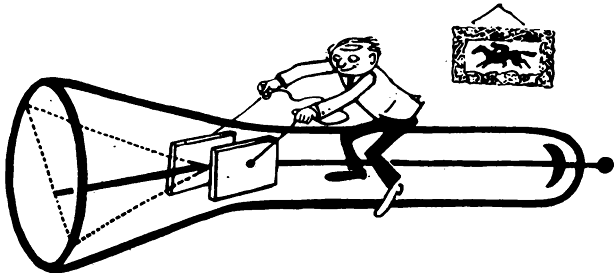
1.22



By reversing the voltage applied across the plates, the spot can be shifted downwards.

1.23

A second pair of plates makes it possible to shift the beam and the spot to the left and right.

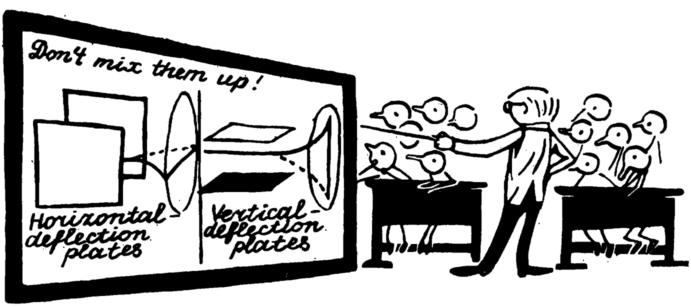


1.24

So as never to confuse the plates it is necessary to learn one rule once and for all: the plates shown in the left part of the poster, even though they are positioned vertically, deflect the beam from left to right and are therefore called horizontal-deflection plates.

On the other hand those plates which are arranged horizontally are called vertical-deflection plates, because they deflect the beam upwards or downwards.

The two pairs of plates are, as it were, an aiming device, which allows any point of the screen to be hit by aiming the beam at it.



Armed With A Gun

A diode is already electronics. It was developed to serve definite technical needs. But at first no such needs existed.

Nor was there any electronics. There was only the natural desire of physicists to study the electron. And it so happened that 40 years before the invention of the two-electrode valve (diode) the cathode ray tube emerged, developed by physicists as a strictly experimental device.

At that time no one had any idea of all the uses that the future had in store for the tube. In radar and television, in the reception of signals from space, in many laboratory investigations, in the memory devices of electronic computers, this tube is a must. But physicists Plucker, Kirchner, Hittorf, Crookes, Perrin and Villard who conducted the first experiments with the tube had a much more modest aim: they wanted to know how the electron behaves.

The device inside the tube which produces a controlled beam was aptly named a "gun" by someone.

And indeed, the electrons are like cannon balls, while the positive potential of the anode takes the place of the pressure of gases which eject the ball from the barrel. The barrel in this case is the focusing electrode that ensures close grouping of shots (see I.19). The deflecting plates are similar to the aiming devices of a gun (see I.20-I.24).

Who could know that in time this device would justify its warlike name of "gun" and would help real guns hit enemy targets without missing?

But by the time when the "electron gun" was used in the indicators of radar stations, it had much to its credit for peaceful services.

A mere century ago physicists studied the nature of rays (at that time they bore the name of "cathode rays"), which were produced by "electron guns".

First of all it was established that these rays always deflect towards the plate connected to the positive terminal of a voltage source. Hence the conclusion that the rays are a continuous stream of particles possessing a negative charge.

Then it became possible to measure the speed and calculate the mass of these particles. Thus, the "electron gun" helped acquire knowledge about the properties of the invisible electrons, turning them from incorporeal portions of electricity into particles "embodied in flesh".

Later on with the aid of the very same guns, engineers managed to obtain clear pictures on television screens. And many years before the advent of television a laboratory instrument—the oscilloscope—was developed that made it possible to observe many electrical processes, which investigators formerly could only imagine.

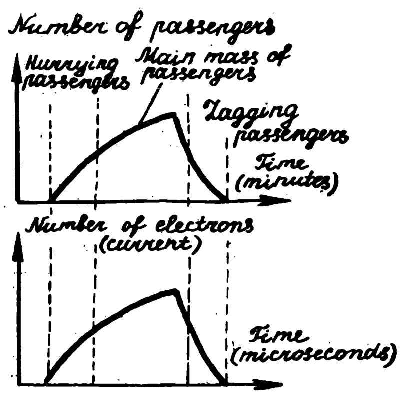
Take, for example, an electric pulse. Just what is it? A shock that is produced by a multitude of electrons flowing simultaneously through the wires and components of a circuit.

When you have a chance watch the escalator at one of the underground stations. It is not loaded uniformly. When a train pulls up at the platform, the passengers all at once rush towards the escalator. Those who are in a special hurry even run there. Then comes the main mass of the passengers and the moving stairs become especially crowded. A little later the escalator is empty. The pulse has ended. With the arrival of the next train the cycle is repeated.

This picture is similar to the one which is observed in pulse circuits. The trains can be compared to a pulse generator, the escalator, to a conductor section and the passengers in this case behave just like electrons.

A curve showing the variation of current in time is very much like that showing the number of passengers carried by the escalator to the ground surface.

However, unlike the events which take place in the underground and last many minutes, electric pulses usually emerge and vanish in millionths of a second. Is it possible to see anything in so short a period of time? Who will have



time to notice a pulse that builds up and ceases in millionths of a second?

But as it has turned out here is no need to be hasty at all. The instantaneous pulses can leave a trace on a screen, and this trace will remain sufficiently long for an engineer or scientist to judge of its shape and to watch how in a brief instant an electric current builds up, stays on and ceases.

This possibility is provided by cathode-ray tubes.

Traces Of Things Invisible

Millionths of a second ... A time so short that it is hard even to imagine it.

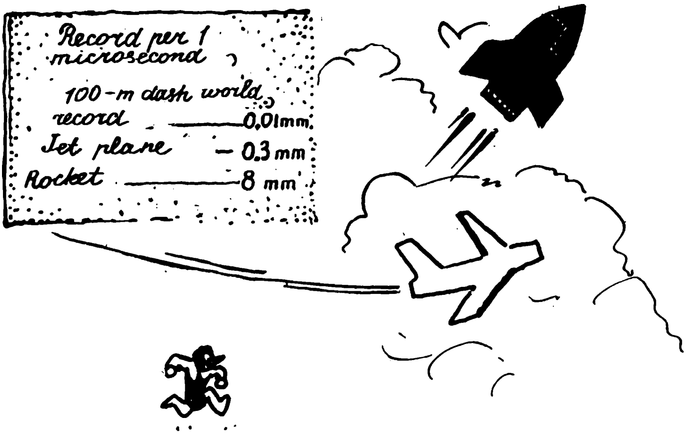
The world record holder, whose time for the 100-metre dash is 9.8 seconds, covers ... only one hundredth of a millimetre in one millionth of a second.

Only three tenths of a millimetre is covered by a jet plane in so short a time. And it flies at the speed of sound! A rocket boosting a satellite into an earth orbit at cosmic speed travels only 8 millimetres in that time.

And in an electronic circuit so many events happen in a millionth of a second that it would take hours just to tell about them.

Electrons exist in a different time scale. They are so mobile and agile that in one millionth of a second they can do a multitude of various things.

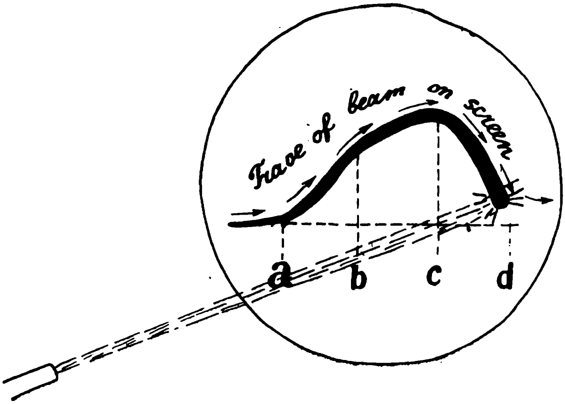
... A pulse lasted one millionth of a second. During this time the beam of the cathode-ray tube managed to traverse the whole screen from left to right. At the moment when the beam began its dash, the pulse arrived at the vertical-deflection plates and deflected the beam upwards. But, being deflected, the beam continued to travel from left to



right and, when the pulse ended, it returned (descended) to the middle of the screen and completed its travel. As a result, the trace of the beam was left on the screen. What we have actually seen is the shape of the pulse. Looking at the trace, we can see how in a millionth of a second an electric current builds up (section *a—b*), stays on (section *b—c*) and ceases (section *c—d*).

The screen of the cathode ray tube has really worked a wonder, making it possible to see the movement of invisible passengers on invisible escalators, i.e. the flow of current through wires and other circuit components.

The image on the screen does not last long: the screen is coated with a special compound which can glow for seconds or fractions of a second after passage of the beam. But electronics seldom deals with single pulses. Usually they follow one another, and each of them causes the beam to deflect and renew the trace. While the pulse lasts, the beam crosses the screen from left to right. Then very quickly, instantaneously, it returns to the left edge of the screen to repeat its travel.



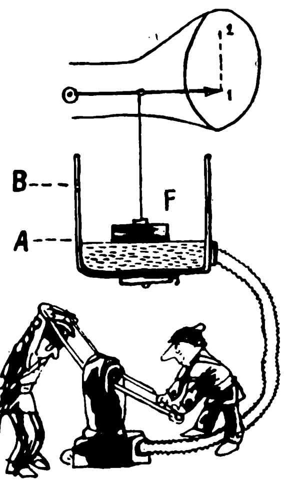
But what is meant by very quickly? The beam passes from left to right in one millionth of a second. In this case the speed of the forward trace (i.e. the trace from left to right) will, in terms we are used to, be about 100 kilometres per second or 360000 kilometres per hour. If the beam had not moved across the screen but along the surface of the earth, then it would have traced ten circles around the Earth in one hour!

Isn't it fast? Yes, it is. But in electronics even such a velocity is far below the record. From left to right the beam travels fast, but from right to left (i.e. during the retrace), it travels about a hundred times faster.

What determines the speed of the trace? What makes the beam on reaching the edge of the screen, return? To answer these questions, we shall have to say a few words about the principles of controlling the electron beam.

Almost Like In A Problem Book

The beam is controlled by electrons. Many electrons are involved in the process: some develop an electric pulse, others, on flying out of the gun, speed from the cathode to the screen of the tube, while still others at that very same time control the beam. That is why in a millionth of a second so many events take place in an electronic circuit that a detailed report about them would take hours. We are not going to discuss all the details now. But the very principle of controlling the electron beam is worth going into it in greater detail, for we are now familiarizing ourselves with the first electronic device in which the action of a multitude of electrons forms a single, complicated process. But since this electronic process is intangible and invisible we shall first try to explain it with the aid of a conventional model. In this model everything is "bulky, coarse and visible", but nevertheless, it gives a fairly good idea of the process of controlling the electron beam.



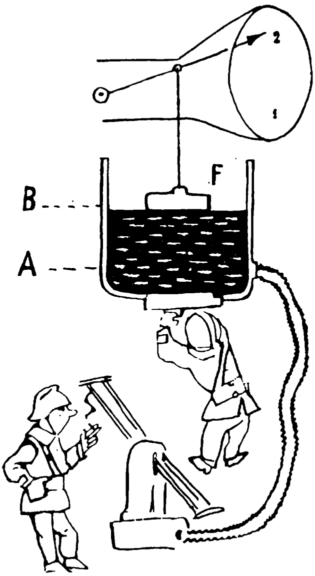
Imagine a tank of a certain capacity, say C litres, which is filled with water through a thin hose. In time T_1 the water level in the tank will rise from A to B.

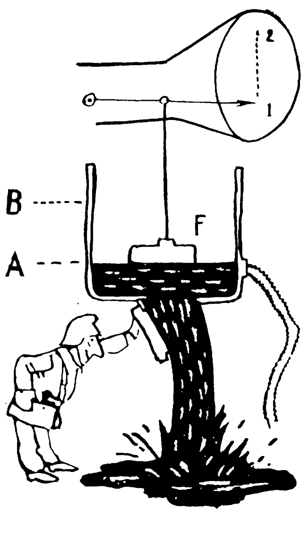
Float F rises as the tank is filled, turning the arrow which in our conventional model stands for the beam. In time T_1 the end of the arrow will shift upwards along the screen from point *1* to point *2*.

At this moment a port in the bottom of the tank is opened and the water level drops from B to A. Since the port is much wider than the hose, the water runs out much faster than it has been pumped in, say in time T_2. Then the arrow—beam—will return from point *2* to point *1*. Doesn't the system remind you of those innumerous tanks in school problem books, in which x litres of water pour in through pipe A every minute, while through pipe B, y litres of water run out. But there is also a difference. There the water usually runs along both pipes simultaneously. But in our system the pipes function by turns. As a result, in time T_1 the arrow slowly rises, and then quickly falls during time T_2.

The described process is shown graphically, and we can see that in time T_1 the water level slowly rises from A to B, and then in time T_2 falls rapidly from B to A.

Now it is, probably, easier to understand how the process proceeds in the electronic circuit. Here the "tank" is capacitor C, the "pump" is current source E, and the "hose" is high-value resistor R_1.





As the capacitor charges, the level in the "tank" rises, in this case we mean the level of the voltage across the capacitor plates, which is usually designated as V_c.

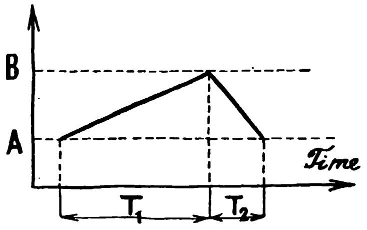
Key K is a sort of a "port": it enables the current to flow through low-value resistor R_2, thus implementing the "run-off". Since resistance R_2 of the "drain" is much lower than resistance R_1 of the "hose", the voltage across the capacitor falls very quickly from V_c to zero.

We have already studied the graph of the process.

Instead of the water level in the tank, we shall now plot on the vertical axis voltage V_c across the capacitor.

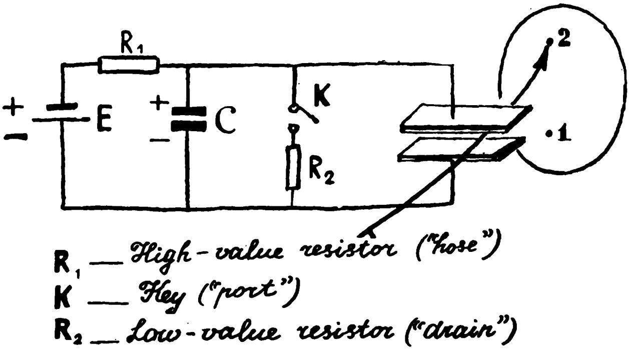
It is not hard to see that the shape of the curve is similar to a sawtooth. If the process is repeated many times, several teeth will emerge, thus forming a saw-shaped curve. And such a sawtooth voltage is the one that controls the beam. If the capacitor is connected to the vertical plates, the beam is deflected in the horizontal plane. In time T_1 (the long slope of the tooth) the beam shifts from left to right, and in time T_2 (the short slope of the tooth) it rapidly flies back.

It should be noted that the speed of the beam depends on the "tank filling rate", i.e. on the speed with which voltage V_c builds up. While the capacitor is little charged, this speed is almost constant and so is that of the beam crossing the screen. To maintain the speed of the beam,

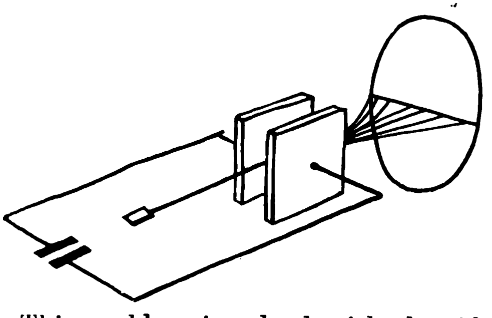


the "tank" is always made with a surplus capacity, so that it would not be "full to the brim".

To understand this principle fully, we have only one more question to settle.



In our conventional model, we opened the "run-off port" at the right moment ourselves. And who closes key *K* at the right moment in the given circuit?



This problem is solved with the aid of a three-electrode valve, or triode. So it is the triode that we are now going to consider.

THE GRID MADE A REVOLUTION

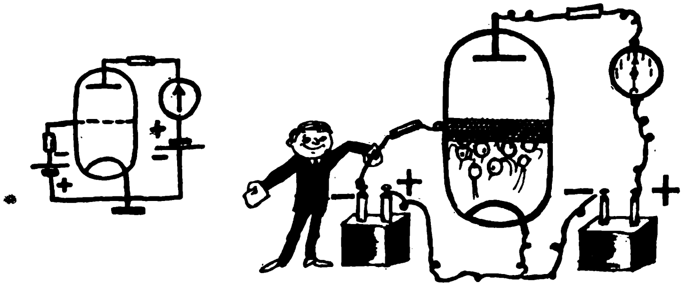
THIS LIES AT THE BASIS

I.25

The introduction of a third electrode (control grid) between the cathode and the anode of the above-mentioned valve—diode— has made it possible to control the current flowing through the valve.

The advent of the three-electrode valves—they became known as triodes — immeasurably broadened the field of application of electronic valves.

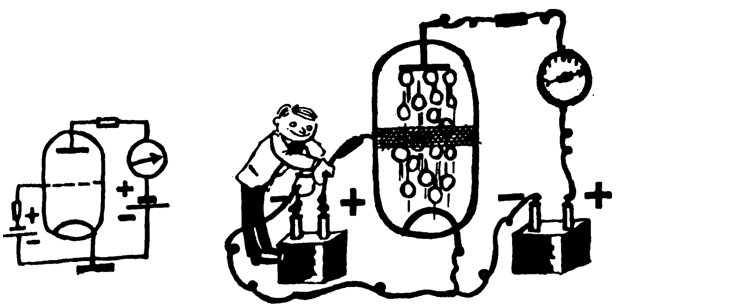
I.26



In the triode current is controlled by means of a voltage applied between the cathode and the grid. With a high negative grid potential (with respect to the cathode), the grid becomes an insurmountable barrier for the electrons. They will "crowd" in the space between the cathode and the grid; the valve will be cut off, since no current will flow from the cathode to the anode, even though like in the diode the cathode is connected to the negative terminal and the anode, to the positive terminal of a voltage source.

1.27

In order to eliminate this "babel" it is sufficient to reverse the sign of the grid voltage. With a positive grid potential the grid will help the anode, since its positive potential will be added to that of the anode. A heavy current will flow through the valve. However, with too high a positive grid potential the grid may turn from a helper of the anode into its competitor: some electrons will be drawn to it and will not reach the anode. In this case a harmful grid current appears in the valve.



1.28

Everything that has been said about the processes taking place inside the three-electrode valve may be illustrated by a curve. The curve shows how the anode current in the valve changes, depending on the voltages applied between its electrodes. This curve is known as the characteristic of the valve.

1.29

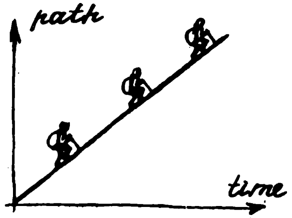
The characteristic of a valve is a graph.

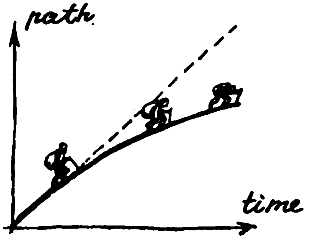
What do graphs serve for in general? For the visual representation of the relation between any two variables. Well, for example.

The longer the time a pedestrian walks along a road, the greater the distance he covers. This is the shape of the graph showing this relation, if the pedestrian walks at a constant speed.

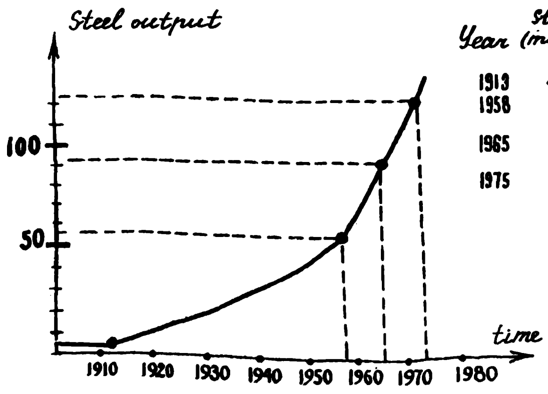
But if the pedestrian gets tired at the end of his route, the graph will look like this.

In this case it is said that the relation between the path and the time is nonlinear; it is no longer expressed by a straight line but by a curve.





1.30



Year	Steel output (millions of tons)
1913	4 2
1958	5 5
1965	90
1975	120

We are all well acquainted with a graph of a different sort: the one showing the growth in the output of a certain product. In the Figure we see a graph showing the output of steel. Again the relationship here is nonlinear: with time the output of steel grows ever faster.

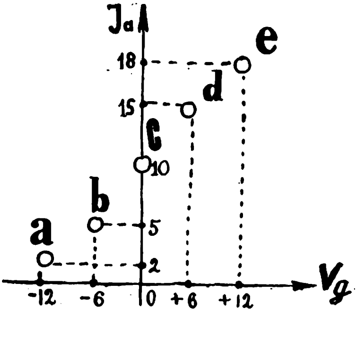
In the foregoing examples each graph showed how some variables (path, amount of steel) was related to time. It is just as easy to show the relationship between any variables with the aid of a graph. One can show how the range of an aircraft depends on the quantity of fuel; how its speed depends on the power of the engine; how the air resistance depends on the speed, and so on, and so forth.

I.31

Now let us return to the characteristics of a valve. The relationship between the anode current (I_a) and the voltage between the cathode and the grid (V_g) is called the anode-grid characteristic of the valve. That between the anode current (I_a) and the anode voltage (to be more precise, voltage V_a between the cathode and the anode) is called the anode characteristic of the valve.

The anode-grid characteristic is plotted in the following way. Suppose that at a voltage $V_g = -12$ volts the anode current $I_a = 2$ milliamperes (i.e. 2 thousandths of an ampere).

Let us plot—12 volts on the horizontal reference axis and 2 milliamperes on the vertical axis. The intersection of two straight lines drawn parallel to the axes of reference gives us point *a*.

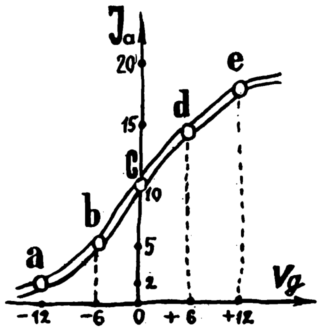


I.32

For different values of voltage V_g at a constant voltage V_a we obtain different values of current I_a. Plotting these values, we obtain points *b*, *c*, *d*.

Having plotted many points for different values of V_g from —12 to +12 volts, we connect these points and obtain the anode-grid characteristic of the valve.

As you see, in this case the graph is again non-linear: at point *a* the current rises slowly, between points *b* and *d*, rapidly (and what is more, linearly), and at point *e* it ceases to rise.



I.33

The most detailed characteristic cannot give a clear image of a human being.

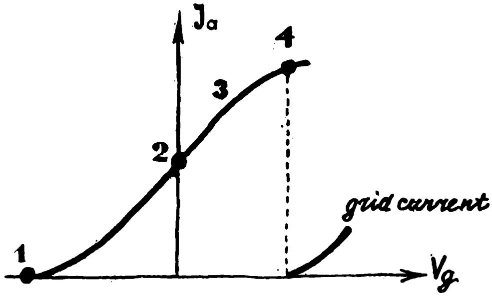
The characteristic of a valve provides exhaustive information about its behaviour. It illustrates all the processes which were dealt with in Sections I.26 and I.27.

Point 1. The voltage between the cathode and the grid has a high negative value. The grid has become an insuperable barrier for the electrons. The anode current is zero (see I.26).

Point 2. The battery is disconnected from the grid. Some electrons fly to the anode.

Point 3. There is a positive potential at the grid. The grid helps the anode, and the anode current increases (see I.27).

Point 4. The grid begins to compete with the anode. A harmful grid current appears (see I.27).

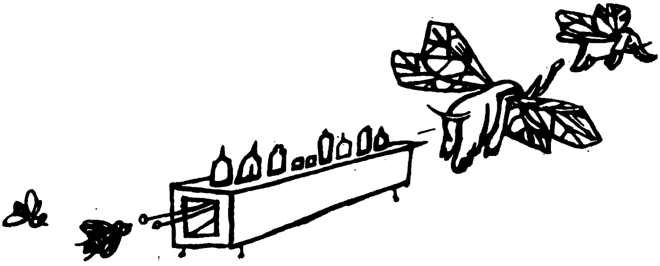


I.34

The curve makes it possible to determine that when V_g changes, for example, from —6 to +6 volts, i.e. by 12 volts, the anode current changes from 5 to 15 milliamperes, i.e. by 10 milliamperes (see I.32).

The signal applied to the grid is usually much weaker. Suppose that the voltage between the cathode and the grid changes from —0.6 volts to +0.6 volts. i.e. by 1.2 volts. In this case the anode current changes by 1 milliampere. (Incidentally, it should be noted that within the linear section of the curve the current varies in direct proportion to the voltage.)

If the resistor connected into the anode circuit has a value of 24 kohms (24 000 ohms), then the anode current variations will produce fluctuations of the voltage across this resistor, the peak-to-peak value of these fluctuations being 1×10^{-3} amp $\times 24 \times 10^3$ ohms = 24 volts.



This means that 1.2 V fluctuations of the voltage applied to the grid have turned into those of 24 volts across the anode load—the valve has amplified the fluctuations 20 times. This amplification is explained by the fact that the grid in the triode is located close to the cathode and slightest variations in the grid potential produce significant changes in the anode current and, consequently, in the voltage across the anode load. By connecting several amplifier valves (they are also known as amplifier stages) in series a weak signal can be amplified hundreds of thousands and even millions of times.

The ability to amplify signals is a very valuable property of the triode, the one that electronics makes use of practically everywhere.

With The Aid Of The Grid

On October 5, 1956 the French inventor Lee de Forest was awarded the order of the Honorary Legion. Present at the solemn awarding ceremony was the prominent scientist of our time, physicist Louis de Broglie. In his speech of welcome, Louis de Broglie noted that the name of Lee de Forest had become one of the great names in modern science and technology thanks to the discovery made by him half a century ago.

In conclusion Louis be Broglie said that specialists in all branches of science should express their respect, gratitude and admiration to Lee de Forest.

And what was this great discovery that continued to call forth admiration and gratitude half a century later?

At first glance it does not look so significant at all. Three years before the discovery made by Lee de Forest, Fleming had already developed the two-electrode valve that we know so well (see I.14 and I.15). All that Lee de Forest did was to introduce yet another electrode between the anode and the cathode of the diode.

And what is there so great about that? — one would think. Formerly the valve had two electrodes, then it acquired a third one.

But what unforseen opportunities have opened up before engineering with the development of three-electrode valves!

Lee de Forest called his valve an "audion". With time this name was forgotten and the valve with three electrodes is now called a triode*.

Subsequently valves with two, three, four and five grids emerged. But in the words of Louis de Broglie, no matter how important are the modifications brought with time into the original triode invented by Lee de Forest all modern valves of this type are always based on the following basic principle introduced by Lee de Forest: the control of the current flowing through the vacuum valve between the cathode and the anode by means of other auxiliary electrodes.

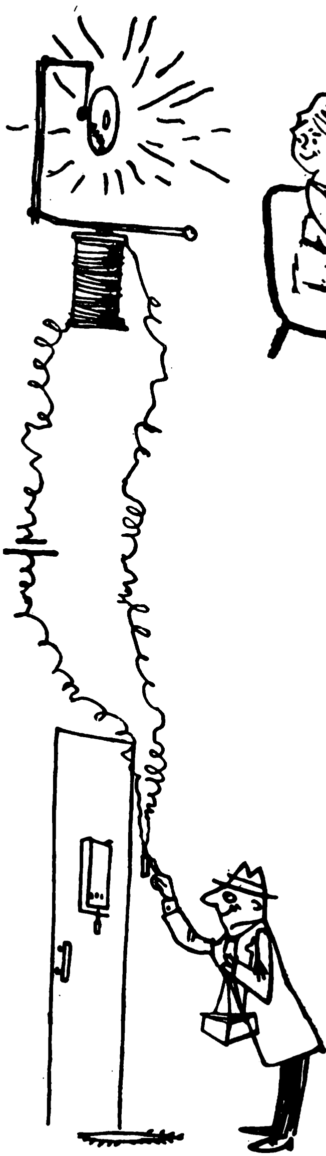
All workings of genius seem very simple. One of the best examples confirming this is the first grid which made a whole revolution in engineering, no field of which can now get along without electronic valves.

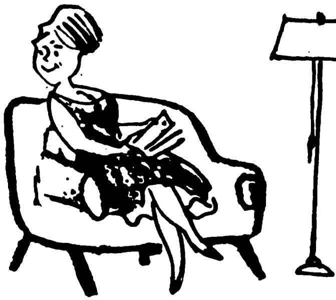
And it is practically impossible now to find an electronic device that operates without triodes. True, that instead of the triode we have just familiarized ourselves with more and more use is being made of the semiconductor triode or transistor. But, despite the differences in their principle of operation, all triodes (vacuum and semiconductor) solve the same problems: either they amplify and convert signals or they are used for switching current on and off, i.e. they serve as a plain "key". Or, to be more exact, the key in this case is the grid, while the triode is like a lock.

It is no coincidence that the first three-electrode valves were called vacuum relays. In electrical engineering the word "relay" implies a device which switches over the sections of a circuit. Before the advent of three-electrode valves this could only be done with the aid of an electromagnet. By attracting the armature the magnet breaks one contact and makes another. The triode has made it possible to make and break a circuit without a magnet and contacts, the switching time being reduced several thousand times.

It was precisely this that the first triode developed in our country by the research team with Bonch-Bruevich at its head was called to do. That is why it was named vacuum relay. But it was another ability of the triode that won it the greatest glory: today no field of electronics can do without amplifying signals of some kind or other.

* In general, the names of all valves spring from the number of electrodes: the diode (dia—two), triode (three), tetrode (tetra—four), pentode (penta—five), etc.





About The Saw, The Beam And The Key

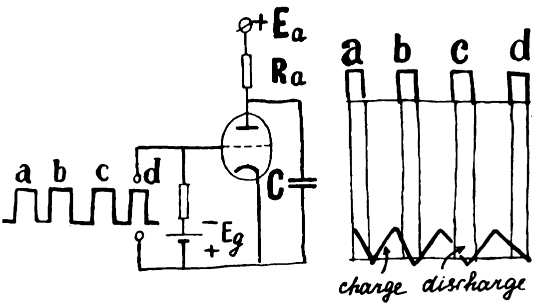
Now, that the main properties of triodes have been discussed, we can return to the processes considered in the Section "Almost Like in a Problem Book" and draw up a complete circuit for controlling the electron beam. If you remember, in the circuit, mentioned earlier, where the capacitor serves as a "tank", a triode functions as key K (see page 40).

The capacitor is connected to the anode of the triode. While the triode is cut off, the capacitor charges; current flows from source E_a to earth via capacitor C and high-value resistor R_a.

The voltage across the capacitor grows slowly, producing the long slope of the sawtooth curve. Then a pulse arrives at the grid and, charging it positively, opens the triode. The open triode is similar to a large open port in the tank:

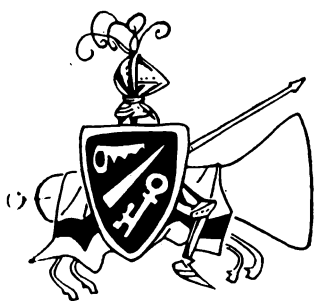
all the charge stored in the "tank" flows through it very quickly to earth. The discharge time (T_2) corresponds to the short slope of the tooth. During this time the beam flies back across the screen.

This in essence is the very principle of the device that makes it possible to see the invisible. Perhaps, it is worth



while to review the Sections "Traces of Things Invisible" and "Almost Like in a Problem Book", to have a clear idea of how the "saw", beam and key interact.

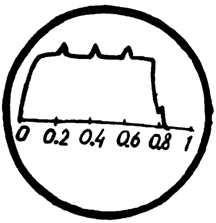
It remains to touch on one important circumstance. For the image of the pulse on the screen to be clear and stationary, it is necessary for the beam to follow the same path every time it makes a trace on the screen. This problem is solved best of all by using the "self-service" principle: the pulse which is to become visible should be made to start itself the sawtooth voltage at the necessary moment. The sawtooth voltage is started (triggered) with the aid of an additional triode-key. The pulse is first applied to the grid of this triode and, on opening the latter, it makes the beam fly across the screen. The same pulse appears on the screen a little later (for this purpose use is made of special pulse delay circuits), when the beam has moved away from the edge of the screen. Because of this delay the pulse will be in the middle of the screen and fully visible.

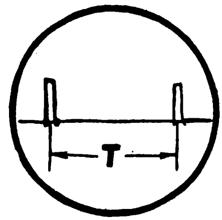


The same thing will happen to the next pulse, and it will also be at the middle of the screen. With the arrival of each pulse the beam repeats its travel along the same path on the screen, thus renewing its own trace.

Time Under A Microscope

The principle that we have considered is applicable not only to the observation of pulses or other electronic processes. It can also solve a problem of great importance: it can measure time to an accuracy within millionths and even hundred-millionths of a second It is quite obvious how





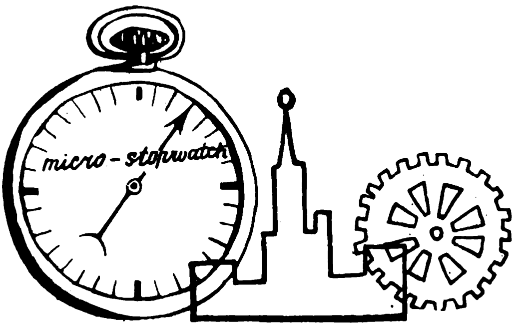
important this is for electronics itself, since electrons are so fast that they perform nearly all their tasks in millionths of a second.

To measure the time a pulse lasts it is sufficient to know its width on the screen and the speed of the beam. If the beam sweeps across the whole screen in one millionth of a second, i.e. in one microsecond, then the duration of the pulse in the Figure will be 0.8 microsecond. For greater convenience in measuring the beam can be made to deflect slightly by marker pulses which are used to read, say, tenths of a microsecond.

It is possible to measure the time between two different pulses. That is just what is done in radar: by the distance between pulses on the screen the distance to the target is determined.

Suppose that pulse-1 appeared on the screen at the moment when another pulse was radiated by the radar antenna. In time *T* the lastly named pulse reached the target, was reflected, and returned to the radar. Here it was amplified by the radar receiver and again deflected the electron beam. A new pulse appeared on the screen (let us call it pulse-2).

The pulse travels at the speed of light, i.e. at 300 000 kilometres per second. A distance of 150 metres to the target and 150 metres back it will cover in one millionth of a second, i.e. in exactly the time that it takes the beam to travel across the screen. This means that there is a definite relationship between time T on the screen, i.e. the distance between the pulses (at a definite beam travel speed) and the distance to the reflecting target. To determine distance to an accuracy of 10 metres, time must be measured to an accuracy within tenths of a microsecond. Such a problem can be solved only with electronic devices which make it



possible to expand millionths of a second on the screen, just as a microscope "expands" microscopic objects by magnifying them several thousand times.

Imagine that someone decided to measure millionths of a second without using electronics. Would it be possible to do this with a stopwatch?

Suppose that its hand makes a complete revolution in one second. If one millimetre of its dial were to correspond to one millionth of a second, then the length of the dial circumference would have to be one million millimetres or one kilometre, which means a dial diameter of about 300 metres. This would make the stopwatch face as tall as a skyscraper!

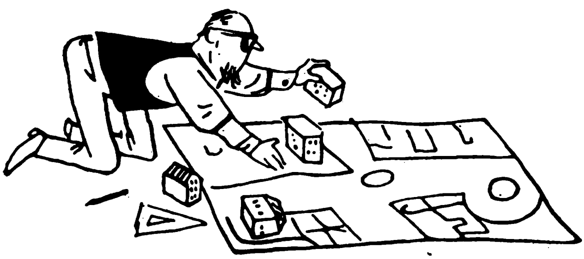
Perhaps the hand should be made so as to complete a single revolution in one microsecond. Then in one second it will have to make one million revolutions. If this mechanism were to be driven by a motor which makes 100 revolutions per second, then a step-up gear would have to be employed. Let us try securing the hand of the "micro-stopwatch" to a wheel with a diameter of one centimetre. Then the input wheel of the step-up gear would have to be one hundred metres in diameter.

How much energy would then have to be expended to rotate a 100-metre gear at a speed of 100 revolutions per second?

The result is paradoxical: a tiny microsecond would require a fantastically big clock to measure it. Actually, there is nothing to wonder at. Mechanical equipment is too bulky to measure millionths of a second. This requires a different "mechanism" and different "parts"—mobile and light—in short, something like an electron.

Foundation Of An Enormous Building

The chapter is drawing to a close. What has been said is, naturally, far too little to get a clear idea of electronics as a whole, but is sufficient to find a definite approach to it.

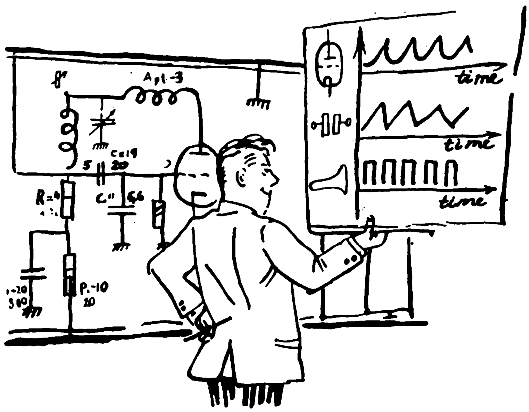


There are two aspects of electronics, and both of them are equally necessary for him who has decided to know something about it. On the one hand there are basic conceptions and laws, design details and circuit components of electronic devices. On the other hand, the aggregate of many concurrent processes, their complex interrelation. These processes cannot be understood without the knowledge of the laws or design details. At the same time, knowing all these elements, it is not always easy to link them together.

The reader has already come across one of these processes. This is the process of tracing an invisible electrical pulse on the screen of a cathode-ray tube by the electron beam. Here vary simultaneously the current flowing through the valve, that flowing through the capacitor, the voltage across the tube plates and the path of the electrons which form the beam.

There are many such processes in electronics. And to understand how they proceed in circuits account should be taken of a multitude of synchronous events and phenomena which have to be linked together.

When designing a new building, the architect mentally sees it in space. Electronics specialists, when developing any device, must visualize it not only in space, but also in time, and make a picture of how the stream of electrons flows, how, born by this stream, continuously pulsating



electromagnetic waves immediately fill the space, how the electrons and waves interact at any moment of time in various parts of space inside complex electronic devices.

So, now, following in the electronics specialists' path, we shall go the same way from the first, simplest devices to modern sophisticated units, such as, for example, travelling wave tubes, klystrons, magnetrons, etc.

So far we have only dealt with electrons. Now we have to acquaint ourselves with waves, because the very basis of electronics is the interaction of electrons and waves.

CHAPTER II. HOW WERE WAVES DISCOVERED?

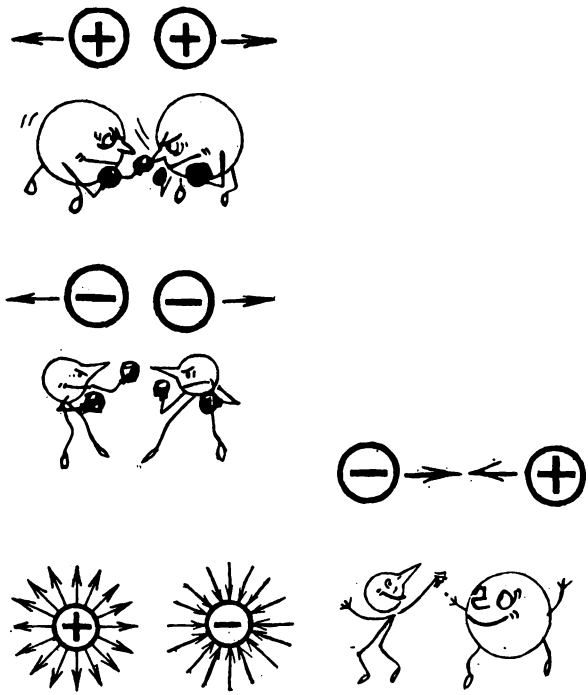
NOW THE READER WILL SEE FOR HIMSELF THAT FOR ELECTRONICS THE ELECTRIC FIELD IS NO LESS IMPORTANT THAN THE ELECTRON. HE WILL GET ACQUAINTED WITH WAVES, WHICH WERE DISCOVERED BEFORE THEY COULD BE DETECTED, AND WILL LEARN HOW RADIO COULD MANAGE WITHOUT ELECTRONICS AND WHAT IT WAS CAPABLE OF.

NO EMPTY SPACE AROUND CHARGES!

THIS LIES AT THE BASIS

II.1

Electric charges are surrounded by electric force fields. The mutual attraction of charges of opposite signs and re-

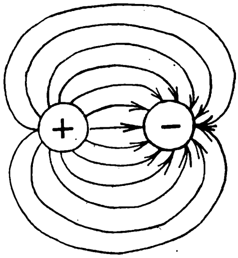


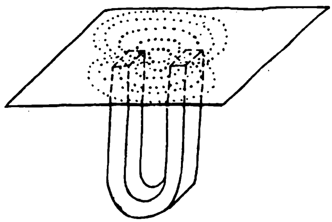
pulsion of those of the same sign are due to the interaction of these fields.

The forces acting in the space around a charge are conventionally designated by arrows. It has been established (also conventionally) that arrows emerge from a body charged positively and enter the one carrying a negative charge.

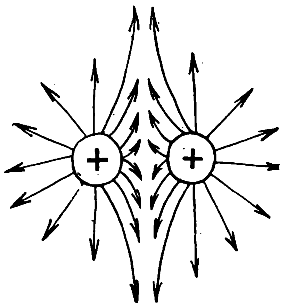
II.2

This is what the electric field of charges of opposite signs looks like. And next to it is the field around the poles





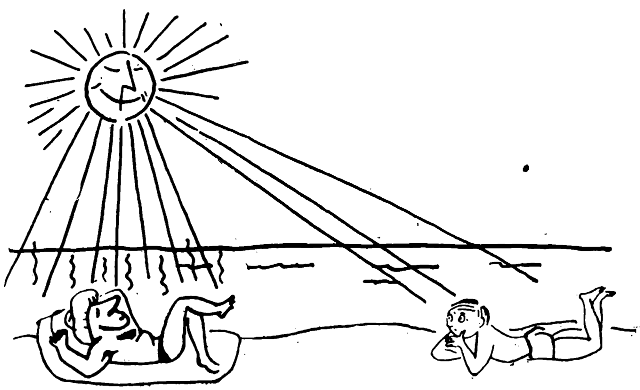
of a magnet. The resemblance between electric and magnetic fields is quite evident.



II.3

This is what the lines of force of an electric field look like when two charges of the same sign collide. The lines of force resist the convergence of these charges, as if these lines were resilient springs.

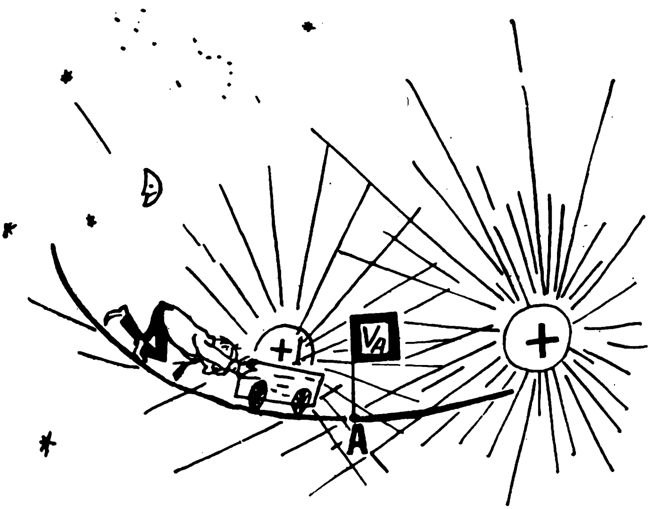
II.4



A charge can be compared with the sun and the lines of force, with its rays. The farther away from the sun, the fewer rays reach the surface of each particular area; the weaker the interaction between a charged body and a point charge.

To overcome the opposition of the fields, when charges of the same sign are brought together, some energy must be expended and work done.

II.5



Try to picture infinity. Hard, isn't it?

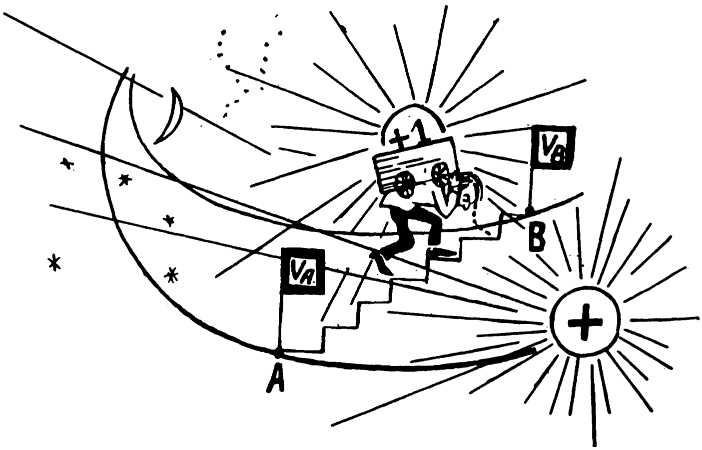
And now imagine that someone has taken along a unit charge and covered with it the path from infinity to point A, located in the field of an initial charge.

The work which this someone has had to do to move the unit charge from infinity to point A in the field of our charge determines the *potential* at point A (designated as V_A).

II.6

The journey from infinity to point B vill require a different amount of energy to be expended and, therefore, potential V_B differs from potential V_A.

Infinity is not a very tangible conception. But now, that the path from infinity to points A and B has been successfully covered, everything becomes much clearer: the work which must be done to move a unit charge from point A to point B is equal to the difference between potentials V_A and V_B, i. e. $(V_A - V_B)$.

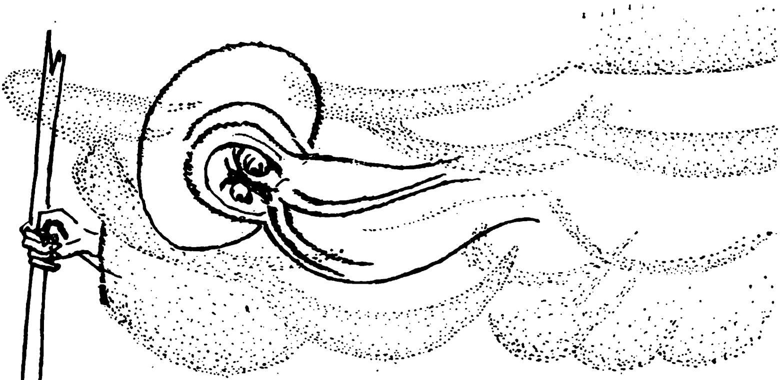


Links With The Past

The magnificent edifice of electronics grows parallel with progress in theory and practice, and the foundation stone of this enormous edifice is the tiny, invisible electron.

But if the foundation were made of electrons only, then no one would be able to build this "colossal" edifice. Before creating electronics man had to collect "stone by stone" vast information about charges, about their movement and interaction with a field, about the properties of electric and magnetic fields, about the laws of induction, about direct and alternating currents, about electromotive force, about the effect of electric current on a magnetic needle and about the behaviour of a current-carrying conductor when a magnet is brought close to it.

And then the mighty Maxwell's intellect, having assimilated all the information gathered bit by bit in hundreds of laboratories, perceived the indissoluble connection of electricity and magnetism, expressed it in an orderly system



of his equations and forecast the discovery of electromagnetic waves.

After the death of Maxwell these waves were obtained by Hertz.

Popov made use of them for wireless communication.

And subsequent development of radio communication has led to the development of diodes, triodes and other electronic devices and valves.

Such is the pre-history of electronics. But what was the beginning of the electronics proper? Perhaps, the discovery of the electron? No, the discovery of Helmholtz did not mark the beginning of electronics: at that time no one could *control* electrons.

It was the cathode-ray tube that helped to control them. But it did not start electronics either:

until the advent of electronic valves, the tube lived a secluded life within the precincts of the temples of pure science and was unknown to anyone except a very few physicists.

The birth of electronics, may it not be connected with the invention of three-electrode valves? But for what purpose did Lee de Forest introduce his grid? It appears that all he wanted was to control electrons by means of a field. Then prior to developing triodes it was necessary to study the properties of fields.

But what were triodes needed for? To improve radio communication. Popov's transmitter little resembled modern transmitters: it could only transmit the Morse code in the form of short bursts of radio waves. The transmission of speech, music or images was out of question. All this became possible only after the development of the triode.

So, the triode enabled Popov's method to be improved. Popov made use of the waves obtained by Hertz. Hertz confirmed Maxwell's brilliant idea. Maxwell generalized the facts established by Faraday.

And Faraday...

Another link with the past. But where is the beginning? It should be sought in ages bygone.

Amber Rod

People knew about electricity for a long time. Since time immemorial it appeared before them in the terrible semblance of thunder and lightning. Knowing nothing about the nature of thunderstorms, our ancestors regarded them as the manifestations of the wrath of gods. Even the most daring thinkers of antiquity never thought of restraining this force and making it serve man.

The second electrical phenomenon which man encountered was of such an innocent nature that it was hard to see in it anything in common with the manifestations of the raging elements.

An amber rod rubbed with wool attracted light objects, such as fluff, pieces of paper. According to the ancient Greek philosopher Thales of Miletus, who lived in the 6th century B. C., this phenomenon was discovered by weavers handling wool. Perhaps people knew about it before, but the first precise description of such facts, the nature of which at that time was not clear to anyone, we find in the works of the wise man of Miletus.

And right up to the end of the 18th century not a single attempt was made to look deeper into these phenomena and understand their essence. In the 19th century, however, electricity became the basis of progress, an integral part of all technical achievements and scientific theories explaining the structure of our world. No one was any longer surprised by the fact that the same forces give birth to what would seem totally unlike phenomena: the interaction of particles inside the atom and the movement of powerful electric motors, the stroke of lightning and the attraction of strands of wool by the amber rod.

Electricity was being found everywhere. And not just because it came in vogue, but because most of the phenomena taking place in our world are really caused by magnetic and electric forces.

These forces apart, science knows only about the force of inertia, forces of universal gravitation (so-called gravitational forces) and the forces acting inside the atomic nucleus.

Nuclear forces have a small radius of action—their effect does not spread beyond the bounds of the nucleus. Gravitational forces exert little influence on the atom—it is too light to feel the terrestrial gravity. And it is only electromagnetic forces that participate successfully in the interaction of atoms and molecules. These forces govern the structure of molecules and atoms, as well as their interaction, the course of all chemical transformations, the structure of crystals, the properties of various physical bodies.

The age of electricity means not only powerful motors and generators or precise measuring instruments, but also a new world outlook, a new vision of the nature of many phenomena originating from the interaction of electromagnetic fields.

And it all began with the amber rod. Even the very name "electricity" came from the word "amber" which in Greek is "electron".

Now do you see how narrow seemed the conception "electricity" at first? Something like a "force concealed in amber". But subsequently these bounds were broadened to such an extent that they have encompassed the whole world. For the world consists of atoms and molecules, and they, as a single whole, exist owing to the interaction of electromagnetic forces.

Such, in brief, is the history of the science of electricity: in the beginning there was the amber rod and at the end is the vast, boundless world. This was well expressed by the French poet Paul Valéry who said that there was nothing more incomprehensible to the human mind than the history of a small piece of amber, which so obediently displayed a force lying hidden in all of nature and, being, perhaps, nature itself, the force that during all the centuries except for the last one was manifest only in amber.

The First Law

Just what happens to the amber rod when it is rubbed with wool? Only at the end of the 18th century did science provide a more or less clear answer: the rod becomes charged with electricity. And what is electricity? Where has it come from?

In the 18th century science could give no answers to these questions. It limited itself to a statement of facts.

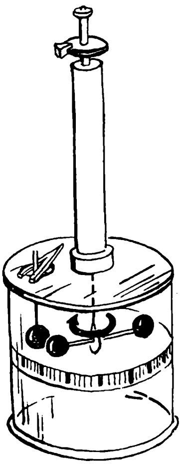
In 1734 the French scientist du Fay established the existence of two types of charges. Charges of the first type appeared on the amber rod when it was rubbed with wool. Since amber is nothing more than petrified resin of trees, du Fay called this type of charge "resin electricity". Charges of the second type appeared when a glass rod was rubbed with a piece of leather and he called this type of charge "glass electricity".

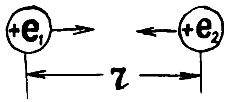
Subsequently, to differentiate between these charges, they were arbitrarily designated by the signs "minus" and "plus" and these are in use to this day.

It has been established that bodies carrying charges of the same signs repel one another, while those with charges of the opposite sign attract one another (see II.1).

In 1775 Coulomb made the first quantitative experiment. His aim was to determine what is it that the forces of mutual attraction of two point charges depend on (Coulomb called these forces "electric fluids") and what is the magnitude of these forces. And what is a point charge? May it not be that Coulomb meant an electron?

No, Coulomb hadn't the slightest idea about the electron. By the point charge he meant any charged body, the size of which was many times less than the distance to other charged bodies. He wanted to determine how the force of mutual attraction of point charges depends on distance. At the same time it was necessary to take into account the quantity of the charge given to each body: the force is the greater the larger each charge. At that time force could be measured with sufficient accuracy. In particular, Coulomb measured the force of interaction of two charges with a specially designed torsion balance. To measure the distance between the charges was not hard at all. But





$$F = K\frac{e_1 e_2}{r^2}$$

what about the charges? Before Coulomb no one had attempted to measure them. There were neither measuring units nor instruments which could compare charges.

Coulomb's method was most ingenious. He took two charged balls and determined the force with which they attracted each other. Then he took a third, uncharged ball and made it touch a charged one. At the moment of contact the charged ball gave up half its charge to the uncharged one, since both balls were made of the same material and size. After this the force was halved. Then Coulomb began increasing the distance between the charged balls 2, 3, 4 and 5 times. The force began decreasing 4, 9, 16 and 25 times, respectively.

In this way the law of interaction between two point charges was established: *the force of interaction is proportional to the magnitude of both charges and inversely proportional to the square of the distance between them.*

In honour of this experiment the law was called Coulomb's law. And the units which were subsequently used for measuring charges were also called coulombs. Compared to the charge of a single electron a coulomb is a veritable giant: a body must accept 6 290 000 000 000 000 000 electrons to acquire a charge of one coulomb. The figure is enormous. If every second a body is given one million electrons, a charge of one coulomb will accumulate only in 200 years.

What Is Void Filled With?

Thus science was gradually developing. First, the only known fact was that unlike charges attract each other, then a strict quantitative law was established. The first formula expressing the behaviour of two charged bodies was derived. By this formula the force of attraction between unlike charges may be determined. But why do they attract each other? How can they act on each other when there is nothing between them but an empty space?

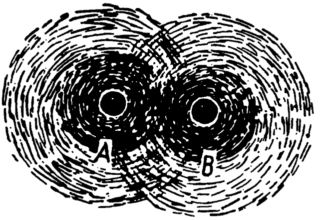
Does this mean that a charged body feels somehow the presence of another charge at a distance? An "unknown force attracts" it to charges of the opposite sign!

This is approximately how this phenomenon was explained by the remote action theory which existed at that time. But what kind of an explanation is this? One might think that it was the feelings of two lovers that were being considered, and not the interaction between physical bodies.

And nevertheless, science could at that time offer no better explanation. Electricity was still too little known. What a difference is mechanics! Here everything is clear: bodies act upon each other through impacts, pressure, traction. No force manifests itself until the bodies come into contact. But then... then... Does not every physical body experience the Earth's attraction at a distance? The Earth exerts influence upon all bodies over distance without any rods, links, levers. Why?

Any object possessing a mass is affected by the force of gravity. A charge nearby another one is also subjected to the action of forces. Is it possible to visualize these forces?

Yes, it is. This is just what was first done by Faraday. He surrounded a charged body with arrows indicating the force direction (see II.1).



Each charge has a definite "sphere of influence". Forces extend from the charge into space, just like the rays from the sun (see II.5).

So this is the secret of the influence extended through space! The space around charges no longer remains empty! They are surrounded by a *field*—the field of action of forces. There is no remote action—the forces act in the immediate vicinity. At each point of space there is a field which acts on any charge introduced into it.

This was a brilliant guess. Even Faraday himself could not foresee the consequences of this profound and far-reaching idea.

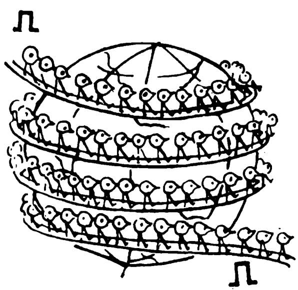
ELECTRONS WORK COLLECTIVELY

THIS LIES AT THE BASIS

11.7

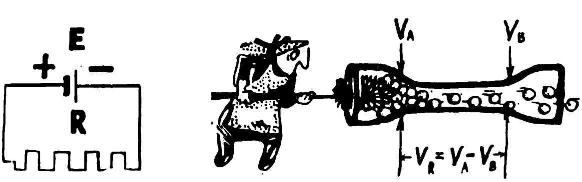
The charge and mass of a single electron are so infinitesimal that no one would ever notice the work done by it. But the electron never works alone. It is sufficient to connect a piece of wire to a current source and all the electrons will immediately begin moving, no matter how long the wire is.

11.8



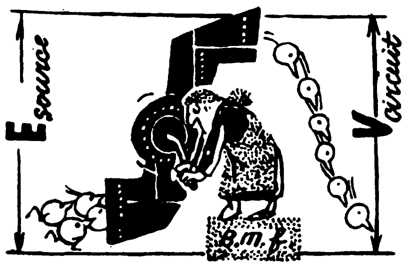
Even if the length of the wire were 300 000 kilometres and it could girdle the equator in seven and a half turns, it would take only one second for a pulse applied to one end of the wire to reach the other end. Of course, this does not mean that in one second electrons have travelled 300 000 kilometres. Simply they start moving *practically simultaneously*, like a column of soldiers who all begin marching at the command "forward, march!".

11.9



An electrical circuit consists of three main components: a voltage source (E), load resistor (R) and connecting wires. The external circuit (the wires and the load) has a definite resistance. Because of the energy possessed by the source, the latter can "push" electrons through this resistor. The ability of a source to "push" electrons through an external ciıcuit is called the *electromotive force* (E) of the source or, shortly, e.m.f.

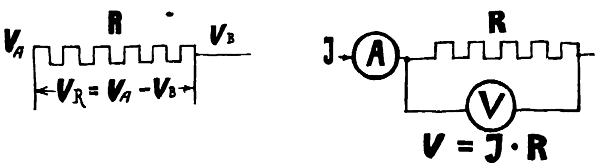
II.10



A current flowing through an external circuit produces a *voltage drop* across it (V_{cir}).

The voltage drop across the entire circuit is always equal to the electromotive force of the source, i.e. $E = V_{cir}$.

II.11



Wires usually have a low resistance. The voltage drops mainly across load R. The electrons passing through it produce a difference in potential ($V_A - V_B$) between the ends of the load resistor. This potential difference is equal to the *voltage drop*, i.e. $V_R = V_A - V_B$.

The relation between the current flowing through the load (I) and the voltage drop across it (V_R) is determined by the well-known Ohm's law:

$$I = \frac{V_R}{R}$$

The current depends on the number of electrons which pass through resistor R in one second.

At a current of 10 milliamperes (i.e. ten one-thousandths of an ampere) the number of electrons passing through the cross-section of a wire in one second equals about 63 quadrillions (63×10^{15}). Approximately the same number of electrons pass every second through triodes and diodes. And in the filament of an incandescent bulb, where the current is as large as several fractions of an ampere, the "crowd" of flowing electrons is fifty times greater still.

II.12

On passing through a resistor the electron loses some of its energy, which is released in the form of heat. The amount of heat produced by one electron is so small that it cannot be noticed. But a "collective" of electrons can heat a resistor to a very high temperature. There is a good number of well-known *consumers of electric energy* where the energy of the moving electrons is released in the form of heat.

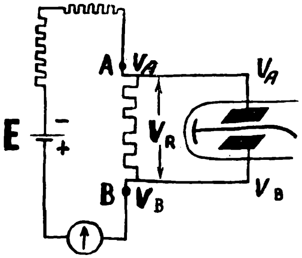
Every consumer has a certain resistance which causes a definite voltage drop across it:

$$V_R = V_A - V$$

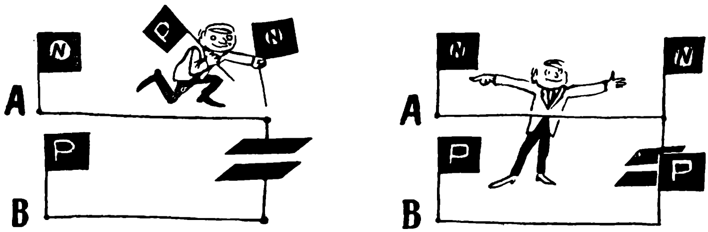
We already know that the energy depends on the potential difference (see II.6). Moreover, according to Ohm's law, the "collective" of electrons passing through resistor R will be the greater, the greater is V_R (see II.11). So, with an increase in V_R the energy lost by each electron and the number of electrons also increase. Therefore, power P dissipated in the load increases as the square of V;

$$P = \frac{V_R^2}{R}$$

II.13

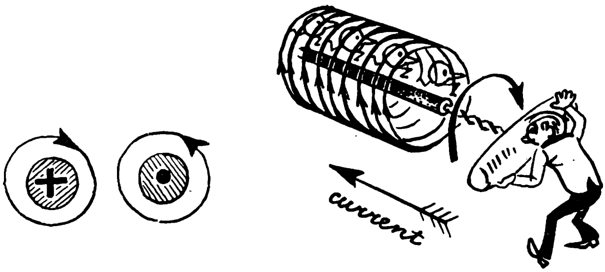


If the deflecting plates of a cathode-ray tube are connected to terminals A and B of a current-carrying resistor R, then the potential at one of the plates will be equal to V_A, and that at the other one, to V_B (on condition that the resistance of the connecting wires is so low that it can be disregarded).



In this case it is said that voltage $V_R = V_A - V_B$ is "taken" across resistor R and "applied" to the plates. If an alternating voltage is applied to the input of an electron valve (between the cathode and the grid) and the voltage across a resistor connected in series with the anode of the valve is taken, then the lastly named voltage will be several times higher than the former one, i.e. the input voltage will be amplified (see I.34).

II.14

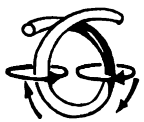


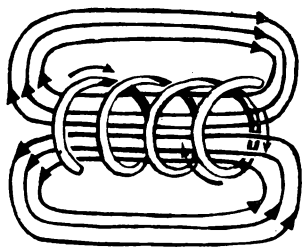
In addition to heat, the electrons flowing along a wire release another form of energy—the energy of a field.

A current-carrying conductor is always surrounded with lines of magnetic force. The direction of these lines coincides with that of the rotation of a corkscrew, if the latter is advanced in the direction in which the current is flowing. (Incidentally, in all rules used for determining the interaction of current and magnetic field, it is so-called "technical current" that is meant, which flows in a direction opposite to that of the electron movement. The reasons for this "confusion" are historical: these rules had been established earlier than the electron was discovered.)

II.15

In a wire coiled into a spiral the lines of magnetic force also work "collectively"—their efforts are pooled together in a common flow that is directed along the axis of the



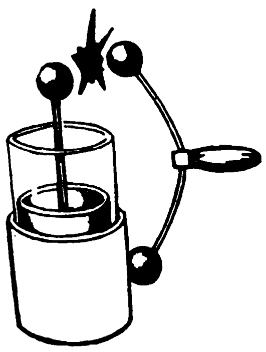


coil. And so we have come to a so-called *solenoid*. If a heavy current is passed through the solenoid and a core possessing good magnetic properties is placed inside it, the solenoid becomes a powerful electromagnet.

Lightning In A Jar

In Faraday's time the science of electricity developed tempestuously. Any discovery soon found its application and served as food for new research and ideas.

Coulomb investigated the properties of charges several decades earlier. At that time no one knew what to do with charges: there were no sources of electricity as yet and no one even imagined that charges could be transported by wires. But mechanics at that time was a well-known subject. So it was decided that the first and wisest thing to do was to turn to mechanics for aid. Instead of rubbing the amber rod by hand, a special wheel was used for the purpose. The rod itself was replaced by a large glass jar, which was lined inside and outside with lead. Thus, in laboratories of the Dutch city of Leyden were developed the first condensers (capacitors) which came to be known as Leyden jars.



It was expected that the machine would produce an invisible "electric liquid" which would fill the Leyden jar to the brim.

Mechanics proved its worth. If a comb rubbing against one's hair could produce electric sparks which were barely visible in the dark, the wheel made it possible to obtain large charges in the Leyden jar. These experiments became so fashionable that they were conducted not only in laboratories, but even in the reception-rooms of aristocrats and kings' palaces.

Louis XV would form a chain of soldiers and amused himself watching the grimaces of the men, when the discharge

current of a Leyden jar passed through this living circuit. The amazed public watched lightning-like sparks obtained from the jars. The aristocracy were astounded: "What a wonder—lightning in a jar! What science is capable of!" But things went no further.

Such was not the case in Faraday's time. Progressive scientific thought was focussed on electric and magnetic phenomena. Ampere and Davy, Volta and Ohm, Oersted and Helmholtz approached the same problems from different angles. Ideas permeated the air like electricity before a thunder-storm. This was no longer science for the sake of science, not the curiosity of single men—practical life set aims for the science, and kept demanding solutions to more and more problems.

And if science comes across something unknown when solving these problems? So much the better! This means that there will be new grounds for new practical tasks.

Thus, electrolysis which was developed to obtain pure metals and gases helped discover the electron. The same chemical process formed the basis for the first current sources which were developed as the result of the discoveries made by Galvani and Volta and which came to be known as galvanic or voltaic cells.

With the advent of these sources the interest in electricity grew still more. Man learned to transmit charges along wires and noticed immediately that the current flowing along a wire produced heat. And heat could be made to work. This thought was well assimilated, and it gave birth to a whole revolution in engineering, which brought glory to the past century.

Similarity Or Kinship?

Faraday had not the haziest notion about electronics. And Coulomb, still less. At the same time theirs was nearly the key part in its development. Coulomb studied the charge. Faraday introduced into the science the concept of field. And what does electronics deal with?

Many things. Satellites and television, computers and many things besides! But if we look closely we shall see that the whole of this diversity can be reduced to various cases of the interaction between charges investigated by Coulomb and fields discovered by Faraday.

True, in addition to Faraday's fields, electronics also has to investigate other fields.

Faraday studied fields produced by stationary charges. These fields are like motionless sand dunes in perfectly calm weather.

Charges in electronic devices are exceedingly mobile. The electrons emitted by the cathode flow in an endless stream to the anode. From the anode they flow through wires and other components to other units, other wires. And the field follows the electrons like a shadow. This is no longer a stationary field. It varies with the changes in the current. The space around wires carrying an alternating current does not resemble motionless dunes, it is like a turbulent sea with its waves constantly in motion. These are electromagnetic waves.

Electromagnetic field. Electromagnetic waves. These conceptions represent a confluence of two different but inseparably bound by nature phenomena—electricity and magnetism.

The connection between them was not discovered all at once. At first their similarity was noticed. The amber rod attracts pieces of silk. The magnet attracts iron filings. A charge is surrounded by an electric field. A magnetic field surrounds a magnet.

The field is not Faraday's figment. If you wish to see a magnetic field, spread some iron filings onto a sheet of paper and bring a magnet under it, and there will immediately appear lines of force like those shown in the drawings made by Faraday himself (see II.2).

Differences were also noticed: a positive charge and a negative charge can exist independently of each other. But the poles of a magnet cannot be separated. The magnet can de broken into two parts, and still each piece will have a north and a south pole. The magnet is reminiscent of that fabulous dragon who would grow a new head if his was chopped off*.

And so science knew of two phenomena which were very similar in some ways and different in others. Electricity and magnetism. They were investigated separately, independently of each other until a connection was found between them by a sheer stroke of fortune. In 1819 the Danish scientist Oersted was demonstrating experiments in electricity to students. Near a wire lay a compass which had nothing to do with the experiment.

"Why does the compass needle deflect when you switch on the current?"—the lecturer was asked. This question made not only Oersted but the whole of his contemporary scientific world ponder.

Here certainly was something to think about. The *electric* current flowing through the wire gave birth to a *magnetic* field. There were two different phenomena, and then, all of a sudden, they were found to be closely bound together.

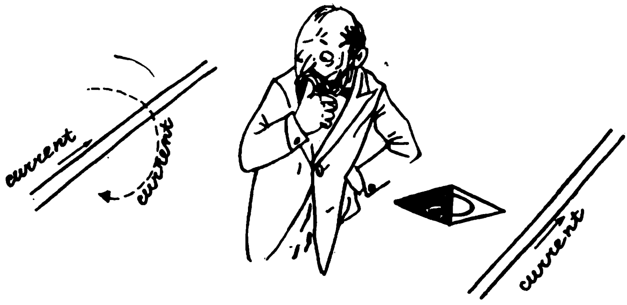
Following In Oersted's Footsteps

In a short time news of the experiments conducted by Oersted spread throughout the world. At that time the current-carrying wire attracted not only the magnetic needle, but also the attention of scientists the world over. Small wonder: everyone understood that the world was on the threshold of new discoveries, though no one could yet give a full explanation of even the essence of the first experiment which would seem so simple.

And still, what is it that makes the needle deflect from the wire? Oersted himself supposed that it was turned by the electric current which allegedly flowed not only inside wires, but also around them. Ampere suggested a different hypothesis. He believed that a current flowed inside the magnetized needle and the two currents interacted: the current inside the wire and that in the needle.

Which of them was right? Perhaps they both were wrong. New experiments were required either to confirm or refute the hypotheses, to explain everything fully.

* Incidentally, later certain substances were found to be able to retain stationary electrical charges, owing to a certain orientation of their molecules or ions. Such substances are called *electrets*. If we break in two a rod made of an electret, we again will have two poles in each piece—"minus" and "plus" ones.



In Paris, London, St. Petersburg, Florence, Munich, Heidelberg, Geneva, Oersted's experiments were repeated innumerable times: a wire was placed near a magnetic needle and then current was switched on. And every time the needle behaved in the same way: as soon as the current began flowing through the wire, the needle immediately set at right angles to it.

The great Ampere, inspired by Oersted's discovery, locked himself up in his laboratory to investigate how charges influence one another, if they are not at rest, but are moving along wires. By the way, this was most unusual for Ampere. Hitherto he discovered everything on paper, and always preferred his study to the research laboratory. But this time he could not get along without experiments: each thought had to be thoroughly checked.

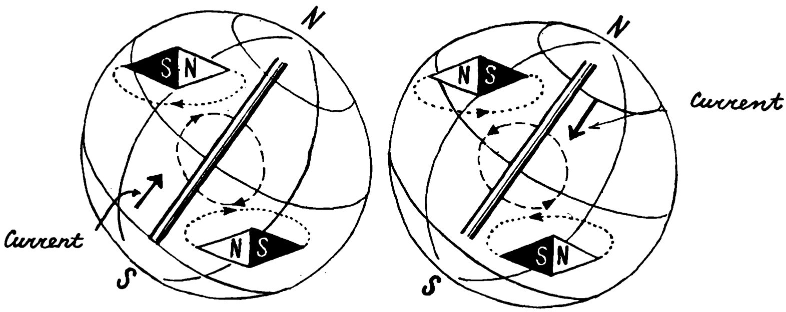
In seven reports brilliantly delivered by André Ampere at the meetings of the French Academy, he made known all the results of his work. The seven Ampere's reports are like seven posts along the borderline between two regions. On the one side of the border is all that concerns stationary charges, and on the other side, charges in motion and those phenomena that are born of the electric current.

The first region was given the name of electrostatics (the word static means motionless). Before this Coulomb had already been interested in the properties of stationary charges. The second region is electrodynamics—the science, concerned with the action of moving charges, for which the foundation was laid by Ampere's works. At the same time Ampere also made a number of brilliant discoveries, including his famous solenoid, on the basis of which the American scientist Henry soon developed electromagnets capable of lifting weights of up to two tons (see II.15).

Which Way Will The Needle Turn?

In Paris, the glorious Ampere lays the foundation of a new science. And at the same time Michael Faraday, a young modest worker at the Royal Institute in London who has just left the bookbinding trade, following Oersted, also places a wire near a magnetic needle and switches on the current.

Nature had endowed Faraday with a remarkable quality: he wanted to touch everything with his own hands, he did not want to believe in any conclusions till he had checked everything himself.

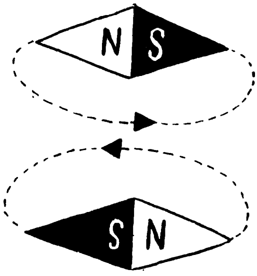


Yes, the needle really turns under the influence of the electric current. But what makes it turn? Is this a current flowing in space around the wire, or the one surrounding the needle? No, this still has to be checked.

If the current flows from south to north, the north pole of the magnetic needle placed under the current-carrying wire turns to the west*. And what happens if the needle is placed above the wire? The same pole will face the east. Why? And if the direction of the current is reversed? Then everything will also reverse. The needle under the wire will turn to the east. The needle above the wire will face the west. What causes all this?

A suspicion crosses Faraday's mind: may it not be that the current produces a magnetic field? Suppose that ring-shaped lines of magnetic force are formed round the wires (see II.14). How will these rings act upon the needle?

* Here is meant the technical direction of the electric current (see II.14).



The unlike poles of two magnetized needles attract each other. What is more, their lines of force are directed opposite to each other. Is it not the same law that is at work here?

Let, for example, the current flow from south to north and the lines of magnetic force round the current-carrying wire be directed clockwise. In this case the lines of magnetic force produced by the current will run counter to the lines of force of the magnetic needle, if it is placed under the wire, and the north pole of the needle will turn to the west. Wonderful! This is fully confirmed by the experiment! Well, and what happens if the needle is above the wire? For the lines to run again in opposite directions the same pole of the magnetic needle must face ... east!

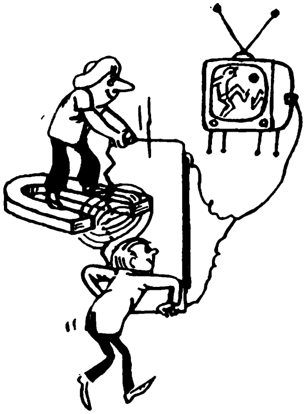
There it is, the real truth! The phenomenon shortly before disclosed by Oersted is explained by the interaction of two magnetic fields!

In this way the causes underlying the influence of the current-carrying wire on the magnetic needle were uncovered. Now every schoolchild can tell at once which way the needle will turn, because school physics text-books contain a very simple rule: if a corkscrew is advanced in the direction of the current, the head of the corkscrew will rotate in the direction of the lines of magnetic force surrounding the current-carrying wire. Should the current reverse, the corkscrew will go backwards. And then its head will rotate in the opposite direction, and the needle will also behave in the opposite sense. Just as in Faraday's experiments.

WITHOUT MOTION THERE IS NO INDUCTION

THIS LIES AT THE BASIS

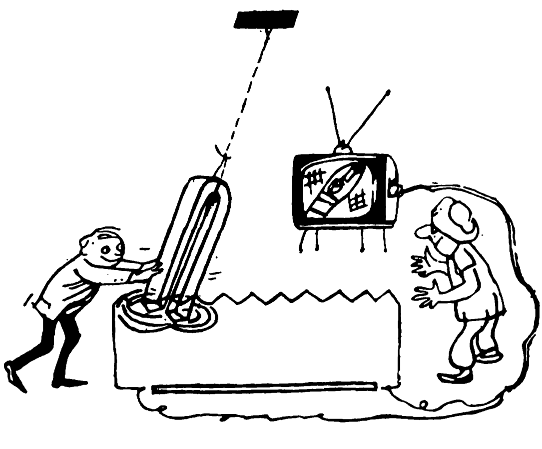
II.16



When a closed conductor moves in the field of a magnet, a current is induced in it, which is known as the *induced current*.

II.17

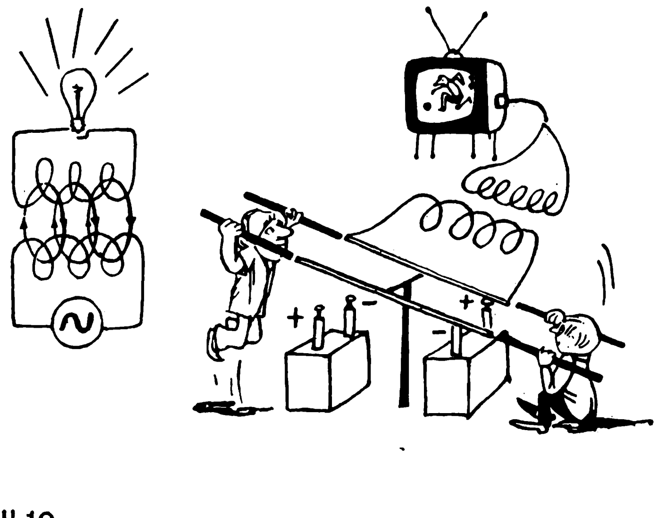
The conductor may be stationary. Then, in order to induce current in it the magnet must be moved. And so, it makes no



difference which is in motion, the magnet or the conductor, as long as the lines of force of the field intersect the conductor in which the current is induced.

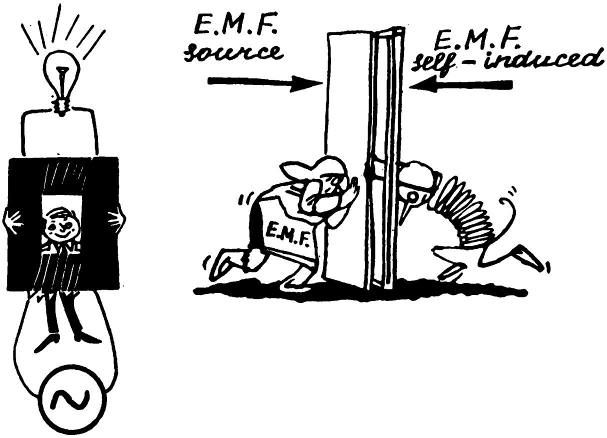
II.18

Without motion no current is produced. But motion can be of many kinds. The circuit itself may remain stationary. Current is induced because here we have a *different kind of motion*: due to variations in the current flowing through the first winding there occur *variations in the magnetic field* surrounding it. The changing magnetic field induces a varying *secondary current* in the other winding.

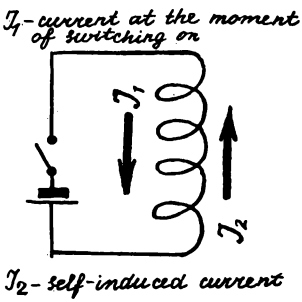


II.19

This is exactly how the *transformer* operates: an alternating current in the primary winding produces a varying magnetic field, which induces an alternating secondary current in the secondary winding. The transformer windings are usually wound on a *core* made of a magnetic material, for example, of iron. The core increases the magnetic fields set up in the transformer.



11.20



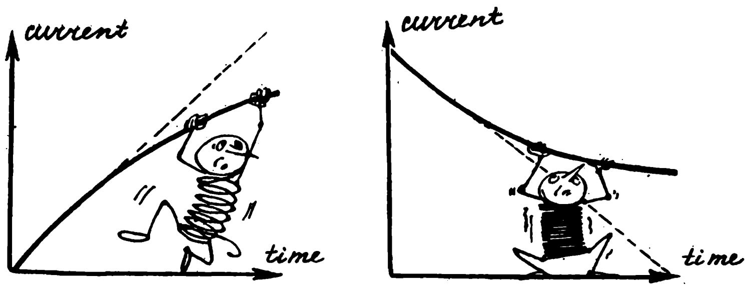
The induced current appears even if there is no secondary winding. At the moment of energizing of a winding a varying magnetic field produced by the growing current induces a *secondary current* in the same winding. This phenomenon is known as *self-induction*.

The self-induced e.m.f. always resists any change in the current flowing in the circuit. This is how the rule established by Lenz reads.

11.21

Owing to the self-induced current, a coil acquires a singular property of inertia: the coil opposes, as it were, variations in the current that flows through it. If the current in the coil decreases the self-induced current begins to sustain it, but if it increases, the self-induced current will flow counter to it and thus will begin decreasing it.

The greater the inertia of a body the harder it is to stop or accelerate it. The higher the *inductance* of a coil, i.e. the number of turns per unit length of the coil, the greater the inertia (self-inductance), the slower the current in the



coil builds up or falls down. Inductance has its own units of measurement which are called henries (after the physicist Henry).

Faraday's Intuition

The famous experiment of Oersted confirmed the link between electricity and magnetism. There were two different phenomena: electricity on the one hand and magnetism on the other. And then a bridge suddenly appeared between them. But if it is possible to cross the bridge from the left bank to the right, is it not possible to go back along the same path? Current engenders magnetic field. Is it not possible that magnetic field is capable of producing electric current?

Faraday seeks a way to obtain this current. He connects a galvanometer to a wire and places a magnet nearby. No current appears in the wire. Does it mean that he is mistaken? No, something does not tally! Obviously these phenomena are reversible—Faraday's intuition makes him check the supposition again and again.

For ten years Faraday carries in his pocket a length of copper wire and a piece of magnetized iron. At the most inopportune moments, forgetting where and with whom he is, Faraday, like a maniac, produces his "toy" and begins arranging the wire and the magnet in various ways. From time to time he tries again to detect current with a galvanometer. But there is still none of it.

And all these ten years the sixth sense of the scientist (or perhaps, the seventh or the one of a still higher order) continues to tell him that he is on the right path.

Unbelievable persistence—to have faith for ten years in something that cannot be confirmed!

Success came unexpectedly. Once he connected a battery to a wire spirally wound on a drum and then suddenly perceived that a galvanometer connected to another isolated winding showed the presence of current for one tiny moment. A hardly noticeable spurt of the pointer and Faraday at once understood the thing that had eluded him for ten years.

Current cannot be induced as long as the magnetic field is stationary. For current to appear, the field has to be varied. When Faraday had connected the battery, a magnetic field was immediately formed, and during the instant that it was building up, he accidentally noticed the slight abrupt deflection of the pointer. Was it so? Not much of an accident! The search for this event had lasted for ten years!

But then everything went smoothly. It was not so difficult to guess that current would also be induced, if the current in the primary winding remained constant, but the magnet was moved with respect to the wire (see II.17). Or let the magnet remain stationary, and the wire moves so as to intersect the lines of force surrounding the magnet (see II.16).

In all these cases it is the varying magnetic field that acts upon the wire and induces current in it.

Current is only produced when the magnet moves with respect to the wire, but not in virtue of any properties inherent in the magnet when it is at rest, writes Faraday in his scientific diary. Such is the essence of the laws of *electromagnetic induction*—the excitation of electric forces by magnetic ones.

The laws established by Faraday were laid at the basis of new powerful current generators where current was produced in the windings because of their rotation in magnetic fields. Then current transformers were developed (see II.19).

The world admired the great discovery of Faraday. And still the nature of induction was not understood fully. Probably at that time no one realized this better than Faraday himself. How does one coil influence another, when there are no connecting wires between them? Obviously this is the work of a field. But just what is this field?

Oersted proved that current engenders magnetic field. Faraday proved that magnetic field produces current.

These mutually reversible phenomena still escaped comprehension, it was necessary to go anew deep into their nature, to seek some more intimate link between them.

Dual Waves

Such is always the case with science: first facts are accumulated and then the necessity of generalizing them arises.

By the time Maxwell set himself the aim of summarizing all that was known about electricity and magnetism, there had been a plethora of facts. Science and practice had found lots of applications for the magnetic field produced by current and had known dozens of ways of converting the energy of magnetic field into electric current.

These two principles had formed the basis of all measuring instruments.

The same phenomena had been used everywhere. Current is produced by magnetic field, magnetic field acts upon current. Here everything is reversible, like in a dynamoelectric machine. If current is fed to the windings of the machine it becomes a motor, if the machine is driven by another motor, it begins producing current. This reversibility is of the same nature: either the magnetic field set up by current makes the rotor of the machine revolve, or by letting the rotor rotate in magnetic field, we have current flowing in the windings.

By varying a magnetic field near a wire a current can be induced in it, and fields are built up in the space surrounding the current-carrying wire. Current flows along a wire, and in the space around it electric and magnetic forces interact.

But what if no wire is there, and an electric field is made to vary? What will happen then?

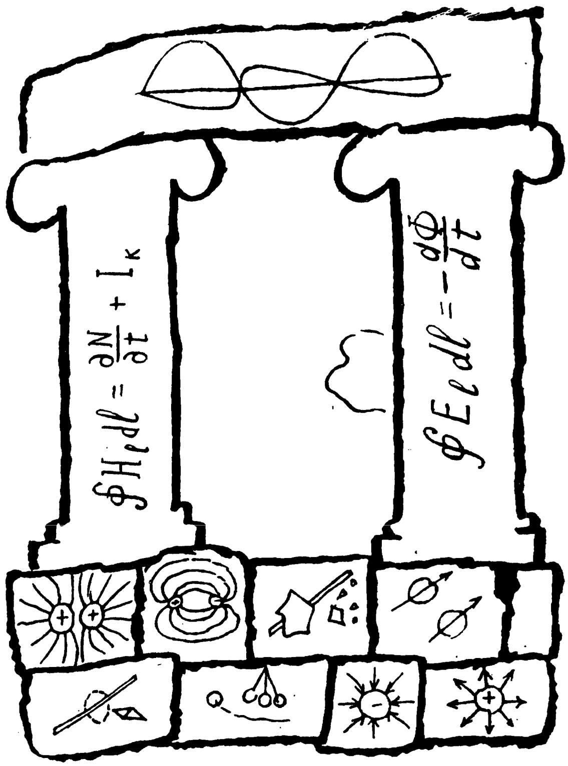
James Clerk Maxwell was the first to put this question and he himself provided the answer. And not simply an answer, but an orderly and consummate system of mathematical equations—the theory of electromagnetic fields. Only one link was missing in the chain of all the known phenomena connecting electricity and magnetism and Maxwell introduced this link into the theory.

If a variable electric field exists in space, then it produces a magnetic field. As if there is an imaginary wire in this space and an imaginary current flows along this wire. Maxwell called this current a *displacement current to* differentiate it from the ordinary *convection current* — the motion of charged particles.

Science had known of no phenomena where these fields would interact without a current-carrying wire. But all the known facts had spoken in favour of such a guess. Thousands of experiments, hundreds of instruments, based on the indissoluble connection between electric and magnetic fields, had confirmed this supposition. True, both in the instruments and the experiments the wire and current had always been present. Well, this means that our possibilities are limited as yet, we simply have not learned to detect the electromagnetic field directly, have not studied all its properties—decided James Maxwell and history confirmed that he was right.

This thought has found its expression in his system of equations, and the theory has become remarkably harmonious. All the discoveries made by science have become particular cases of Maxwell's equations. Like a mirror these equations reflect the mutual connection and reversible nature of the phenomena: one of them expresses the dependence of the electric field upon variations of magnetic fluxes; the other shows how the magnetic field is influenced by changes in electric forces active in space.

Being formed at a place where there is a current-carrying conductor, the electromagnetic field will propogate through space, occupying an ever increasing volume. While it is pos-



sible to separate the field from the conductor, electric fields cannot be separated from magnetic ones—they are inseparably bound in a single *electromagnetic wave*.

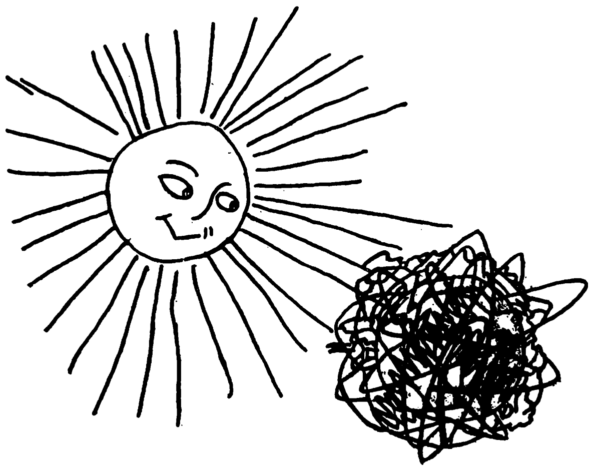
There is no remote action in nature, well then the electromagnetic field cannot act upon a body instantaneously, if the body is located at some distance. The electromagnetic wave approaches gradually. From Maxwell's formulas it follows that the wave travel speed exactly equals the speed of light.

And this is called "gradually"! Travelling with such a speed, in only a second the wave will circle the globe nearly eight times! (The speed of light in empty space is approximately 300 000 kilometres per second.)

Unexpected Conclusion

Maxwell's contribution is enormous. But still it must not be forgotten that many years before Maxwell's discoveries they had been forecast by Faraday. Back in 1832, attempting to reveal the nature of induction, Faraday came to the conclusion that in these phenomena excitation is transmitted over a distance by certain oscillations resembling "the oscillations of the surface of ruffled water or the sound oscillations of particles of air."

In addition he wrote that the active cause (which he called magnetism) propogates from magnetic bodies gradually and



for this it requires a definite length of time which, obviously, will be found to be quite insignificant.

But this is exactly what Maxwell proved!

Among numerous Faraday's ideas this was, probably, the only one that he could not check with his own hands. Evidently, that is why he did not dare to speak it out loud. Faraday left a letter which he requested to be opened up only after a lapse of a century.

In 1938 this letter was read by the members of the British Royal Society and it provided one more confirmation of the striking intuition that Faraday possessed. For by that time these ideas had been confirmed not only theoretically, but also by Hertz' experiments and numerous means of communication based on the use of electromagnetic waves travelling at a fantastic, but still finite speed (just as Faraday had predicted!).

Maxwell proved that this speed is equal to that of light.

What is this, just a coincidence?

No, Maxwell did not believe in a coincidence. He strove to find a mutual link between different phenomena. Since electromagnetic waves travel at the speed of light, that means that *light is also electromagnetic waves.*

Thus, as a result of investigations of the ties between electricity and magnetism, a totally unexpected kinship was suddenly discovered. Dozens of scientists studied the connection between electric and magnetic forces. But who could ever think that the same forces give birth to visible light!

Daring Maxwell's genius revealed this unity. The waves of light are of the same nature as the waves which arise around a wire carrying an alternating current. They only differ in the wavelength. Extremely short are the waves of light. At that time longer ones could not be discovered.

Not later than 12 years after Maxwell's demise Heinrich Hertz managed to radiate and receive these waves, confirming the ideas of his great forerunner.

And several decades later thousands of radio stations were already filling the space all around the globe with these waves, and they carry communications from all ends of the earth and in all languages.

The History Of Light

The science of light had covered a long and thorny way before Maxwell's ideas linked light with electromagnetic waves.

People have been curious about light since time immemorial. No special instruments have been required to discover it. The universe is filled with sunbeams and it is only due to light that man has been able to learn about this sunny world. That is why the first "scientific debate" about light was held as far back as three and a half thousand years ago. The sponsor of the "debate" was Pharaoh Amenophis IV, who lived in the XIV century B.C.

Rejecting the then existing theories that light is radiated by the eyes of god Ammon, Amenophis IV came to the conclusion that light is emitted by the Sun. The Sun was also considered a god known by the name of Aten. Amenophis IV legalized the new concepts: be ordered that Aten should be worshipped instead of Ammon and in honour of this reform he changed his name of Amenophis for that of Ikhnaton. Amenophis means "pleasing to Ammon", and Ikhnaton means

"welcome to Aten". The new name was in full accord with the spirit of the new ideas.

The ancient Greeks had different views. Having established the fact that man can see objects only because of light, they concluded that light is radiated by the objects themselves. "Particles of light" reach the human eyes and because of these particles a thing can be seen.

However, in the works of the ancient philosophers one can also find different ideas. Plato, for example, in his famous "Dialogues" says that of all the organs it is the *light-carrying eyes* that the gods have created first of all.

Compared to Amenophis-Ikhnaton this is already some progress. According to Plato, not only the gods possess "light-carrying vision", but even man himself.

But then it is hard to say whether this is any closer to the truth: Amenophis claims that light exists outside man and Plato, that the source of light is man himself. It is as if his eyes "feel" objects with the beam they emit.

Things were made clear much later. Approximately in the XI century A.C. the famous Arabian scientist Abu-Ali Al-Hasan Ibn Al-Haytham (he is known in history by the name of Alhazen) was the first who proclaimed that we see the *light reflected by objects.*

But just what is this light?

The great Newton has left us his theory of light in which the ideas of the philosophers of antiquity are revived. He also believed that light consists of particles. Truly, his particles (he called them corpuscles) are not radiated by the eye, nor by objects: Newton understood well that visible objects only reflect light.

And then Maxwell advances his electromagnetic theory of light which fascinates the minds of scientists to such an extent that no one thinks of the light corpuscles any longer.

But now scientists begin remembering Huygens and Fresnel, Newton's contemporaries and opponents, who had asserted that on encountering obstacles light behaves as if it consists not of particles, but of waves.

And then, several decades later, science comes across a penomenon which demands again that the ideas about light be reviewed.

Under the action of light metal emits electrons, as if it were bombarded by a hail of particles. Maxwell's waves cannot explain such phenomena. Studying this effect (it has become known as photoeffect), Einstein has taken up anew Newton's corpuscle idea and added a particle of light—the photon—to the formerly discovered series of elementary particles of matter.

This is a typical example of dialectics: revaluation of former views and former ideas at a new stage of development. From Newton's corpuscles of light to Huygens' and Fresnel's waves, from these, to Maxwell's ideas about electromagnetic waves, and then, to Einstein's photons which have eliminated the "white spots" in the wave theory of light—such are the main stages marking the evolution of views held by the science of light.

And now, finally, the modern theory of light—yet another vivid example of the dialectical unity of conflicting qualities of phenomena: in some phenomena light manifests its wave properties, and in others, behaves like a stream of minuscule particles.

But why the history of light in a book on electronics?

One would not have to go into this history if not for photonics which has come up in recent years, giving rise to the development of light generators and vying with electronics in the solution of a great number of problems.

Where Does Radio Begin?

Now, we have radio and electronics—two fields of engineering closely linked together. Where is the borderline between them?

Electronics deals with the development of electronic devices: valves, cathode-ray tubes, semiconductors. The role played by radio needs no explanations. And yet...

Can radio exist without electronics? It is hard to imagine a modern transmitter or receiver without semiconductors or valves. But now it turns out that communication can be realized by means of photonic devices. In this case it is light rays and not radio waves that are employed.

Is this radio or is it not? We shall have to go once more deep into the meaning of the word "radio" to answer this question. The word "radio" comes from the Latin word "radius" which means "ray". Radio can operate with various rays. The more so, as the waves employed by radio up till now and light are of one and the same nature.

Maxwell established this truth about a hundred years ago. Why is it that only recently systems employing light rays have come into being?

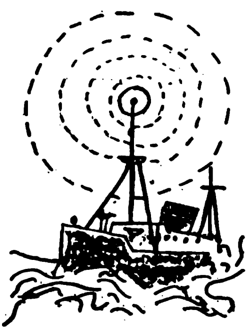
The thing is that in the early years of the development of communication engineering it was easier to deal with longer wavelengths. After Maxwell's discoveries science was persistently seeking ways of obtaining these invisible waves. What for? Not simply to confirm or refute Maxwell's ideas. Many understood that having studied these waves, science would be able to apply them for practical purposes. For what purposes precisely? Who could know what possibilities were latent in the waves that no one had yet observed? It was hard to predict anything, when their properties were totally unknown.

Even Heinrich Hertz, who was the first to obtain the waves, asserted that his discovery was of no practical value.

Nevertheless, it was precisely in Hertz' experiments that the principle was born which subsequently became the basis of all kinds of wireless communication: *radiation and reception.*

"A device should be invented which would substitute electromagnetic senses that man lacks"—that is how the problem was posed by the prominent Russian scientist Alexander Popov.

And soon he proved that such devices really could be developed. On the 25th of April (7th of May) 1895 A. Popov expounded in his epoch-making report the results of his first experiments in wireless communication. Two years later in the course of his report delivered at the St. Petersburg University A. Popov demonstrated the possibility of transmitting radio signals over a distance of 250 metres which separated the chemical laboratory, where the transmitter was set up, from the physics room in which the signals were received. At that time the navy was in great need of such



a communication. On land wires could do the task. But one cannot stretch wires from the shore to a ship that has put out to sea!

Two more years passed and the radio station built by A. Popov was already keeping up communication between two ships lying forty kilometres apart, and in the year 1900 the operations involved in the salvage of the battleship "General-Admiral Apraksin", which had run aground near the island of Gogland, were coordinated by means of wireless communication between Kronstadt and the island.

By using the same station Popov transmitted to the captain of the icebreaker "Ermak" a message of the Admiralty that a storm had set adrift an ice floe on which 27 fishermen were stranded. The ship that went to their rescue arrived in time. Wireless communication helped to save human lives.

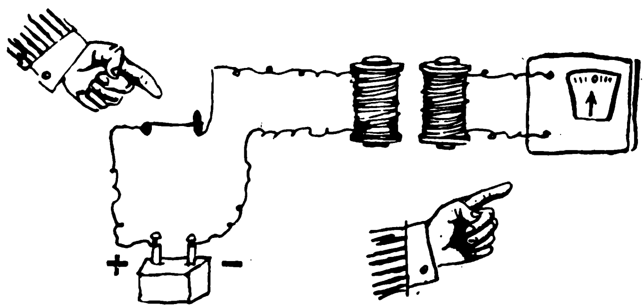
Thus radio began to be acknowledged, but nobody had yet heard of electronics.

Once again radio without electronics, for Popov's first radio stations had no electron valves!

About Wireless Communication

So, it turns out that for radio communication valves are not at all necessary.

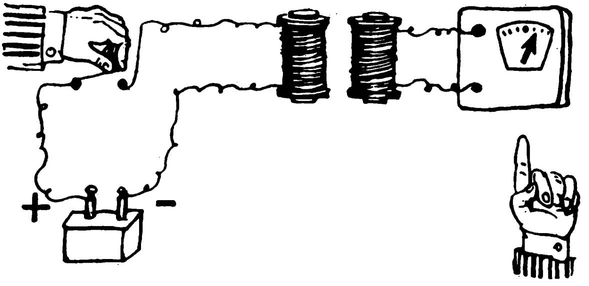
Evidently everyone has had something to do with a transformer. But hardly anyone knows that there is a radio communication between the primary and secondary windings.



Nevertheless it really exists: the secondary winding serves as the receiver of the waves which are radiated by the primary circuit.

Suppose that there are two coils put close one to the other. Let one of them be connected to the terminals of a battery, and the circuit of the other include a measuring instrument. When current flows through the primary winding, the pointer of the instrument reads zero.

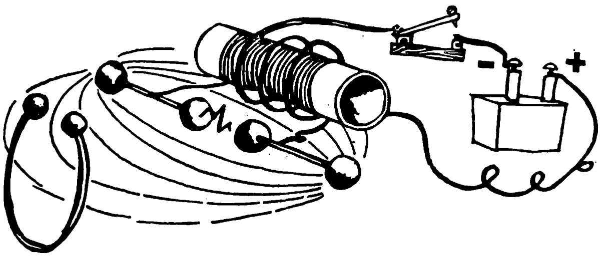
Now we disconnect the primary winding from the battery, and the pointer of the instrument connected to the secondary



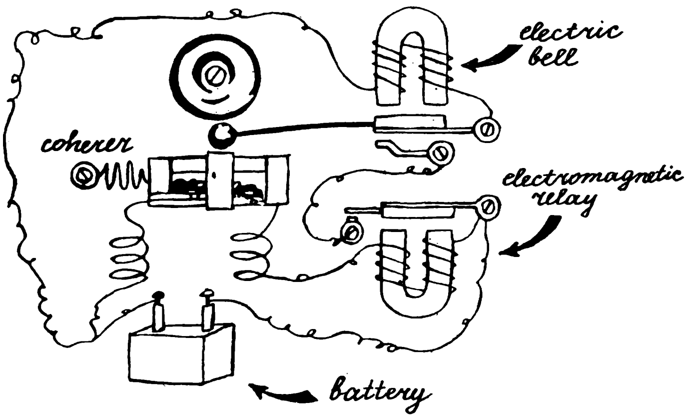
winding makes a short swing aside. Why? Because at the moment of disconnection the field of the primary winding changes and electric current is induced in the turns of the secondary winding located at a certain distance from the primary one. This can be observed any time, only the coils in all cases should be arranged close to each other and then such a peculiar "radio communication" will set in between them. In the transformer the windings are fitted on a common iron core, which serves as a favourable medium to establish a "reliable link" between the magnetic fields. If the current in the primary winding continuously changes, it will excite a varying field. This in turn will induce a varying current in the secondary winding (see II.19). In transformers the coupling between the windings is effected via the iron core, and in coils put close to one another, via the space separating them.

But cannot the windings be moved farther away from each other and still retain the coupling between them? It turns out to be quite possible. This is precisely what Heinrich Hertz proved with his famous experiment. True, to increase the coupling the ordinary coils had to be abandoned and replaced by a special dipole, while the field in the space surrounding the dipole was produced with the aid of sparks. The spark flashed between two spheres which received a definite charge.

Already in the experiments with Leyden jars it was noticed that the spark jumping between the linings of the jar behaves in a strange way: during a brief instant it changes

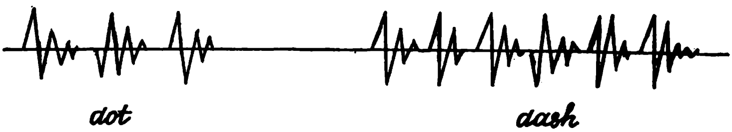


its direction several times and, consequently, the signs of the charges at the two linings also change the same number of times. *The spark gives birth to oscillations.* This is what Hertz proceeded from in his experiments.



Near the discharging device he placed the loop of a second dipole with other spheres at its ends. The field produced by the spark induced current in the loop, and a weak spark also flashed between the spheres of the second dipole. To increase the coupling between the radiating and the receiving dipoles, Hertz placed them in the foci of special reflectors.

Taking as a basis Hertz' experiments Popov developed the first radio station, the operating principle of which was described in hundreds of newspapers, magazines and books. Like in Hertz' experiments a spark jumped between two electrodes when they were being brought close to each other. Radio waves spread from it in all directions. To couple the receiver and the transmitter Popov employed antennas and the principle introduced by him is valid to this day. The waves taken up by the receiving antenna caused particles of metal in a so-called coherer to come closer together and the



conductance of the coherer greatly increased. Then a relay responded, giving the coherer a "light shaking", and the particles again fell apart inside the coherer until the arrival of the next "burst" of radio waves.

This simple device had one shortcoming—the signal was too short. The spark flashed over instantaneously, and the waves which it produced decayed having hardly emerged.

What can be transmitted by such signals? Only a telegraphe code: dots and dashes. To transmit the human voice is much more difficult. To do this it is necessary to produce undamped radio waves, to learn how to make the sound "ride" the radio waves and, on having caught these waves with the receiving antenna, to amplify them so that they could drive the cone of a speaker, reproducing the sound.

It was for the purpose of radiating continuous signals and amplifying them that Lee de Forest developed his famous triode.

And it was then that electronics was born.

Incidentally, we cannot find the term "electronics" in the dictionaries and catalogues compiled in those days. The term appeared later. And still, the valve and cathode-ray tube were the first two shoots of electronics from which was destined to grow a tree which yielded a plethora of unexpected and wondrous fruit.

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CHAPTER III. ELECTRONS, WAVES, FIELDS

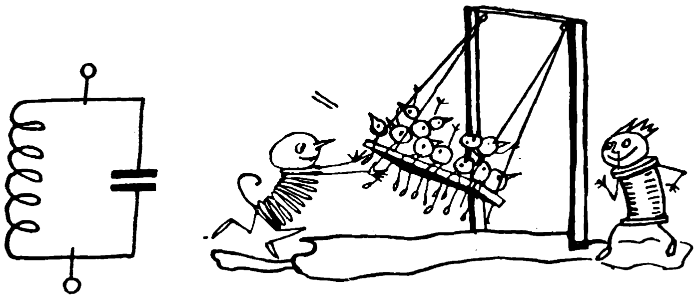
HOW ELECTRONS CAME TO BE-CONTROLLED WITH THE AID OF A FIELD. ABOUT THE CO-OPERATION BETWEEN WAVES AND ELECTRONS, WHICH GAVE BIRTH TO WORLD-WIDE RADIO COMMUNICATION.

THIS LIES AT THE BASIS

III.1

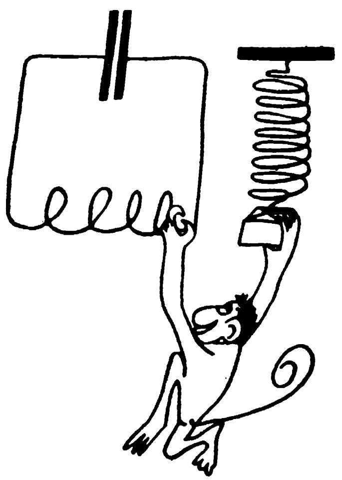
A coil and a capacitor connected in parallel form an oscillating circuit which plays a prominent role both in electronics and radio.

Within the circuit oscillations are born, which are similar to those of a pendulum or a taut string. But the pendu-



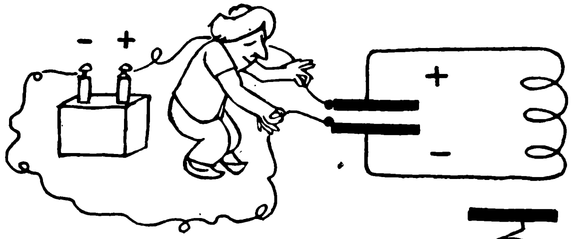
lum and the string oscillate themselves, while the components of the oscillating circuit are motionless. Here oscillations are produced by electrons—it is electric current that oscillates.

III.2



Formal resemblance may sometimes be misleading. In this device the spring, which outwardly looks like a coil, actually plays the part of the capacitor. And the weight suspended from the spring, though bearing no resemblance to the coil, has much more in common with it. The weight possesses inertia. The coil also does. Those who have forgotten what inertia is due to can take another look at Figures II.20 and II.21.

III.3

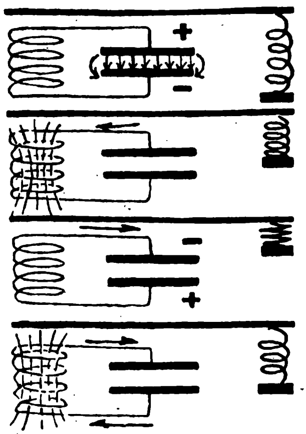


If a voltage source is connected for a short time to the plates of a capacitor, all the energy will first be concentrated in the capacitor. The spring with the weight suspended from it will be in a similar condition, if the spring is first stretched out and then the system is released.

III.4

The spring will begin contracting, the weight will return to its former position, but motion will not cease there: the inertia of the weight will cause it to continue moving upwards and, having compressed the spring, the weight will again turn all the energy over to it.

The same thing occurs in the oscillating circuit. The capacitor has given up all its energy, but the current in the circuit does not cease to exist. It keeps flowing "by inertia". Its direction is still the same (the weight is still moving upwards). On the upper plate of the capacitor the crowd of electrons grows denser and denser. At first they



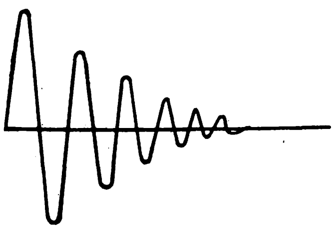
have reduced the positive potential to zero, but the current continues to flow "by inertia" and the zero gives place to a negative potential. At the same time a positive potential is built up at the opposite plate.

Formerly the spring has been stretched, and now it is compressed. The plate charges have become redistributed, and the plates have changed their sign.

When the spring is compressed to the utmost, a moment comes when the direction of the weight motion is reversed: formerly the weight has been moving upwards, now it will begin moving downwards.

After the capacitor has acquired a charge of the opposite sign, the current changes its direction*.

III.5



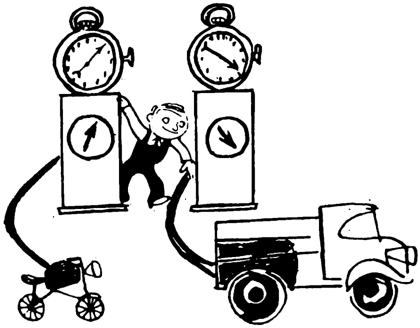
Again the weight reaches its initial position and then stretches the spring by inertia. Again the "plus" and "minus" signs at the capacitor plates have reversed.

The system has returned to its initial position (see III.3). The cycle (or period) of the natural oscillations of the circuit has been completed.

Why "natural"? Obviously the reader has already noticed that an extraneous source has been required only at the very beginning of the process (see III.3). Then it has been disconnected, but the circuit gets along on its own, it produces

* All the figures show the technical direction of current.

its own oscillations which have their natural frequency. The cycle is repeated many times over, the system several times passes in succession through the positions shown in Figure III.4, but each time the swing of the oscillations will become smaller and smaller, and finally they will cease completely.



III.6.

How long does each cycle of the oscillations of the circuit last?

This time evidently depends on the properties of the "spring" and the "weight". And indeed, the time of each cycle is determined by the capacitance of the capacitor and the inductance of the coil. The larger the capacitance, the longer the charging and discharging of the capacitor will last, and the larger the inductance of the coil, the slower will the current in the circuit build up and decay (see II.21).

III.7

The number of complete cycles (periods) per second of natural oscillations of the circuit determines its natural frequency.

With an increase in the capacitance and inductance the period becomes longer and the number of cycles per second decreases—the natural frequency falls down.

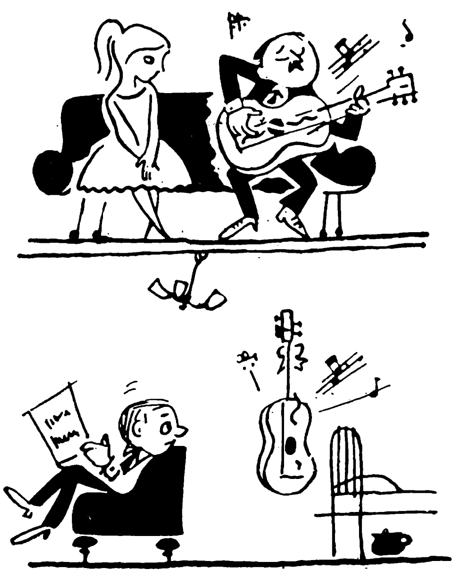
This relationship is expressed by Thomson's formula:

$$F = \frac{1}{6.28\sqrt{LC}}$$

In this formula F stands for the frequency (number of oscillations per second), L, for the inductance (in henries) and C, for the capacitance (in farads).

III.8

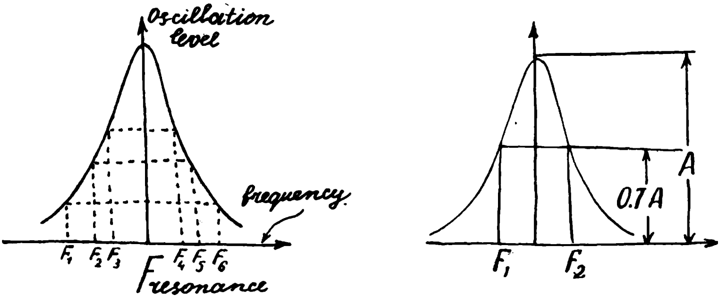
The phenomenon of resonance is familiar to all. For example, due to resonance a taut string responds to the sound



of another string. And the string will sound especially loudly if the frequency of the external sound corresponds to its natural frequency. An oscillating circuit behaves in the same way. The oscillations of current in the circuit will be especially powerful, if the frequency of oscillations (signal) applied to the circuit coincides with its natural (resonance) frequency.

When the frequency of the signal deviates to either side from the resonance frequency, the oscillations in the circuit will begin to decrease. This property is well illustrated by a bell-shaped curve. Such a curve is called the *resonance characteristic* of the oscillating circuit.

III.9



The circuit will not respond to signals whose frequencies are far from the resonant frequency. It is conventionally accepted that an oscillatory circuit freely passes signals with frequencies between F_3 and F_4 (at these frequencies the level of oscillations is 0.7 of that at resonance).

Singing Arc Oscillator

In the history of radio there was a time when it got along without electronics. But what sort of radio it was!

....World War I was raging. Two kilometres away from Khodynka Square one could hear continuous bursts of discharges—this was the Moscow radio station radiating signals of about 100 kilowatts power into the ether. A hundred kilowatt is not a low power. An ordinary electric heater consumes only about 0.5 kilowatt. But despite the high power, the station could transmit nothing but the Morse code converted into discharge sparks. Similar stations operated in other European cities. Ships of the navy also made use of radio telegraph communication. The signals transmitted by radio could easily be intercepted by the enemy. With their aid the Germans kept a watch on the manoeuvres of the English and the French. The Allies took the bearings of the German warships and tried to crack the secret codes of the transmitted commands.

And then something unusual happened: all the German stations went off the air. This caused panic in the headquarters of Russia, England, France: the Germans were, doubtlessly up to something, they were keeping secret some kind of a novelty.

The secret was unravelled by the prominent Russian scientist Mikhail Shuleikin. It turned out that the Germans had changed over to a continuous radiation of waves. But the receivers of the Allies were designed to catch spark telegraph signals: a spark at the transmitter, a click at the receiver. But here the wave ran continuously and carried with it traces of the Morse code, which the old types of receivers could not detect.

Shuleikin found a way which allowed the radiations of the new German stations to be deciphered with the old receivers. He suggested to interrupt the signal directly at the receiver input, i.e. to make it resemble the usual bursts of waves. And then with the arrival of a signal clicks could be heard again.

Subsequently it was learned that the first continuous waves were obtained by the Germans by means of a "singing arc oscillator". The oscillator was developed by the Irishman Duddell who took an oscillating circuit (see III.I) and began feeding it with a continuous stream of sparks.

To obtain the sparks Duddell made use of voltaic arcs. The oscillating circuit was tuned to audio frequencies and during operation the oscillator emitted a musical sound, whence its name of "singing arc oscillator".

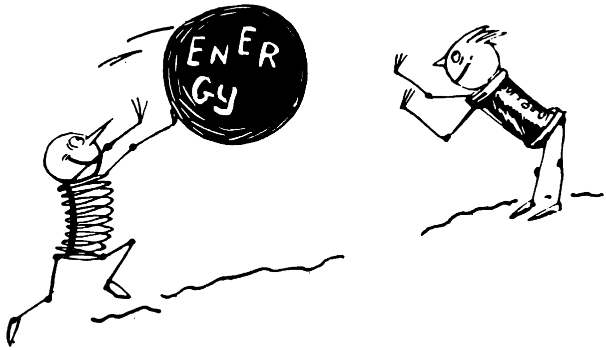
How Oscillations Are Born And Decay

The oscillating circuit is a very simple thing. A coil of wire and a capacitor connected in parallel (see III.1). Both components have been known to science for a long time. The capacitor is akin to the Leyden jar. The coil is the very same Ampere's solenoid (see II.15). But when the American scientist Thomsón made these components operate together, there occurred such processes which are of importance to this day.

The oscillating circuit gives birth to oscillations, a phenomenon with numerous analogues in totally different fields of engineering.

One could recall a pendulum, string, tuning fork, swing. Being given an initial impulse, all these devices will continue to oscillate at their definite natural frequency (see III.5).

A swing, string, pendulum oscillate all by themselves. The components of an oscillating circuit are stationary. Its



moving "parts" are invisible: in the circuit it is the electrons that oscillate, producing an *alternating*, *oscillating* current (see III.1).

The coil and the capacitor alternately transfer energy to each other, like tennis-players shuttling the ball.

However, it has long since been established that a "perpetuum mobile" cannot be developed. If the system is brought into motion, then due to friction a part of the energy will inevitably turn into heat. If the energy is not replenished by an external source, motion will cease, because finally all of the energy will be dissipated in the form of heat. Heat escapes into space, so that any "perpetuum mobile" will sooner or later come to a "perpetual rest".

For the same reason a pendulum or swing ceases oscillating. Friction between moving parts and the resistance of the air cause the swing, and the pendulum, and a weight suspended from a spring, to stop. In the oscillating circuit it is the electrons that move. Can it be that they are also affected by friction?

Yes, a peculiar kind of friction exists here too. The coil possesses resistance. Overcoming it, the electrons lose energy, and like in the case of the pendulum or swing, it is converted fully into heat. The oscillations weaken and finally cease altogether.

Radio is very much in need of current oscillations which, having once begun, would continue for a long time. They can easily be converted into continuous waves. And such waves can be used for transmitting anything: speech, music, images or, should it be necessary, an intermittent telegraph signal.

But how can continuous oscillations be obtained?

For this it is necessary to continuously "drive on" the oscillating circuit. What it is more, it is much easier to drive it on if the frequency of the driving impulses corresponds to the natural frequency of the circuit, and this will result in resonance.

But who is to drive it?

Again we need an oscillating circuit. For the driving impulses to run continuously, the oscillations in this circuit should not be damped. This means that again it must be "driven" in step with its natural frequency.

And who is going to drive it? Another oscillating circuit? But there will be no end to this chain. And cannot the chain be formed into a ring?

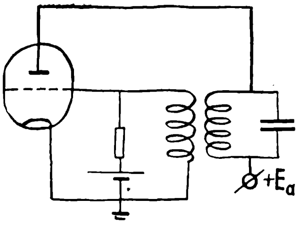
Why Do Rivers Flow?

There is hardly a living soul in the world who does not like rivers. People like rivers because they provide fishing, on a hot day they quench thirst and bestow coolness, and in winter they turn into ski trails and merry ice rinks.

And we also like rivers because they never stand still, that unforgetful, majestic and eternal which finds its reflection in the ceaseless motion of water fascinates us. Days, years and centuries pass, but the water in the river flows on and on. Where from? Where to?

And indeed, whence and whither? This is not poetry, but a serious question.

Everyone knows that rivers run from their source and fall into the sea. But if for ages on end the river gives all its water to the sea, and does not run dry, where then does all the water come from?



It comes from the sky in the form of rain and snow. The sky gets it from lakes and seas and oceans. And that which is lost by the lakes, seas and oceans due to evaporation is again replenished by the rivers. Of course, the reader has already understood why we interrupted our talk about oscillations in a circuit and suddenly recalled the cycle of water in nature. You see, in the motion of rivers there is precisely what we have lacked for maintaining undamped oscillation—a closed circle. From the ocean to the cloud, from the cloud to the river, from the river back again to the ocean.

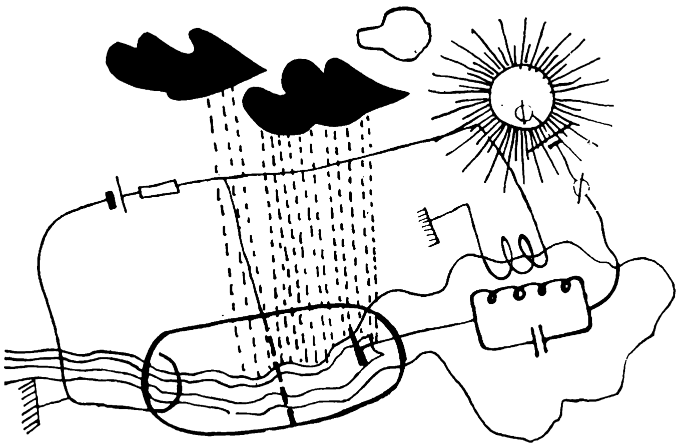
This is exactly how an oscillator operates. The oscillating (tank) circuit is connected to the anode of a triode. For the oscillations not to decay, some of the oscillatory energy from the anode circuit is fed back to the grid of the triode. On being applied to the grid, the oscillations begin controlling the current flowing through the triode. The oscillating current will drive the tank circuit connected to the anode of the valve. As often as the oscillations in the tank circuit are repeated, so many times will the control voltage of the grid change. With every cycle there will occur a surge of anode current that will "drive" the tank circuit in step with its natural frequency. Instead of an endless chain we have a closed circle.

The oscillations, having once developed in the tank circuit, on being applied to the grid, will be amplified and will drive the tank circuit even harder. And from the tank circuit, back to the grid, and from there, again to the anode.

In an amplifier the anode current depends on the signal applied to the grid of the triode (see I.25-I.34). In an oscillator, in addition to this feedforward, there is also a *feedback*; some of the energy from the anode is fed back to the grid, and the valve begins amplifying its own signals.

Such a mode of operation electronics specialists call *self-excitation*.

In the cycle of water in nature, which we have examined, it is also possible to find a certain "feedback". Filling of the seas and oceans by rivers is the feedforward. Filling of the rivers by rains from the evaporation of bodies of water is the feedback. But where does the energy come from in the cycle of water and in the generation of electrical oscillations? In the first case it comes from the Sun. And in the second case, from a source of direct current which supplies the anode. And so, the source is, as it were, the Sun, the anode tank circuit, the sea, the electrons flowing from the cathode to the anode, the river, and the part of the



energy fed from the anode back to the grid is the rains. In this cycle the energy of the d.c. source is converted into that of continuous oscillations.

Only a certain part of the direct current can be converted into oscillations: the oscillator always consumes more energy than is contained in the oscillations it produces. If at least half the energy drained from the d.c. source is converted into oscillatory energy, it is considered that the oscillator is operating well. Incidentally, from our, terrestrial point of view the Sun expends energy much less rationally: nearly all of it is dissipated in space, only an insignificant amount reaching us.

In our oscillators, however, about half the energy of the source is converted into oscillations. The other half is wasted. But losses can be borne, if justified. And here the aim is clear: the alternating, oscillating current generated in the oscillator can be fed to an antenna, producing around it an electromagnetic field in the form of radio waves propagated in all directions.

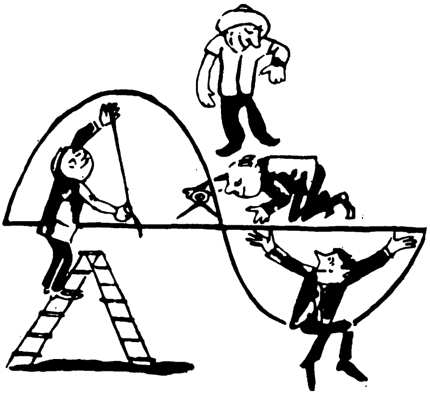
THIS LIES AT THE BASIS

III.10

The very same mathematical equations describe oscillations of current generated in a radio circuit, waves rippling across the surface of a lake, vibration occurring in the wings of an aircraft due to the action of air streams, oscillations of a pendulum, sound, and so on.

As far as physics is concerned these phenomena are of different nature.

III.11



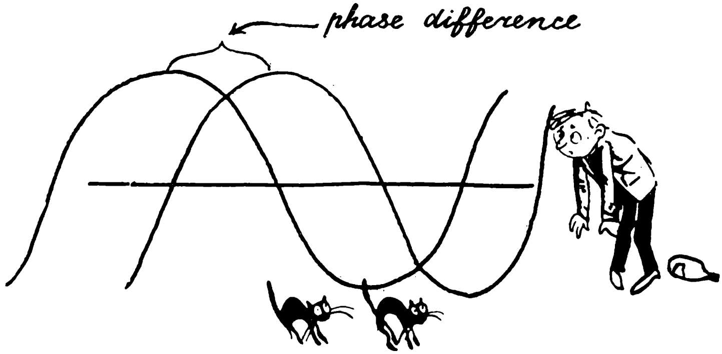
But they also have a common feature. All of them are periodic sine-wave oscillations which are characterized by three quantities: amplitude, phase and frequency.

By *amplitude* is meant the maximum deviation from the median position (frequently this is the zero position).

By *frequency* is meant the number of cycles per second. As for phase...

III.12

As long as a single sinusoidal process is being considered, the phase is usually disregarded. But two oscillations of the same frequency and amplitude may differ in phase. To compare such oscillations the notion of *phase difference* is introduced.

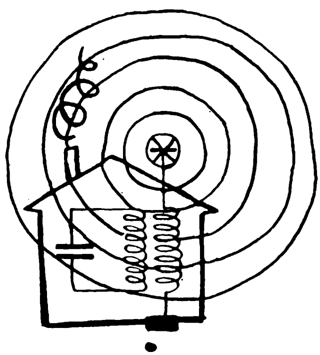


If the phases of two oscillations differ, this means that the crests of two waves arise at different times, that two swings pass through the extreme and medium positions at different moments.

Despite the fact that the oscillations are of the same frequency, they will now trail each other, now run counter, because there is a phase difference between them.

This is exactly how alternating currents behave, produced by two a.c. sources with a certain phase difference.

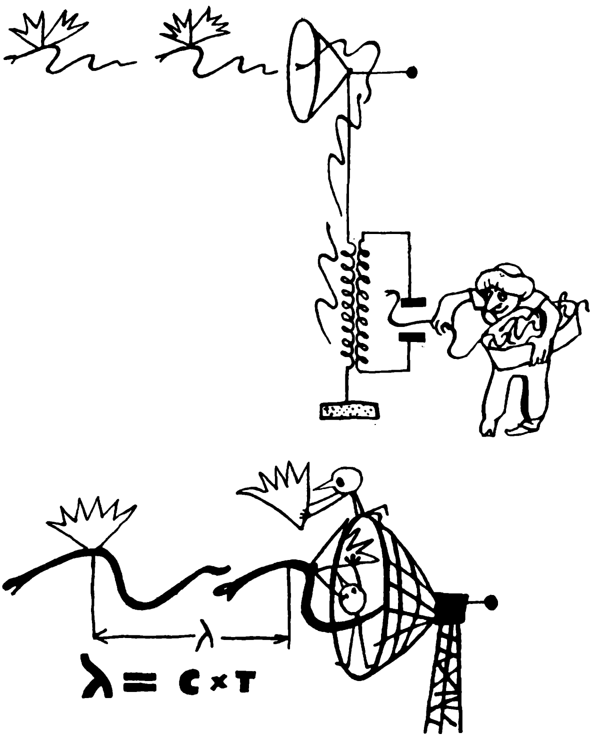
III.13



If an antenna is coupled to a tank circuit in which electrical oscillations occur, the motion of the electrons in the antenna will be reminiscent of a sea surf: the electrons in the antenna will "flood" and "ebb" in step with the oscillations in the tank circuit.

With every "flood" the intensity of the electromagnetic field surrounding the antenna will increase, forming the crest of the waves.

III.14



After a lapse of time T equal to one period of the oscillations in the tank circuit the "flood" will be repeated, forming another crest. At the same time the preceding crest will run away from the antenna at the speed of light C and during time T will cover a distance of $C \times T$.

So, a crest has just arisen in the antenna, but the preceding one is already at a distance of $C \times T$. The wavelength λ is the distance between adjacent crests: $\lambda = C \times T$.

III.15

The less frequently the "floods" are repeated in the antenna the farther one crest travels before the next one is formed. In other words: *the lower the frequency of the oscillations in the tank circuit, the longer the radiated wave.*

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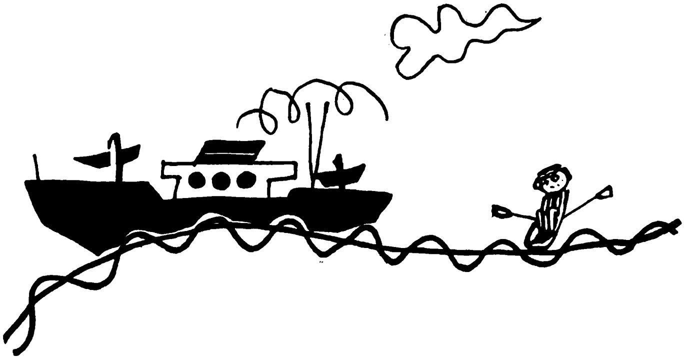
This relationship we shall have to recall very often. To understand it better let us give the following example: the frequency of the roll at sea will be the less, the greater the length of the wave.



III.16

Runners will help us establish the exact relationship between the wavelength λ and frequency F of the oscillations.

If it is known that a runner makes n strides every second and that the length of each stride equals l, it is very easy to calculate his speed V: the length of each stride must be multiplied by the number of strides made per second.

Thus, $V = l \times n$.

The "stride" of an electromagnetic wave is its wavelength λ.

The number of "strides" is the number of periods (cycles) per second F.

The velocity of propagation of waves is also known—it is equal to the speed of light C.

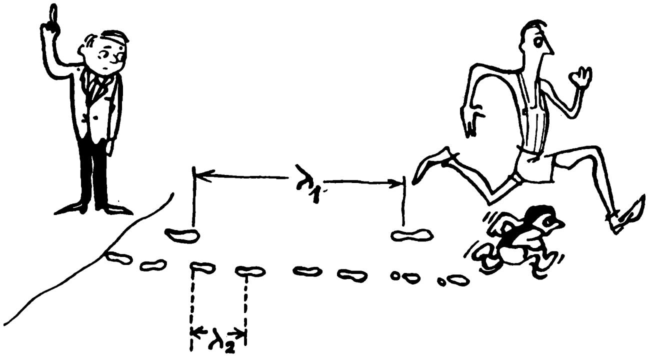
Just as in the case of the runner, the speed is determined by multiplying the length of the "stride" by the number of "strides" per second:

$$C = \lambda \times F$$

This formula may be used to determine the frequency of oscillations if the wavelength is known:

$$F = \frac{C}{\lambda}$$

To get a better grasp of this relationship, it is worth-while to return once more to the runners. Say, they are running at the same speed, despite the fact that the strides of the smaller one are shorter and those of the taller one, longer. But then the little one makes more strides per second.

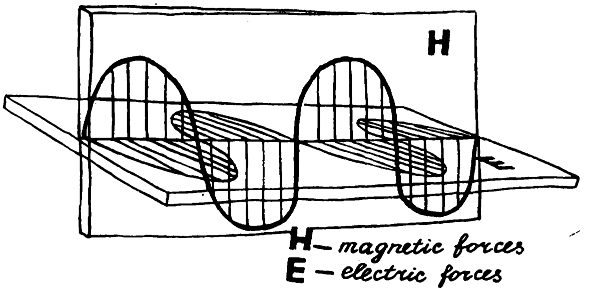


The same is true with waves: the shorter the wavelength, the higher the frequency (number of "strides" per second). But the speed of propagation of waves in space is always the same: 300 000 kilometres per second regardless of the wavelength.

III.17

This is how James Clerk Maxwell first pictured electromagnetic waves to himself. Two sine waves here represent simultaneous oscillations of electric and magnetic forces inseparably bound in space and time.

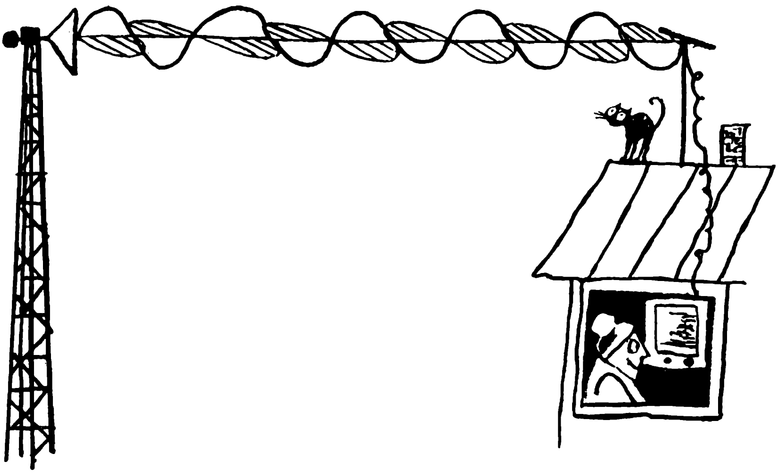
These forces act at right angles to each other, therefore in the conventional representation of electromagnetic oscillations the sine waves are located in two planes.



Overcoming great distances, the wave becomes ever weaker, but no matter how much energy remains, it is equally shared between the two equivalent components of the wave.

III.18

The waves employed in television look just like those shown in Figure III.17. The magnetic forces act in the vertical plane. The wave causes current to be induced in the



receiving antenna, if the magnetic forces cross it transversely. (Those who have forgotten what is meant by induction should look at the Figure II.18.) That is why television antennas are always arranged horizontally.

In the waves used for radio communication the electric and magnetic forces have, as it were, changed places (in this case a specialist would say that the plane of polarization of the waves has turned through 90 degrees). Therefore, to improve reception the radio antennas of cars are always arranged vertically.

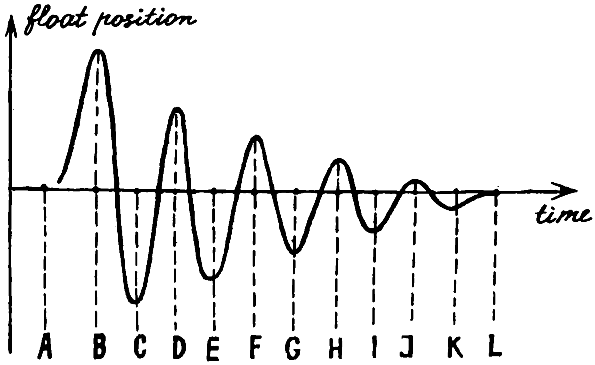
For Mathematics It Makes No Difference

For mathematics electromagnetic waves are not something unusual. It regards this phenomenon only as a particular case out of a multitude, one kind of oscillations which occur in nature at every turn. Mathematics studies oscillations irrespective of their concrete nature. For mathematics it makes no difference what is oscillating: a string, water, pendulum, air, or electric and magnetic forces bound together in electromagnetic waves.

Mathematics describes all these phenomena by the same formulas and the same curves.

And there is no need for us to immediately begin considering the intangible radio waves. It is better to begin with waves that we know well, the waves on the surface of water.

Imagine the following picture. You are sitting on the bank of a lake angling and keeping your eye on the float.



The water is calm and the float, motionless. Then, flashing its scales in the sun, a large fish has leaped out of the water nearby. Plopping back into the water it sets up rings on the surface, and when the first crest reaches the float, it begins bobbing up and down.

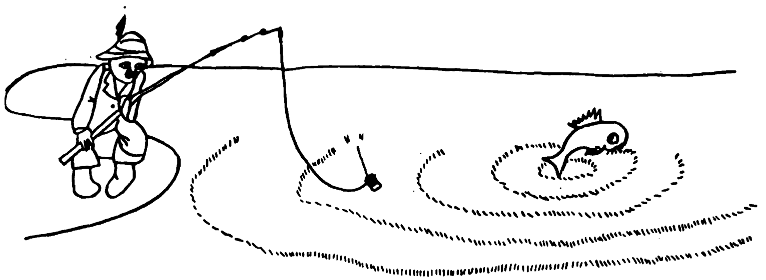
It's a thrilling moment. It seems that the float might go underwater any minute. But no, the waves become weaker and, finally, the float is again motionless on the calm water. And you feel regret that the fish hasn't bite.

Practically the whole story is represented by just such a graph. It takes account of the float and the fish. Probably, the only thing that is not represented are the emotions of the angler.

Point A is the moment when the fish splashed down. After a certain period of time the crest of the first wave has reached the float (point B). The crests and troughs follow one after another, causing the float to bob (points *B*, *C*, *D*, *E*). But gradually they become weaker and at last disappear completely (point *L*).

This is what the *process of decay* of oscillations shown in the graph (page 117) looks like.

If the fingers of a musician strike a string, each part of it will behave exactly like the float. The curve we have just considered can be used here equally well. But the scale



will be different, because the oscillations of the string differ from those of the surface of the lake both in *amplitude* and *frequency* (see III.11).

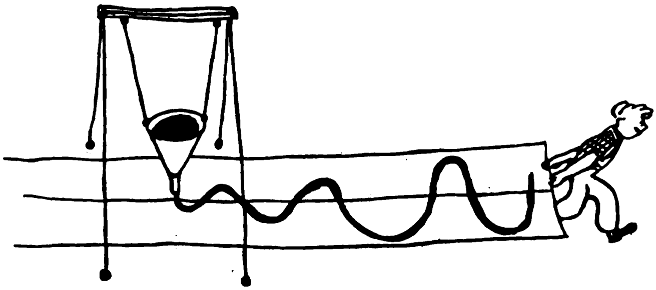
By amplitude is meant the maximum deviation of some point on the string or of the bobbing float from the median position. In our graph each subsequent oscillation has a smaller amplitude, because we are considering a damped process.

Now we shall have to recall once more the oscillating circuit in which an electric pulse causes natural-frequency oscillations with decreasing amplitude (see III.4 and III.5). Another pleasant surprise—the process occurring in the oscillating circuit can be described by the same curve!

If you wish, a swing will produce the same kind of curve. After the initial push the amplitude of the swing will decrease time after time and the curve produced will be very much like those for the oscillating circuit and the float. But is it possible for the oscillations not to decay and for the amplitude to remain constant? Of course. For this purpose an external source of energy is required which would push the swinging (oscillating) body in step with its natural frequency.

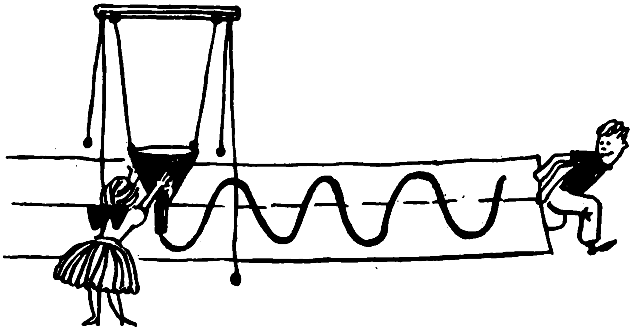
In the case of the swing this problem is solved simply: one more person is required who would keep pushing the swing continuously with the same force. Then the motion of the swing would be represented by an undamped sine wave.

In radio engineering the triode takes the part of this extra person. The oscillatory process occurring in an oscillator is



the very same sinusoidal process. The swing moves first to the left and then to the right. During each period of the oscillations the current in the circuit reverses in exactly the same way.

Thus, phenomena of entirely different nature may be represented by the same curves.



To The Assistance Of A Weak Voice

The antenna connected to the tank circuit of an oscillator is like the fish that has splashed down into the lake: rings of invisible radio waves spread from it in all directions (see III.13).

And the float that bobs on the waves is another antenna, the receiving one, in which according to the laws of induction the radio waves will induce an alternating electric current. The waves travelling from the transmitting to the receiving antenna can carry the sounds of music, speech, television pictures, the Morse code or any pulse code. Thus

the invisible, but durable threads of radio waves have linked all those who are now inhabiting the Earth.

Until radio waves were developed the human voice was extremely weak. A shout can be heard at a distance of one kilometre, and even then, on condition that it will not drown in extraneous noise. Small wonder: even with the aid of sound detectors the loud rumble of engines can be heard at a distance of not more than ten kilometres.

But "astride a radio wave" even a whisper can be heard all over the world.

Why? Because on their way from the transmitter to the receiver radio waves do not weaken as intensely as sound waves do.

And besides, with the aid of electronics, radio waves can be amplified.

Sound waves are elastic oscillations of the air. A string of a certain length produces a pure tone. At regular time intervals compressed layers of air—the crests of the waves—will pass a person sitting in a hall. If 100 crests a second pass the listener, this means that the frequency of the audio (sound) oscillations is 100 hertz*. Incidentally, the human

* The units adopted for measuring the frequency of radio waves obtained by Hertz are now being successfully used to characterize all types of oscillations and waves, including sound waves.

ear can sense sounds with frequencies from 16 to 16 000 hertz. Persons with highly sensitive hearing can perceive sounds with frequencies up to 40 000 hertz.

To appreciate the energy of the sound produced by the voice the following comparison can be made. The sound energy of 100 000 people speaking simultaneously does not exceed

the energy consumed by the lamp of a flashlight. And the sound energy of all the people on the Earth speaking simultaneously does not exceed that of the engine of a small car.

Not possessing high energy, the sounds produced by the voice or musical instruments are dampened by the elastic air and fade away.

By using sound resonators sound can only be amplified several times. And in modern receivers signals can be amplified 10^{14} to 10^{17} times (i.e. 100 trillion to 100 quadrillion times!)

And there is another shortcoming of sound communication: a sound emitted in Moscow would reach Delhi or New York only many hours later.

To save time and strength on a distant journey man avails himself of transportation.

Radio waves are a very convenient means of transportation for sound. The speed of a railway express is nothing compared to it: every second a radio wave can circle the globe along the equator nearly eight times!

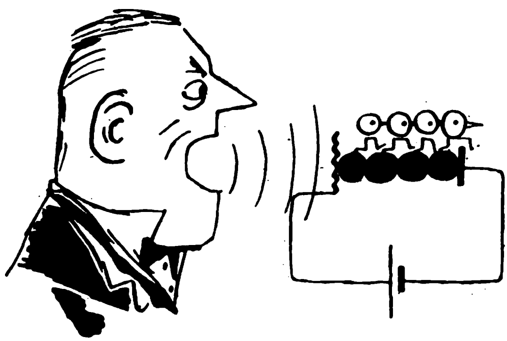
Electrons And Sound

To transmit sound by radio one must first convert the sound waves into an alternating electric current. This is done by microphones.

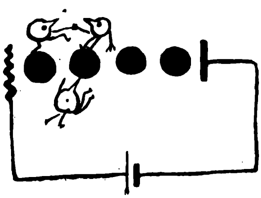
A microphone is a fairly simple device, but if an electronics museum were ever to be established, one of its halls could rightfully be set aside for microphones.

They would provide the visitor with an example of how it is possible for one practical aim to make use of various physical phenomena investigated in different countries and at different times.

Here is a microphone which makes use of the law discovered by Ohm and bearing his name.



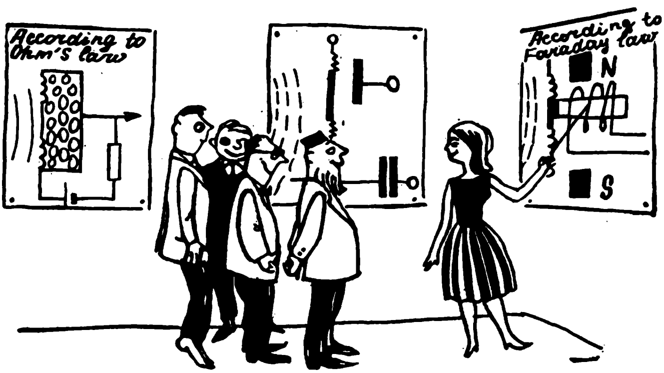
A membrane vibrates due to the action of sound oscillations. When the pressure on it increases, and this happens when the crest of the wave arrives, it compresses harder a layer of carbon powder put behind it. The carbon particles are pressed harder together and can pass electric current with greater ease. At this moment the current increases. As often as the wave crests and troughs arrive at the membrane, so many times will the electric current in the micropho-



ne circuit increase and decrease. With constant pitch of the sound the current will vary sinusoidally with the sound frequency.

It is not for nothing that mathematics has approached all oscillations with the same "yardstick": it is indeed possible to proceed from one oscillatory process to another, retaining the characteristics of the oscillation—their amplitude and frequency.

And here is another type of microphone. This makes use of the laws of induction established by Faraday. A membrane makes a coil oscillate. The coil is in the field of a



magnet. On intersecting the lines of force of the magnet, a current is induced in the windings of the coil. The frequency of the current is equal to the frequency at which the membrane oscillates. The amplitude is the greater, the harder the membrane is vibrated by the sound wave.

And then there are microphones in which sound causes the capacitance to vary. And this in turn causes current to vary.

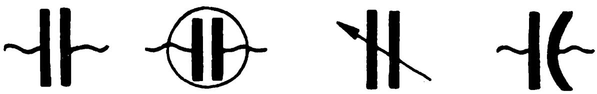
As you see, the methods are various, but the result is the same: sound produces current oscillations of the corresponding frequency.

III.19

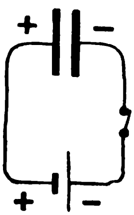
What will happen in the streets of a city, if all the traffic signs are taken away? This is not very hard to imagine: each crossing will become the site of innumerable accidents.

It turns out that in any electronic circuit which amplifies alternating signals there are also dangerous crossings. Instead of traffic signs such crossings are provided with capacitors.

By controlling the traffic of electrons, they help avoid accidents.



III.20

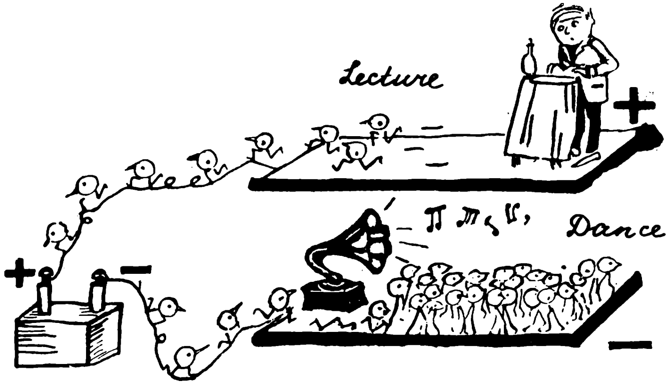


A capacitor is a simple device. In its simplest form it consists of two parallel plates separated by a layer of air. Everyone knows that droplets of moisture condense on the surface of cold glass. An electric capacitor (also known as condenser) connected to a voltage source condenses charges on its plates. That is why it is used as a "reservoir" when controlling an electron beam.

When the capacitor is connected to a d.c. source, electrons are accumulated on one of the plates, which then carries a negative potential.

From the other plate electrons leave along the external wire. The potential at this plate becomes positive.

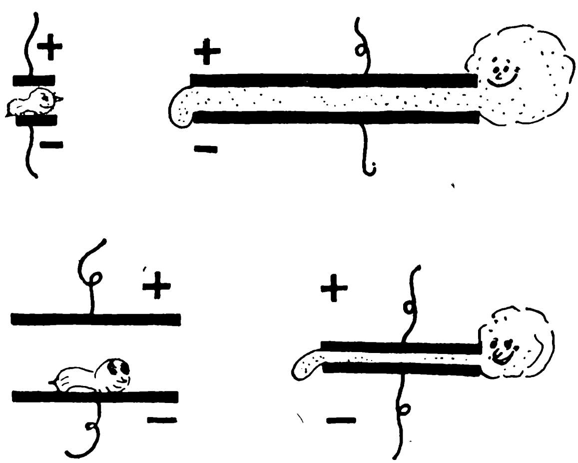
The capacitor becomes fully charged, when the potential difference between its plates equals the voltage of the battery that it is connected to.



II.21

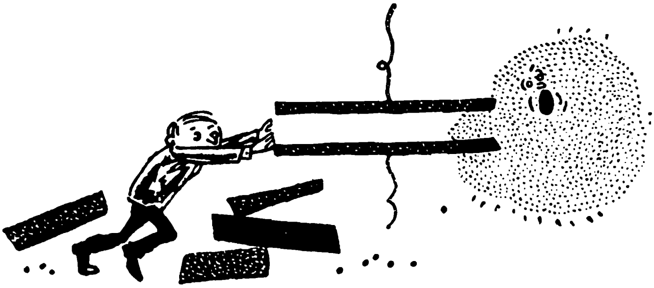
The magnitude of the charge accumulated by the capacitor depends on its capacitance. The capacitance will be the greater, the greater the area of the plates.

The capacitance also increases if the plates are brought closer together. However, in this case a breakdown may occur: at high voltages a spark may flash between the plates arranged close together.

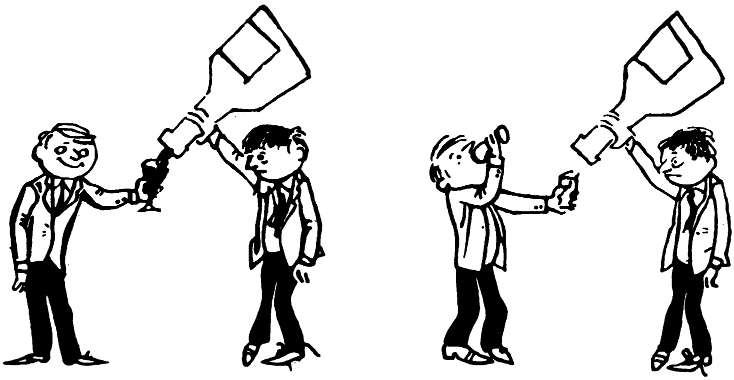


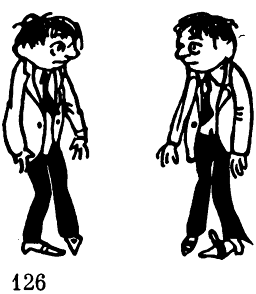
III.22

The capacitance of the capacitor can be increased many times without increasing its size by using an insulator to separate the plates. The insulator is made of special materials such as mica, ceramics, polysterene.



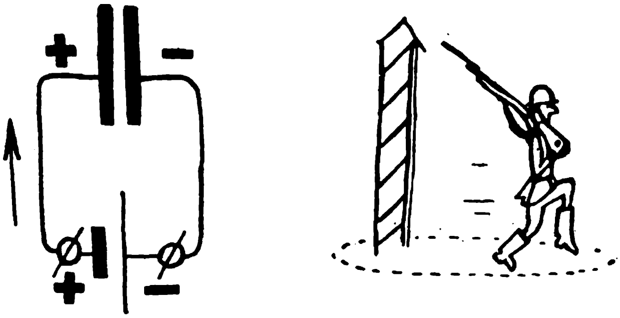
III.23



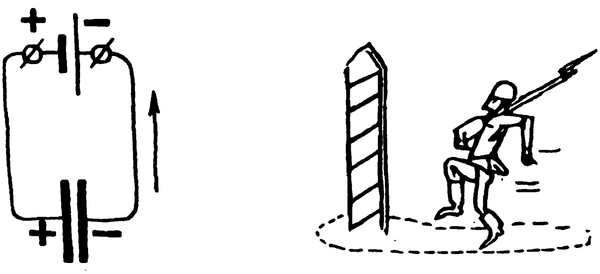


In a circuit consisting of a capacitor and a d.c. source current flows only while the capacitor is being charged. When the voltage across the capacitor equals that of the source, the current in the circuit ceases to flow.

III.24

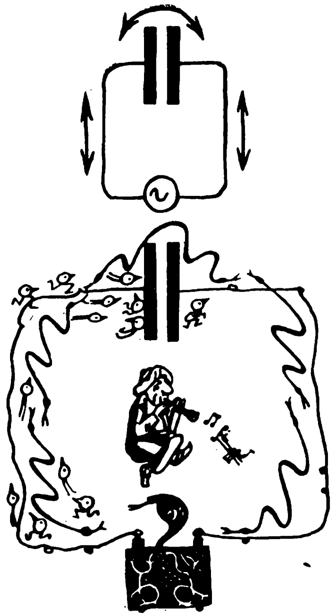


If in the same circuit the terminals of the voltage source are interchanged, then recharge of the capacitor will occur. Current will flow in the opposite direction until the voltage across the capacitor equals that of the source, and in this case each of the capacitor plates will acquire a charge of the opposite sign.



III.25

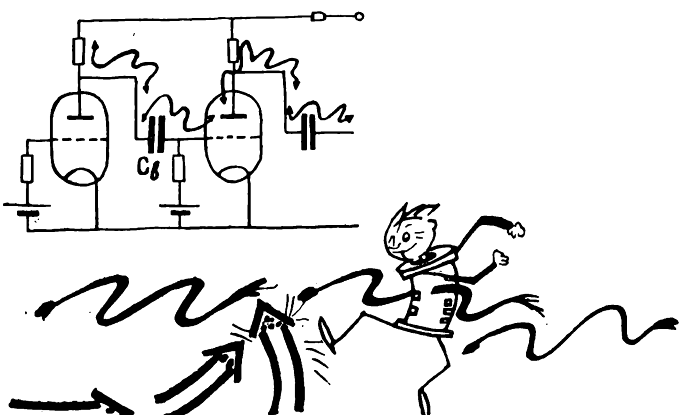
If the capacitor is connected to a source of voltage which alternates, say, 1000 times a second, this means that the sign of the charges on the plates will reverse 1000 times a second and the current in the external circuit will also reverse 1000 times a second. Since the current in the circuit does not cease to flow, it is considered that the capacitor "lets through" alternating current, although in fact no current flows through the capacitor. Not a single electron passes through the layer of insulation separating the capacitor plates. The electrons move only in the external circuit.



In the case of direct current the picture is totally different. The capacitor charges only once and then the current ceases to flow, since not a single electron can overcome the space between the plates. In a circuit including a capacitor direct current does not flow.

III.26

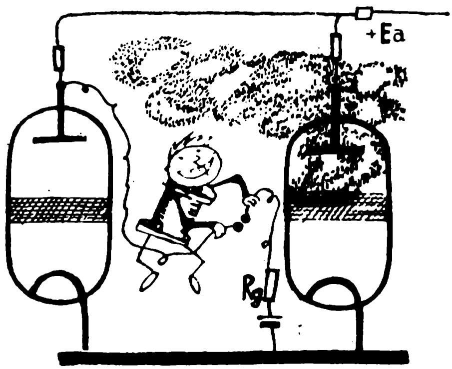
Electronics makes wide use of this property of the capacitor. Capacitor C_b is placed "on the crossroads" of direct and alternating currents between the anode of one valve and



the grid of another. Such a capacitor is called a blocking capacitor: its purpose is to separate the direct and alternating currents.

Opening the road for the alternating current from the anode to the grid of the following valve, it simultaneously blocks the road for the direct current.

III.27

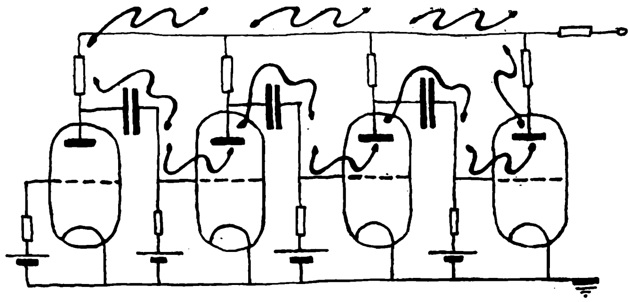


It is sufficient for the plates of this capacitor to come into contact (for example, in the event of a breakdown), and an accident is inevitable: the high anode potential will set up a heavy current through the grid resistor (R_g). The potential of the grid will become equal to that of the anode and the valve will get out of order.

A normally operating capacitor will let pass alternating currents only. That is why it lets flow freely through it the amplified signals to the grid and blocks the way for direct current.

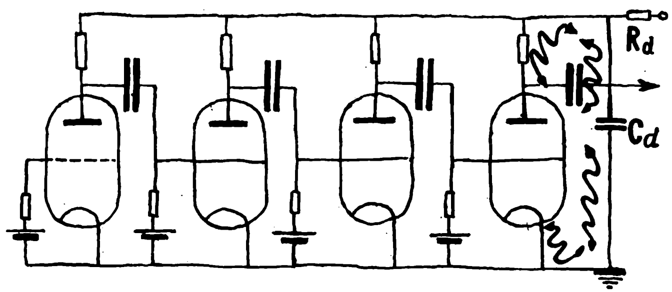
III.28

Another kind of accident may occur if alternating currents flow freely from the anode to the source of the anode voltage. From the last stage a powerful signal can return via the common supply source to the first stages, and then the amplifier is covered by a parasitic feedback. Such an amplifier cannot amplify incoming signals, but begins generating its own oscillations.



To avoid this accident use is made of decoupling capacitor C_d.

For alternating currents it presents a very low resistance, and if the anode circuit of the valve is connected via the capacitor to earth, then the alternating component of the anode current will easily pass via the capacitor to earth and will not get to the common supply source via decoupling resistor R_d.



Excessively Long Waves

How does a radio station operate? It would seem that now we know everything, and we can easily answer this question. Yet...

The microphone converts sound into a varying current. The alternating current fed to the transmitting antenna is radiated into space in the form of radio waves. The radio waves induce currents in the receiving antenna. These can be amplified by means of electron valves. The energy of the amplified current causes the cone of a speaker to vibrate. Isn't this quite enough?

What is lacking is, probably, the main link, without which all the other links cannot be united into a single chain.

"...This is radio Moscow. You will now hear a violin concerto performed by..."

The announcer's voice (the frequency of his sound oscillations lies within 80 to 8000 cycles per second) is followed by the sounds of a violin, which have a frequency of up to 16 000 oscillations per second, i.e. up to 16 kilohertz. (1000 hertz comprise 1 kilohertz, 1000 kilohertz equal 1 megahertz. These are the units that we shall use in future.)

But the receiver is tuned the whole time to the same frequency. To which one? To 80, 8000 or 16 000 hertz? Why is it that with a variation in the frequency of the sound oscillations the receiver does not have to be retuned?

We have just seen how sound is converted into oscillations of current, with the frequency of the oscillations equaling the sound (audio) frequency. But is it not this current that produces waves around the antenna? Are not these the waves that the receiver should catch and reconvert into sound?

If it were possible to radiate audio frequencies into the ether, then the problem would really be solved. Then it would have been possible to amplify the currents produced by the microphone and feed them to the antenna to obtain radio waves.

But the trouble is that the antenna can radiate waves into the ether only if its size is commensurable with the wavelength of the radiated waves.

Let us suppose that a sound is converted into oscillations of current, the current is fed to an antenna and the antenna radiates a wave. Knowing the velocity at which electromagnetic waves travel and the frequency of the current oscillations in the antenna, it is easy to calculate the length of the radiated waves (see III.16).

Sound can produce oscillations of current having a frequency of from 16 to 16 000 hertz. For 16 000 hertz the length of the electromagnetic wave will be close to 19 kilometres. Consequently, in order to transmit such waves it would be necessary to equip the transmitting station with an antenna several kilometres long.

And we have not as yet considered the lowest sound frequencies, which correspond to wavelengths of tens of thousands of kilometres!

But even if it were possible to construct such colossal antennas, the problem would still not be solved. Imagine that all the radio stations are simultaneously radiating audio frequencies within the range from 16 to 16 000 hertz. And your receiver is tuned to these very same frequencies. Instead of one broadcast you will simultaneously hear all the melodies and all the voices!

Fortunately, another method of radio communication has been invented. This method allows the receiver to be tuned to one of the multitude of stations and obviates the need of gigantic antennas.

Transmissions are conducted with carrier waves.

Invisible Express

To transmit sounds over a distance with the aid of radio broadcasting stations electronics produces special waves having lengths from 15 to 2000 metres, which correspond to frequencies from 20 000 000 to 150 000 hertz (i.e. from 20 megahertz to 150 kilohertz).

These frequencies are very low compared to, say, those of light, which equal thousands of millions of megahertz! At the same time they are too high to be audible like the sound is. But it is precisely these intangible waves, which cannot be either seen or heard, that serve as a wonderful "express" for carrying music or speech over any distance.

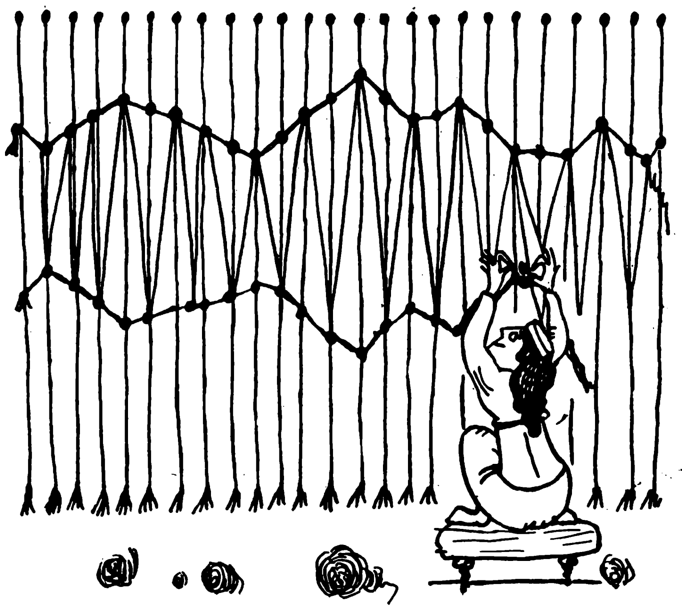
Before starting on its journey the sound, converted by means of a microphone into an electric current which oscillates at audio (sound) frequencies, "straddles" the above mentioned high-frequency signals. Hence the name of carrier signals. And indeed, they carry the converted sound signal first to the antenna and then, being converted into electromagnetic waves, through the ether to receivers tuned to the corresponding wavelength.

Strictly speaking, the sound in this case is carried "bit by bit" on the crests of the carrier wave. But the crests follow one another so quickly that the gaps in the "pattern" cannot be detected even with a highly sensitive electrical instrument. The same happens when you are admiring a tapestry or rug with an intricate embroidery, you do not notice that it is made up of tiny knots or crosses.

But to achieve this it is necessary that the canvas is not too coarse. For the same reason the frequency of the carrier signals should be many times higher than that of any sound. And so, for sounds with frequencies below 16 000 oscillations per second, carrier signals of not less than 150 000 hertz are selected.

But how is it possible to combine the two signals, to make the audio-frequency signal "straddle" the carrier one?

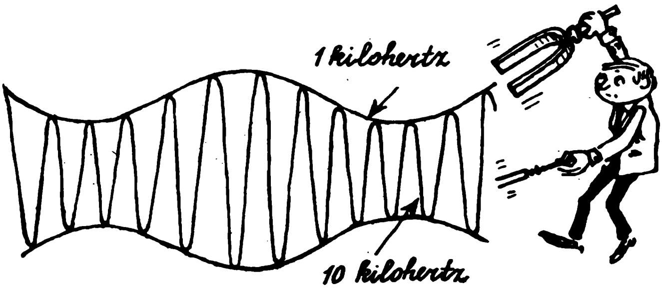
We, probably, have already begun getting used to the thought that whenever electronics is faced with a problem, the triode comes to its rescue.



III.29

The amplitude of damped oscillations decreases with time (see III.5). Continuous oscillations have a constant amplitude.

It is also possible to generate electrical oscillations, the amplitude of which will vary sinusoidally. If the frequency

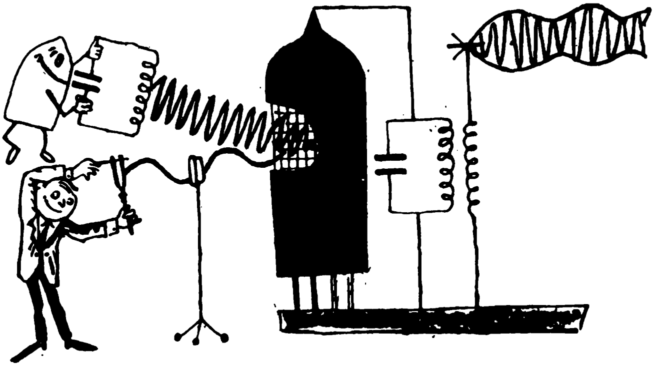


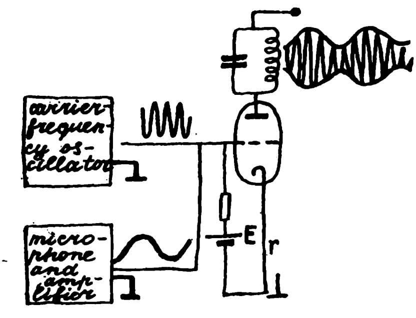
of the oscillations is 10 kilohertz and their amplitude varies with a frequency of 1 kilohertz, then it is said that the 10-kilohertz signal is amplitude-modulated at a frequency of 1 kilohertz.

III.30

An audio-frequency signal obtained from a microphone can, through modulation, be "put on the back" of a carrier signal produced by an oscillator. Both signals (carrier and modulating) are applied to the grid of a triode.

In this case the triode functions as a *modulator*.





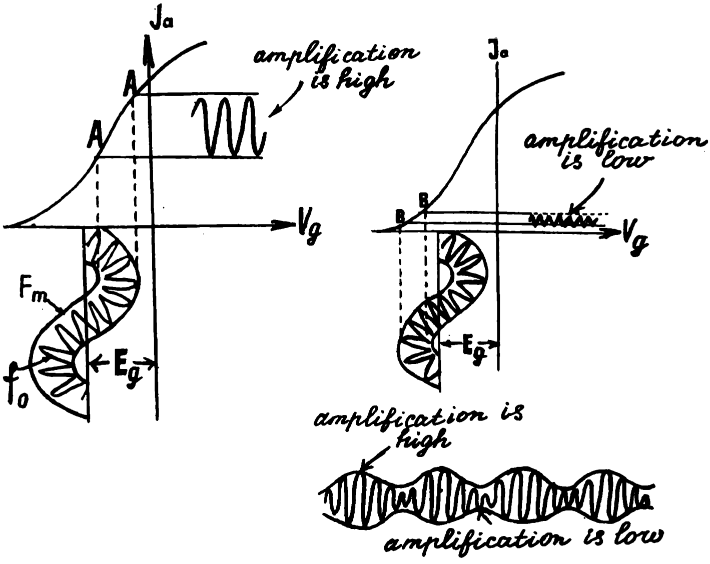
III.31

To understand the modulation process, we shall have to recall the characteristics of the triode (see I.31-I.34).

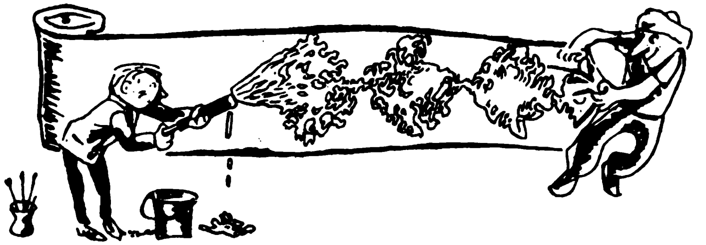
Two alternating signals are applied to the triode grid: the carrier signal with frequency f_0 and the modulating one of a lower frequency F_m. At a certain moment the sum of all the voltages at the grid (d.c. voltage from the grid battery E_g and two alternating voltages with frequencies of f_0 and F_m) happens to be such that the signals act within section *AA*.

At another moment the signals will act within section *BB*. Within this section the oscillations are amplified less, for the characteristic of the valve in this section is significantly curved.

The modulating signal "slides" along the characteristic curve with frequency F_m. This means that the amplification



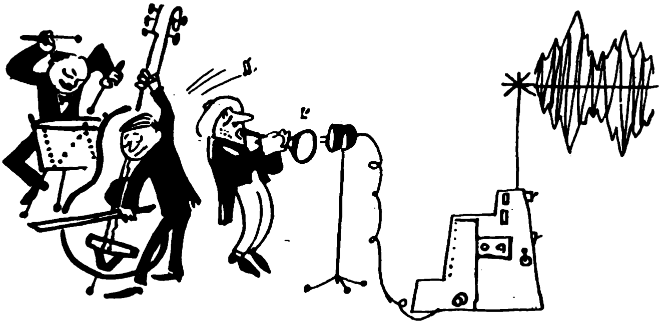
varies with the same frequency. As a result, the carrier signal varies in amplitude with frequency F_m as well. If there were no "curvature" then the amplification would be constant and it would be impossible to obtain an amplitude-modulated signal.



The d.c. voltage at the grid E_g is specially selected so as to get into the curved section of the characteristic, i.e. into its nonlinear section.

III.32

We have considered the process of modulation by a plain sinusoidal signal. When music or speech is transmitted, a more complex signal arrives from the microphone. But the essence of the process remains the same: due to the "curvature" the amplification changes and the complex signal is superimposed on the carrier signal. This superimposed signal contains the voice of the announcer or a singer, or the sounds of music.

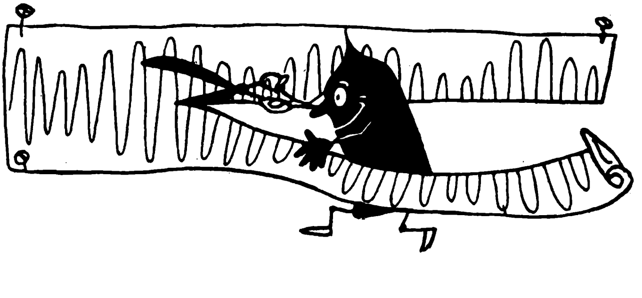


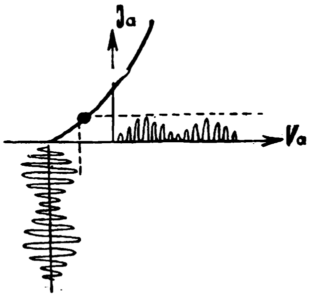
III.33

In the receiver the amplitude-modulated signal undergoes changes. It is subjected to an operation which is the reverse of modulation: the sound signal is separated from the carrier. Otherwise it would be impossible to convert the oscillations of the electrical signal into sound oscillations, since the speaker cone is far too clumsy and possesses too much inertia to react to oscillations with frequency f_0.

To actuate the speaker, it is necessary to supply it with audio-frequency signals only.

III.34





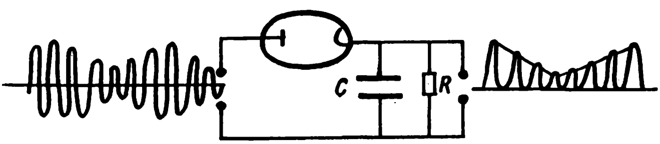
The audio-frequency (sound) signal is singled out with the aid of scissors, as it were, which are called a detector. The principle component of the detector is a diode. And again, the diode copes with this task only because in its characteristic there is a section that possesses "curvature". In this section some part of the signal is "cut off" and the remainder is then applied to an *RC* circuit.

III.35

The diode cuts off the negative half-cycles. During the positive half-cycles it lets current pass through it. This current flows in surges and creates a "fence" of peaks. The first peak charges a capacitor, this being followed by a pause which lasts until the following peak appears. During the pause the capacitor discharges but little: on the right-hand side this is prevented by a high-value resistor, and on the left, by the cut-off diode.

The voltage across the capacitor remains practically constant until the next peak appears.

If the peaks have different amplitudes, then the capacitor will charge differently with each peak and, as a result, the audio-frequency (sound) signal will be separated across it.

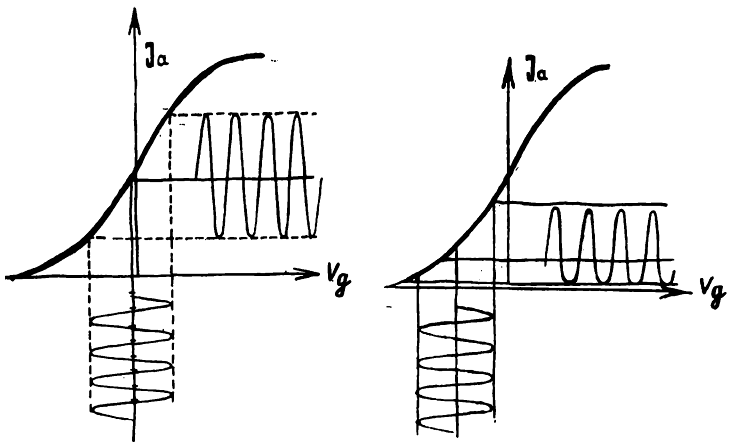


Distorted Portrait

In order to amplify signals without distortion it is necessary to get into the linear section of the valve's characteristic curve. As soon as this condition is violated, then instead of an even sine wave, we will obtain its distorted portrait.

The radio valve becomes something like the crooked mirrors that are hung up in the room of laughs at a side show. By magnifying one part of the image and contracting another the crooked mirror turns a normal face into a funny caricature. Surely no one needs such mirrors in everyday life. And what about a valve with crooked sections in its characteristic?

When a valve must amplify signals without distortion, crooked sections in its characteristic can do nothing but



harm. But engineering knows of many inventions based on the use of those very properties and phenomena, which in other cases cause only harm.

Let us consider, for instance, friction. How much energy is wasted to overcome the omnipresent friction in any mechanism! But if there were no friction, there would be no shafts, no transmissions, no swift cars that race along the roads due to friction of their tyres.

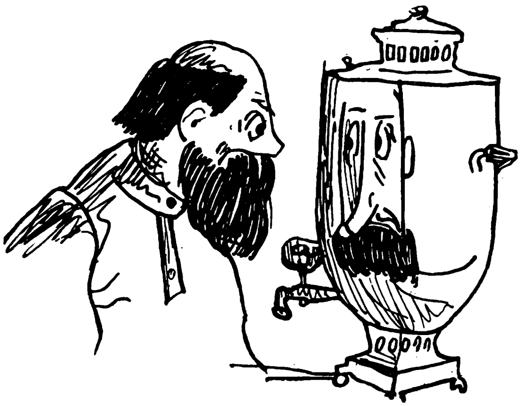
Sparks, which flash between moving contacts, burn these contacts and interfere with operation of sensitive instruments. But even these phenomena people have managed to turn to good: sparks are now used for processing metals.

The triode can serve as another striking example of how in the indissoluble dialectical connection of phenomena the selfsame properties can cause both good and harm.

The crooked sections of the characteristic distort signals in amplification. But if the triode lacked this "shortcoming", it would lose half of the merits, because of which the physicist Louis de Broglie spoke so highly of it.

Kingdom Of Crooked Mirrors

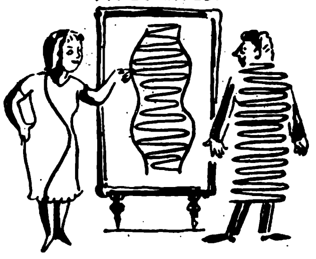
There is a wonderful book by the English writer Lewis Carroll called "Alice's Adventures in Wonderland" and its sequel "Through the Looking Glass". In the latter Alice finds herself in a strange kingdom, where all of reality is reflected



in crooked mirrors. All the ugly things of life look attractive, cupidity turns into generosity, evil pretends to be good. Electronics also has its "kingdom" where only crooked mirrors are used. True, they play an entirely different role: they are called on not to distort, but reveal the truth.

The crooked mirrors of electronics are the nonlinear sections of valve characteristics. With the aid of these sections it is possible to perform a number of necessary operations with signals: to superimpose music or speech on the carrier signal, to separate audio-frequency signals from the carrier ones, or, retaining all that has been recorded on the carrier signal, to change its frequency.

Signals transmitted by radio will not be heard till they have passed through all the "mirrors". One of them is set up in the transmitter: with its aid the sound is superimposed on the carrier signal. This process is called modulation (see III.31, III.32).

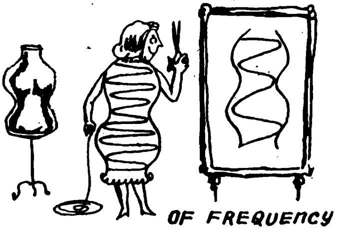


The "canvas" together with the superimposed "design" is radiated by the transmitting antenna in the form of radio waves. The antenna of the receiver catches them. True, at the site of reception the signal is very weak. But there is no harm in that, the signal only needs to be amplified.

The first concern is not to distort the signal—in the linear section of the characteristic both the "canvas" and the "design" are amplified simultaneously.

However, in this way weak signals cannot be amplified to the necessary degree. The thing is that some part of the energy of the amplified signal invariably gets to the input of the amplifier via the common supply source, to which all the valve anodes are connected. This means that from the anode of the last amplifier valve some part of the signal returns to the grid of the first amplifier stage and the whole amplifier is covered by a parasitic feedback (see III.28). And what this may lead to we already know: because of this feedback it is possible to sustain continuous oscillations in a tuned circuit, to generate a continuous signal.

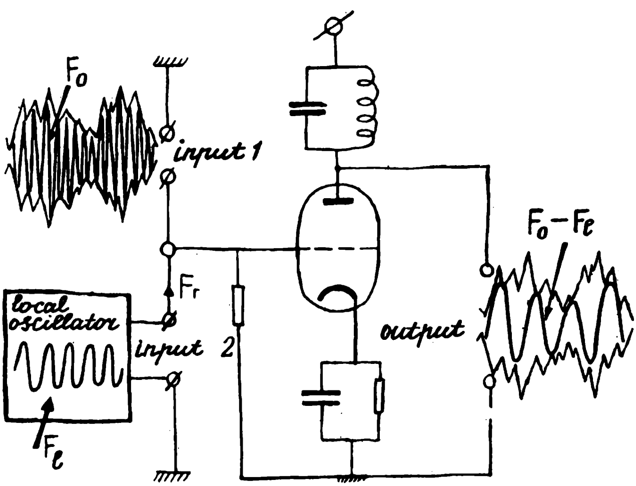
Another example of dialectics: an oscillator cannot operate without feedback, while in an amplifier it does harm. And though engineers, when designing amplifiers, do everything possible to block the way for the return of the signal, it still inevitably infiltrates back to the input.

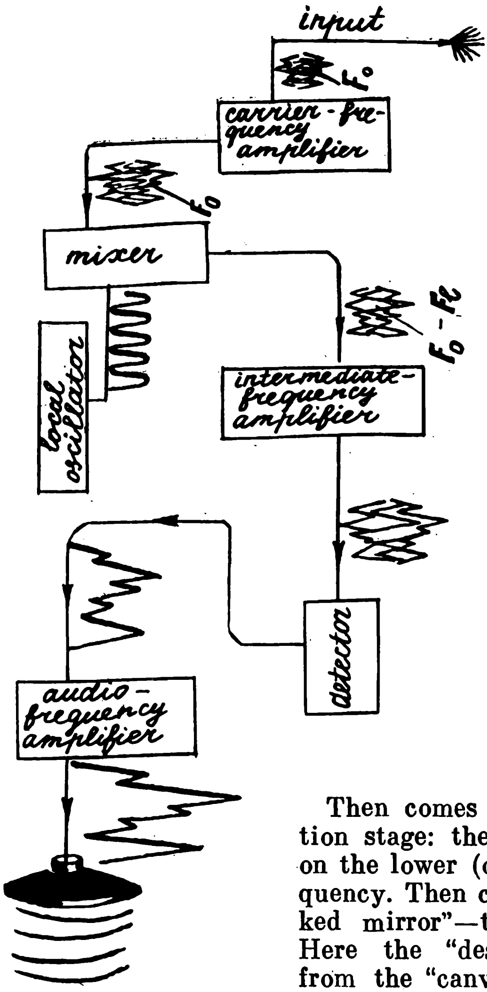


With high amplification the signal at the output of the amplifier possesses high energy. Even a small fraction of it, which returns along the parasitic feedback circuits to the amplifier input, will be amplified again, and the amplifier will begin oscillating at its natural frequency. Then the weak signal arriving from the antenna will be drowned in the natural oscillations of the amplifier, and all that will be heard from the receiver will be an ear-piercing whistle.

In order to avoid such phenomena the amplification has to be effected stage by stage. At each stage use is made of a "mirror".

The first stage is radio-frequency amplification. Then comes the first "distortion": conversion from the radio frequency to an intermediate frequency. This is done in the following way. The signal arriving from the antenna and the signal of an internal oscillator are simultaneously applied to the nonlinear section of the valve characteristic. Such an oscillator is called a local oscillator. The carrier frequency is equal to F_0 and that of the local oscillator, to F_l. The capacitance and inductance of the oscillatory circuit included in the anode circuit of the converter (or mixer) valve are selected so that the natural frequency of the oscillatory circuit is equal to the difference $F_0 - F_l$. The signal of the difference frequency is separated in the oscillatory circuit of the mixer valve, still retaining the original "design" which has been superimposed on the carrier signal. The "crooked mirror" has not distorted the "design", it is now simply recorded on a sparser "canvas".



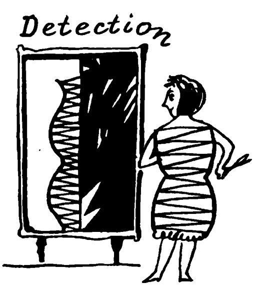


Then comes the next amplification stage: the signal is amplified on the lower (or intermediate) frequency. Then comes another "crooked mirror"—the detector valve. Here the "design" is separated from the "canvas" (see III.34 and III.35).

Before the "design" is fed to the speaker, it has to be amplified again—this is the third amplification stage.

In the receiver standing in your room the signal passes through all the above mentioned stages.

But a receiver is only one province of the great "kingdom of crooked mirrors", it solves only one of many problems. True, it was radio broadcasting transmitters and radio



sets that gave the first impetus to the development of electronics. But at the present time radio broadcasting is but one small area in a vast field of diverse applications of electronics. And among them all there is hardly a single application where electronics can get along without a "crooked mirror", i.e. without nonlinear transformation of the signal: modulation, detection, frequency conversion. Through modulation it is possible to record on the carrier signal not only music or human speech, but any information which it is necessary to transmit. This may include data on radiation intensity, pressure or temperature in the capsule of a spaceship. Such information is not transmitted in words: special sensors convert the radiation, temperature, pressure into an appropriate signal. The signal is fed to a modulator and the result is the already familiar "canvas" with "design".

A carrier signal can have the Morse code or a special, conventional code superimposed on it. In a radar station the modulation produces short pulses which ride "astride" the carrier signal to the target (to an enemy aircraft, for example) and, on returning back, warn about the danger in due time and inform about just where the enemy is. Thus, because of the pulse modulation, it has become possible to endow radar stations with those fabulous qualities which the "Golden Cockerel" in the Russian folk tale of the same name possessed.

And what about the transmission of images? Once upon a time tales were told about that too. Do you remember the various magic rings, magic apples, saucers with magic liquid, and magic mirrors. These magic "devices" made it possible to see everything that was taking place "beyond the hills, the wild, wild seas and in lands so far away".

In reality all this has proved simpler—the mirror does not necessarily have to be magic, the screen of a television tube can do quite as well. But before the image of distant events can reach the television screen, it must also be recorded on a carrier signal by means of electronic "crooked mirrors".

See what an important role the process of modulation is called on to play in electronics—with its aid very many fairy tales have been turned into reality.

Those things that formerly have been the prerogative of magicians are now done with the aid of electronics and its magic "crooked mirrors".

The Ionosphere And Billiards

A word spoken in Europe can be heard by radio in Australia and America. But a game that is telecast from one of Moscow stadiums cannot be seen some hundred and fifty kilometres from Moscow. Why?

Television has helped us to see the surface of the Moon for the first time. And as you know, this is some 384 000 kilometres away!

It turns out that with the aid of television it is easier to see far out into space than to ensure communication on the Earth. What is the reason?

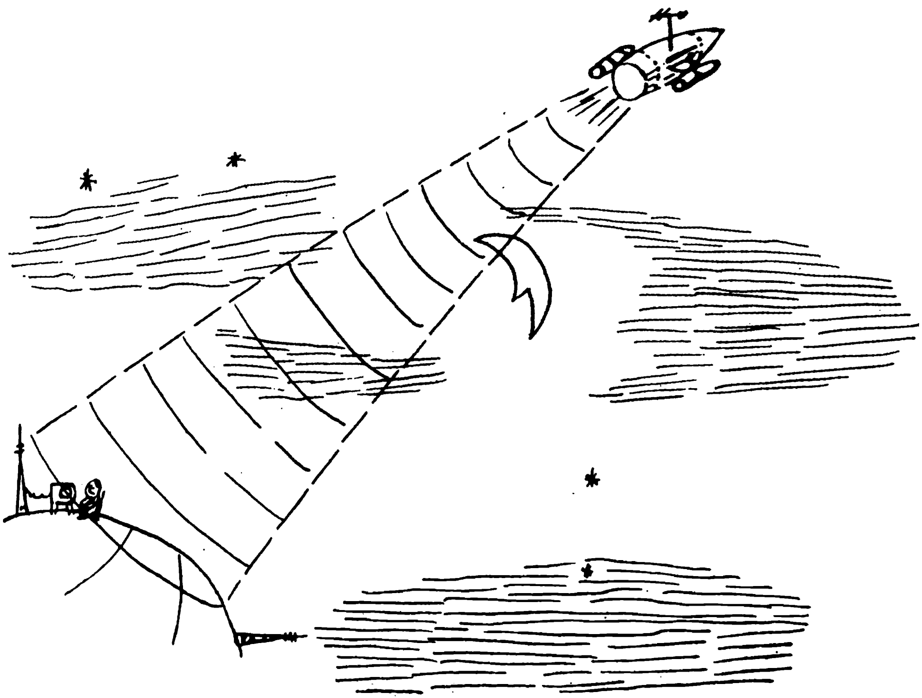
The specialists have a laconic answer to this: television signals cannot be sent beyond the optical or horizon range.

"Optical range" is a very concrete and exact term: the antennas must "see" each other for the signal radiated by one of them to be picked up by the other. Suffice it for the receiving antenna to hide beyond the horizon and communication is at once interrupted. For television the horizon is, as it were, a line that it is forbidden to cross. And in space there is no horizon. The optical range is limitless. You can look even billions of light years away! Whether you'll be able to make anything out, that is a different story. But the road for the signal is open and, as long as a spaceship does not hide behind some heavenly body, television communication can be maintained with it. On Earth it is a different matter: the Earth itself gets in the way.

However, let us leave space for a while, return to Earth and ask ourselves a new question. How is it that transmitted words can reach other continents? Why does not the spherical shape of the Earth interfere in this case?

Forty-five years ago this was a mystery for science. At first electronics (rather radio) made do with long waves (from 800 to 3000 metres) which, possessing the ability of encircling the Earth's surface, provided fairly distant communication. But such waves cannot encircle the whole of the *globe, and so they cannot provide communication between Australia and America or Europe.*

Short waves (from 10 to 100 metres) were also known. But since they propagate along straight lines and cannot encircle the Earth, it was considered that they could not reach beyond the horizon range. So they were classified as inconvenient



waves, and stations operating on short waves were not designed. This range of waves was given over to radio amateurs, of whom even then there were plenty.

And then all at once something happened that nonplussed the specialists. It turned out that with the aid of short-wave amateur stations it was possible to set up communication with any point on the Earth! Little transmitters which consumed no more power than a twenty-candle bulb sent signals farther than long-wave stations with a capacity of several kilowatts!

More than that, those very same transmitters could not be heard at distances of about two hundred kilometres. It seemed as if, having travelled a short distance, the signal "died of fatigue" only to rise again thousands of kilometres away.

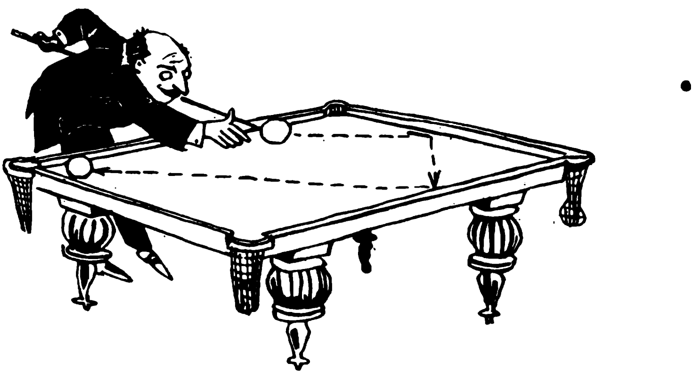
The puzzle seemed insoluble.

The best man for solving such riddles was the Soviet scientist M. Shuleikin. Do you remember how he cracked the secret of the continuous radiation of the stations developed by the Germans during the war?

Shuleikin came out with an exhaustive explanation of the strange behaviour of short radio waves. He calculated that short waves passing along the Earth's surface really lose power fast because they are absorbed by the surface of the Earth's crust much more intensely than long waves. But even if a station radiates a high-power short wave signal, the latter cannot go far along the Earth, because short waves cannot circle it. This means that in all cases the horizon will be their bound.

But nature provided them with another possibility for distant travels.

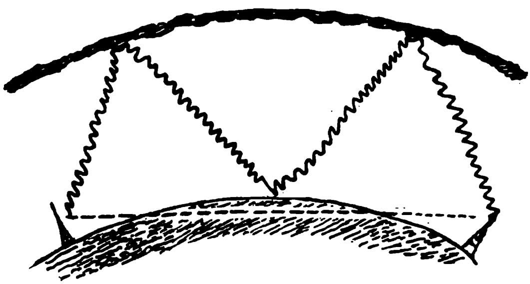
Under the action of solar radiation and the hail of meteorites an ionized layer is formed in the upper part of the Earth's atmosphere. In this layer the neutral air molecules are decomposed into ions and electrons and the whole layer presents a chaos of charged particles. Short waves (from 10 to 100 metres) are reflected from this layer just as light



rays are reflected from the surface of a mirror, or sound from a barrier. Likewise this layer can be compared with the edge of a billiard-table. And indeed, communication specialists use this layer like the edge of a billiard-table: if the ball does not go straight into the pocket, it can be ricochetted.

In the same way the short-wave signals radiated by distant stations get to your receivers on the rebound. What is more they can ricochet several times, for the Earth is also like the edge of a billiard-table.

However, if the receiver is located at a distance of 200 kilometres from the station, no signal will reach it. The ground wave is stopped by the horizon. And the sky wave will not reach the receiver, because it bounces down again



more than 200 kilometres away. It is well known that the angle of incidence is equal to that of reflection. For a reflected (or sky) wave to reach a receiver located 200 kilometres away, it must be directed nearly vertically towards the ionosphere. But then it will pierce the ionized layer of the atmosphere and pass out into space, leaving the Earth for ever. Thus a blind zone is formed on the Earth's surface within a certain radius around the radio station.

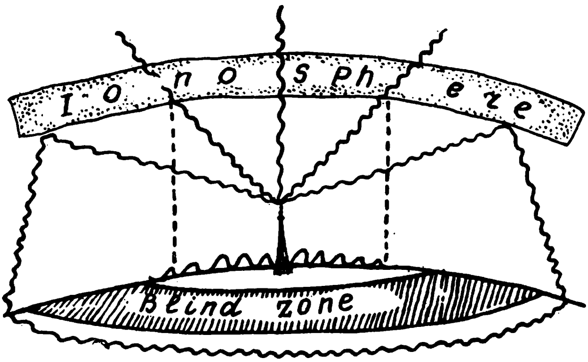
Direct or ground waves are heard in the vicinity of the radio station. At great distances inclined waves bounce back to the Earth. But the blind zone, which is neither far away from nor near to the station, can receive neither the ground nor the sky wave.

It was just this circumstance that led to the misthought about the range of communication by short-wave signals. The disappearance of the signal in the blind zone and its reappearance at greater distances was not so easy to explain.

Now the effect of the ionosphere on waves of any length has been studied. Waves from 100 to 1000 metres (so-called medium waves) are well reflected by the ionosphere only at night. In the daytime the composition of the ionosphere changes and the reflected energy is insufficient for reliable communication in this range. Those who like tuning in distant stations must have noticed this peculiarity of medium waves.

Long waves (longer than 1000 metres) are not reflected by the ionosphere either at night or in the daytime.

As for ultrashort waves (10 metres and less), for them the ionosphere is no more of a barrier than a sieve is for water. All of their energy seeps through this layer without being reflected. That is why television antennas must



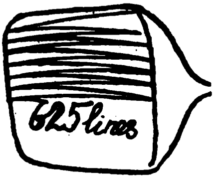
necessarily "see each other"—for the carrier signal in television is an ultrashort wave signal and it does not bounce off the ionized layer.

But why have the developers of television chosen the most inconvenient waves?

Because it is only ultrashort waves that can serve as a carrier for television, only they are capable of conveying to the receiver the complex "design" which contains the visible image. There is nothing accidental about television. Here all has taken long years of hard work: the design of the picture tubes, the methods of obtaining visible images, the length of the carrier waves. And all this is interrelated: in order to select the carrier waves one must know precisely how the television image is created with the aid of electronic devices.

THIS LIES AT THE BASIS

III.36



If you look closely at the image on your TV screen, you will notice that it consists of a great number of horizontal lines. Every picture frame consists of exactly 625 lines.

The movement of the beam along the lines is very much like the movement of the eyes when reading a book: having run along the line from left to right, the beam returns very quickly to the left side of the screen, to the beginning of the next line. In 1/25 of a second the beam traces 625 lines on the screen, which make up one picture. In the next 1/25 of a second the beam traces another picture. Every second 25 pictures are traced.

III.37

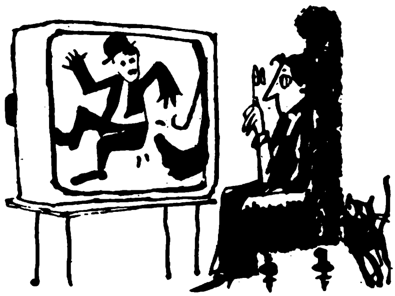
The number of lines in a picture frame and the number of pictures per second have not been chosen by chance. Account has been taken of two properties of our vision: persistence and resolution.

By persistence of vision is meant the ability of the retina of the eye to retain for a certain time the outlines of an image just seen. The object being observed may vanish from your field of vision, but due to persistence its image is retained on the retina of your eye for about 1/15 of a second.

If the television pictures had changed slower than 15 times a second, then the image would have disappeared from the retina before the appearance of the next image on the screen. The eye would then register the change of the pictures. In such a case the viewer would be dazzled.

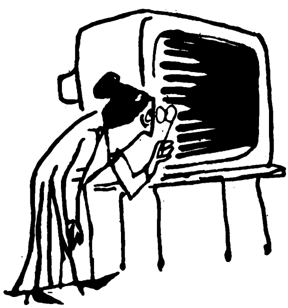
In addition, it should be borne in mind that the image on the screen is usually always moving. If from picture to picture an object moves noticeably across the screen, then the viewer would percieve the motion as a series of jerks.

Perhaps, you have seen how funnily people move in old motion pictures. This is due to the fact that in those days



the number of pictures per second was too small—16 pictures a second. To avoid this the number of pictures per second in television has been increased up to 25.

III.38



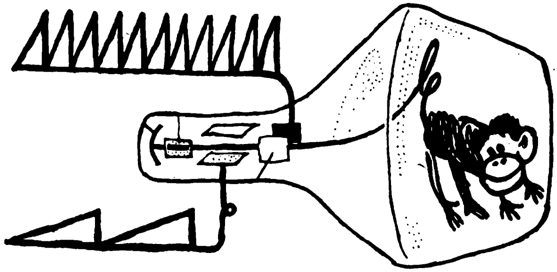
The distance between the lines of a picture frame has been selected so that a person sitting one metre away from the screen cannot discern individual lines. He sees the whole picture at an angle of about 10 degrees, i.e. 600 angular minutes. The resolution of our eye will allow us to see two lines separately if the angle of view exceeds 1 minute. For the lines of a picture frame to merge there should be at least

$$\frac{600'}{1'} = 600 \text{ lines}$$

Actually there are 625 of them.

III.39

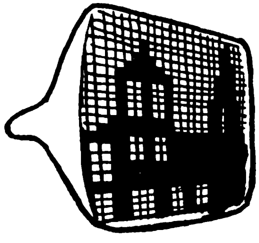
How to make the beam run along the lines we already know: a sawtooth voltage should be applied to the horizontal-deflection plates (see Chapter I, Sections "Traces of Things Invisible" and "Almost Like in a Problem Book"), To obtain the image of a pulse, the beam repeatedly runs along the same line in the middle of the screen. But in television each new line must pass a little lower than the previous one. To do this the beam must be made to move from left to right and simultaneously descend. For this purpose the second pair of plates of the picture tube must be supplied with a slower sawtooth voltage. While one tooth of the slow sawtooth voltage deflects the beam from



the top to the bottom of the screen, the fast sawtooth voltage produces the whole of 625 teeth, making the beam race from left to right 625 times. In TV sets with large screens the beam travels along the lines at a speed of nearly 30 000 kilometres per hour (the circumference of the Earth is about 40 000 kilometres).

In modern television sets the beam is controlled not by the plates, but by magnetic fields produced by coils. The windings of the coils are supplied with a sawtooth current.

III.40



If, when tracing a picture the brightness of the beam remains constant, then the whole screen will be uniformly illuminated and the picture will be blank.

But usually the brightness of the beam varies continuously. Dark and light spots follow one another on the screen, which, like a mosaic, form landscapes, episodes of a football game, a close-up of the announcer—in general, everything that one can see on a television screen.

III.41

If the picture is made up of large details, the adjacent lines are equally bright. When reproducing minor details, then even the adjacent lines may be of different brightness. And into each line can go a definite number of mosaic elements. The greater the number of the elements, the higher the definition of the picture, the better any small detail of the picture is seen on the screen.

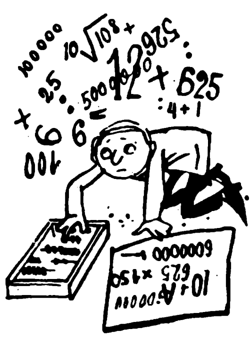
If the brightness of the beam varies with each line, then 625 mosaic elements can be arranged vertically. In the case of a square screen, it is advisable to fit the same number of elements along each line.

Then the total number of elements on the screen will be

$$625 \times 625 = 390\,625$$

Usually the width of the frame is 4/3 of its height. Such a frame will contain $625 \times 4/3 \times 625 = 500\,000$ elements.

Suppose that each element of the image must differ in brightness from its neighbouring element. How often in this case must the brightness of the beam vary? Let us divide all the elements into pairs (light and dark). Passing over each pair, the beam changes its brightness. In each picture the beam will traverse 500 000 elements, or 250 000 pairs. Now it will have to change its brightness 250 000 times (if a given element is light, then the next one should be dark).

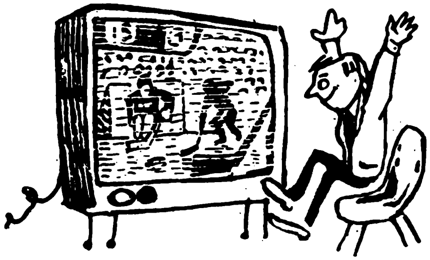


In one second 25 pictures will change. Consequently, in one second the beam must change its brightness $250\,000 \times 25 = 6\,250\,000$ times. This means that the frequency of variation of the beam current should be 6 250 000 hertz or 6.25 megahertz.

III.42

Of course, not every image necessarily contains all the 500 000 elements of the mosaic. But in each picture apart from large ones, there are also small details: features which convey the facial expression of a talented actor, strokes made by the hand of an artist, fine letters of a text, the small puck in an ice hockey game, etc. For all these details to be clearly seen on the screen of your television set, one must allow that the frequency of variation in brightness, in extreme cases, may reach 6.25 megahertz. The beam changes its brightness under the effect of the "designs" which have been superimposed through modulation on the signal carrying the image.

Knowing the frequency with which the "design" can be made to vary, it is not hard to determine the carrier frequency. Since the carrier signal serves as a "canvas" for



the "design", its frequency must exceed that of the "design" approximately ten times. Only in this case will all the shades of the "design" be transmitted point by point on the crests of the carrier wave (see Chapter III, "Invisible Express"). This means that the carrier frequency of television signals should be of the order of $6.25 \times 10 = 62.5$ megahertz.

This corresponds to a wavelength of 4.8 metres. It is exactly these "inconvenient" waves for which the horizon is the restriction line.

How The Image Is Conveyed

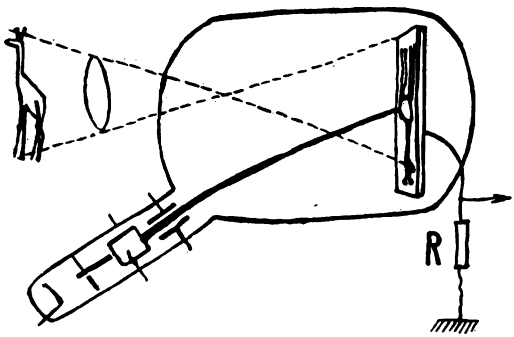
The "design" which contains the announcer's voice or the sound of a musical instrument is made with a microphone. The microphone converts the sound oscillations of the air into an alternating, oscillating current.

And how is made the "design" containing an image?

Here again a cathode-ray tube comes to the aid (it is called a camera tube or iconoscope), but it differs substantially from the tubes we have considered earlier.

The layer covering the screen of this tube has a special property: its electrical resistance will be the lower, the brighter it is illuminated. The transmission is effected in the following way.

An image, which must be converted first into a fluctuating current signal and then into electromagnetic waves radiated into the air, is projected onto the screen by using ordinary optical lenses. Behind the screen, just like in an ordinary television picture tube, slides an electron beam,

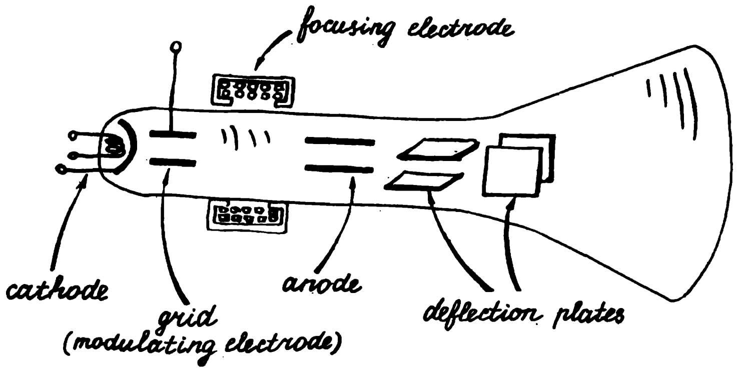


scanning line after line. A stream of electrons "washes" the inner surface of the screen similar to the water from a garden hose flowing down a glass. Rivulets of electrons run along the conducting layer and go to earth via resistor *R*. The greater the illumination of the screen surface, the more copious the rivulet, because the resistance of the conducting layer decreases under the action of the light rays.

When the beam scanning the lines strikes a light part of the image, the rivulet flowing through resistor *R* gains in intensity. When the beam shifts to a less illuminated area of the screen, the current becomes smaller. The beam scans line after line, converting the image into an electric current which continuously varies with time. This is how the "design" is formed. Now, if this current (or rather the voltage produced across resistor *R* by this current) is used to modulate ultrashort waves, then the "design" which contains the image will "straddle" the carrier signal.

The fate of such a signal in a television receiver is similar to that of the radio broadcasting signals: it is also amplified stage by stage, passing through a system of "crooked mirrors". At first the signal is amplified at radio frequencies, then, at intermediate frequencies, and then it is subjected to detection and, finally, in the last stage the pure "design" is amplified.

And then what? What happens to the signal next may, probably, seem unexpected. On arriving at the finish, the signal must again perform modulation: this time it modulates the beam. For this purpose, in addition to the components that we have considered in Fig. I.19, an extra



modulating electrode is introduced into the tube. It is also known by the name of grid, because like the grid in a triode the grid in television picture tubes controls the stream of electrons which form the beam. It is this electrode that the "design" containing the image is applied to. Variations of the voltage applied to the modulating electrode cause changes in the brightness of the beam.

For all the elements of the "mosaic" to appear at the right points on the screen, special pulses are superimposed on the carrier signal along with the image signal. These pulses give the command for the beam to scan the screen of the receiver.

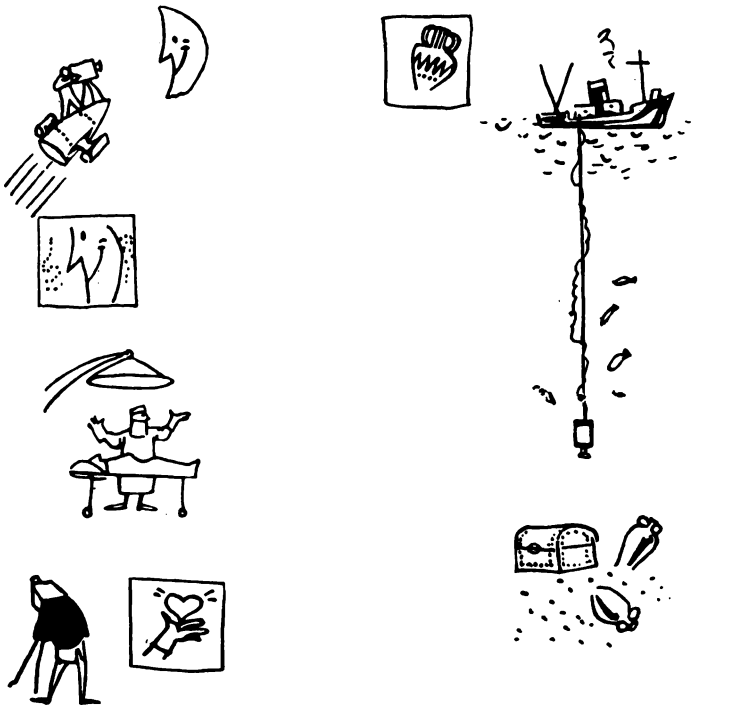
All the time the transmission is on the air the beams of all the television sets simultaneously with that of the camera tube start and reach the finish, beginning and completing the picture 25 times a second.

At any moment millions of beams scan the same elements of the mosaic. On millions of screens millions of beams trace, point by point, the same picture 25 times a second.

THIS LIES AT THE BASIS

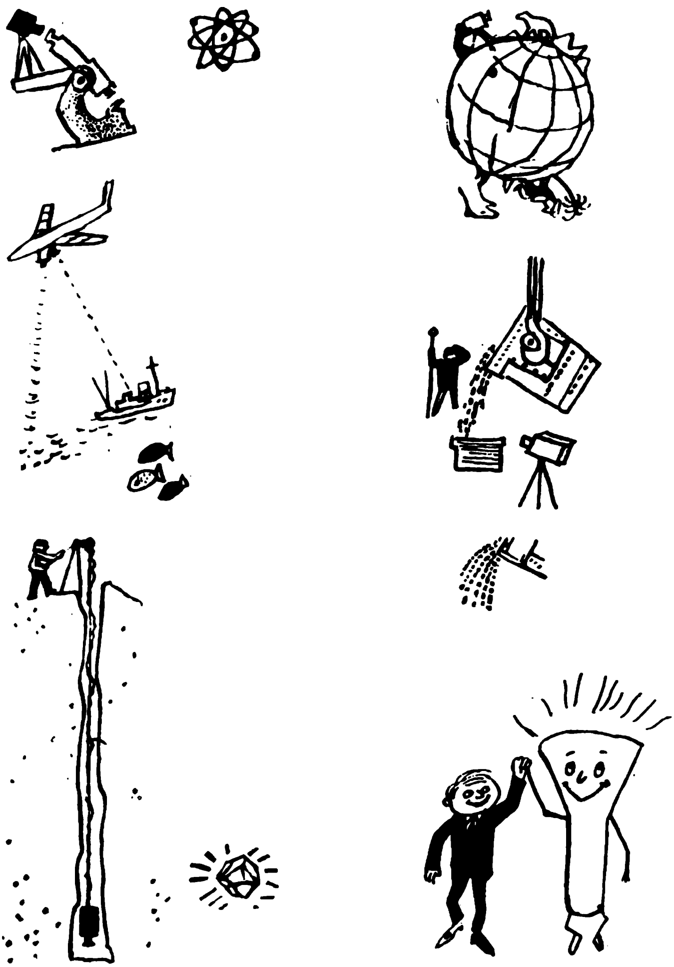
III.43

Television has become part and parcel of our life. In various fields of science and technology it plays a role that is not less important. With the aid of a special electronic



eye, one can observe how molten metal fills a mould and how a life-endangering radioactive process proceeds, it can show a whole auditorium how an experienced and skilled surgeon performs a delicate operation.

A small-sized television camera built in a geological drilling tool allows rocks to be investigated at great depths. Before the advent of television, to investigate each layer rock samples had to be lifted to the ground surface.



Television cameras have helped find sunk submarines and amphoras in which ancient Greeks carried wine from the island of Rhodes to Marseilles.

Fishing ships follow schools of fish with the aid of a guide which is usually an airplane. By installing a television camera in the aircraft it is possible to transmit a picture of the school down to the ship.

Television has helped transmit to the Earth first the pictures of our closest neighbour in space and then the first steps man made across the Moon's surface.

In the future electronic instruments will evidently "see" many heavenly bodies somewhat earlier than man flies there.

Television helps carry out many very intricate technological processes. To keep the diameter of a wire within several microns when manufacturing transistors, it was necessary to measure the thickness of the wire under a microscope for hours. Now a cathode-ray tube looks into the objective lens. The size of the image is compared to a standard signal. If the wire becomes even tenths of a micron thicker or thinner, there at once arises a difference current and an automatic device registers a reject.

In essence an ordinary television camera is "blind"—it only reproduces an image which can be seen by man. But in recent years devices have been developed which can really see objects, detect their characteristic features: tell a dog from a cat, and recognize the letters of the alphabet, regardless of the handwriting or the size of the letters.

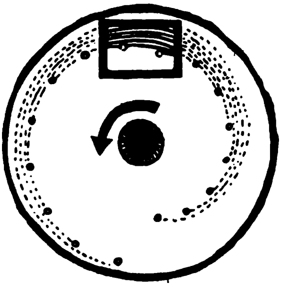
The basis of these devices (they are called perceptrons) is the very same cathode-ray tube. But for the device to "recognize" objects, the signals are subjected to a complicated processing with the aid of computers.

Where Can You Get A Hundred Suns?

The first television project was proposed by the Polish engineer Nipkow. Instead of the camera tube screen he used a disc with a multitude of round holes. The image was projected onto the disc. When the disc rotated each of the holes traced a single line. And as the holes were arranged along a spiral, each following line was traced lower than the previous one. The light passing through the hole fell onto a photocell.

Since any image consists of dark and light spots, the brightness of the beam and, consequently, the current produced by the photocell will vary many times, while any one of the holes is tracing a new line. And all of the 30 holes (and that is exactly the number the Nipkow disc had) were breaking down the image into 30 lines, converting it into an electric current continuously varying with time. This pulsating current was used to modulate the carrier signal.

In the receiver, this current caused an electric bulb to "blink". Another Nipkow disc was placed between the bulb and the screen. Its holes traced lines on the screen in step (synchronism) with the disc at the transmitting end. Such an idea for transmitting an image is fairly simple. But what a fine mess occurred, when an attempt was made to realize it!



Back in the thirties an experimental television studio was in operation in Moscow. It made use of Nipkow discs. What came of it was amusingly described in the magazines of those days:

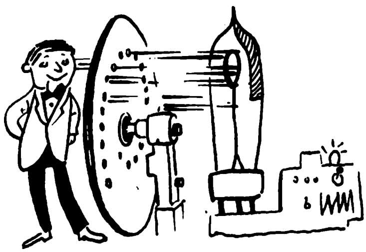
"The television transmission is preceded by many a comic scene. The actor is accustomed to ordinary theatrical make-up. The lips must be red—that is the rule. Imagine his surprise, when the make-up man begins applying dark-green lipstick to his lips. He has played hundreds of roles and been made up to resemble Othello, a Negro and Quasimodo, but has never yet been painted to look like a cockatoo!"

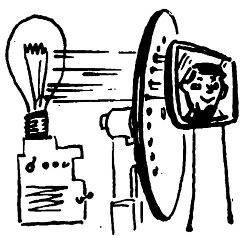
"...A gymnast performs in black shorts against a dark background. On the screen, the shorts disappear. Then the dark background is replaced with a light one. The effect is even more staggering: the shorts are clearly seen on the screen, but... the gymnast has disappeared."

What was actually the matter? Why is it that the Nipkow disc cannot produce the same kind of images as modern screens do?

One of the faults is that the picture frame consists of only 30 lines. It is not so pleasant to look at it: instead of an integral image one sees a lattice of sparse lines. But even this could have been put up with if... If after the shorts the gymnast himself had not disappeared. Why does he disappear? Better or worse, still the object should be seen in the picture even with a small number of lines!

But since the object disappears, this means that the photocell cannot sense the difference between the dispersed light from the background and that reflected by the object. And this is quite natural: only a small portion of the light passes through the tiny holes in the disc, the rest of the





rays are reflected by the disc and wasted. It was this wastage that caused all the trouble: the green lips of the actors and the disappearing shorts.

It was calculated that an image obtained with the aid of a Nipkow disc could possess the same resolution as that of a modern television set, if the source of light exceeded 100 times the direct sunshine!

But is it conceivable to create on the Earth sources of light which will outshine 100 Suns?!

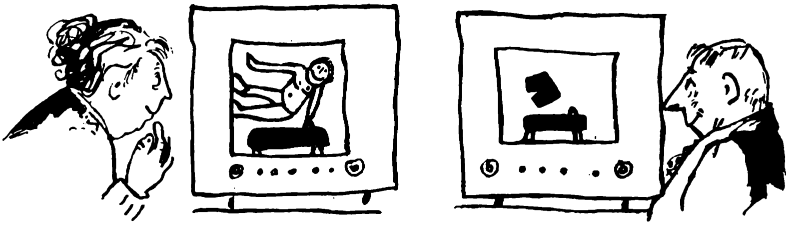
But then, cannot the light, perhaps, be used more economically?

11 Зак. 15299

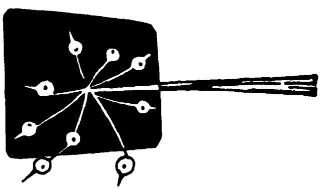
That is exactly the path followed by the engineer Zvorykin. Back in 1907 Professor Boris Rozing of St. Petersburg University proposed using a cathode-ray tube in a television receiver. His disciple Zvorykin worked on the idea and developed a camera tube capable of "accumulating light."

How does it do this?

Very simply. We need but compare Nipkow's method with the one we have considered earlier, and everything



will become clear. In front of the tube screen there are no small holes. All the light reflected by an object in the direction of the camera tube falls on the screen. This is the main advantage of a modern camera tube as compared to the Nipkow disc. And due to this difference the Nipkow



disc has become a thing of the past, while the cathode-ray tube has become an integral part of all television systems.

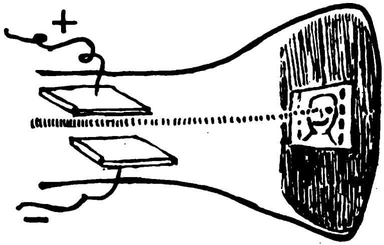
Many methods can be used for accumulating light.

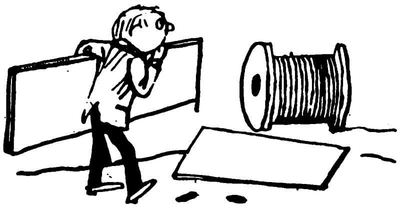
The variation of resistance under the action of light which has been considered in the Section "How the Image is Conveyed" is known as the photoconductive effect. Very often the screens of camera tubes are coated with a substance that produces a photoemissive effect. The difference between the two effects is quite clear from their names. In the case of the photoemissive effect the electrons emerge from the layer like spray from the surface of water. The more intense the light, the greater the number of electron "splashes" coming from the light-sensitive layer. When the electron beam, scanning line after line, gets at a certain point of the camera tube screen, it gives up some electrons to it. The more electrons are sprayed out from the light-sensitive layer under the action of light, the more of them will be given up by the electron beam. The beam scans the image, passing from the light sections to the dark ones and the beam current varies accordingly.

Here again we have accumulation of light. Light falls on the screen during the whole of the transmission, while the recovery of the layer occurs immediately: the layer is recovered by the electron beam scanning the lines.

III.44

In the first tubes the beam was controlled by plates. But when television tubes with large screens appeared, plates could no longer cope with this task, for they could only deflect the beam within a small angle, and of course, in



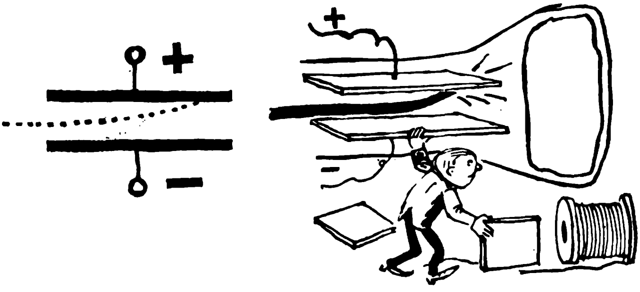


this case the image could not be made to cover the whole screen. In tubes with large screens it is desirable to supply the anode with a high voltage, as a result of which the electrons attain a very high velocity. They fly past the plates instantaneously, and only a very powerful field can deflect them noticeably.

III.45

To overcome this an attempt was made to intensify the field between the plates. For this purpose the plates had to be brought closer together and their areas increased.

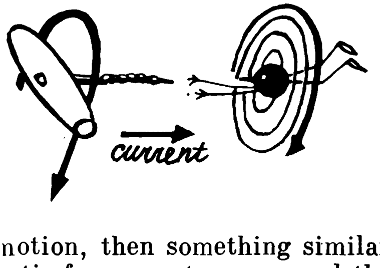
The result was paradoxical: the plates were able to deflect the beam to the necessary angle, but the beam began striking one of the plates.



That is why the developers of television tubes had to recall the fact that electrons can be controlled not only by the electric fields produced between the plates, but also by magnetic fields.

III.46

A magnetic field does not act upon a stationary charge. But since the charges in the electron beam are in constant

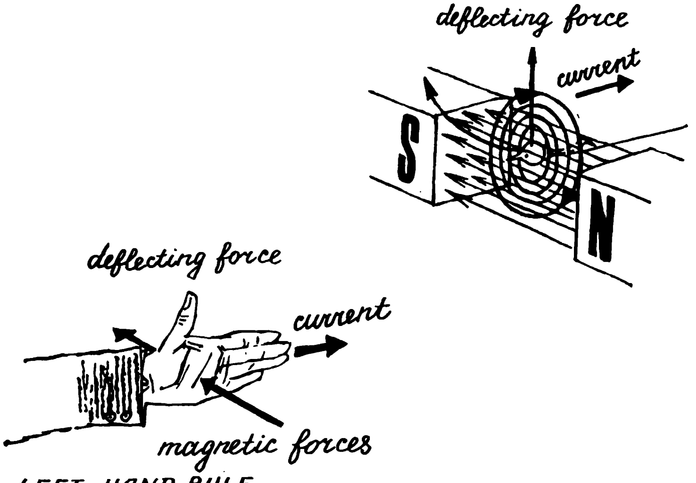


motion, then something similar to aureoles—fields of magnetic forces—sets up around them (just like around current-carrying conductors).

The direction of the forces coincides with the rotation of the head of a corkscrew, if the corkscrew itself is advanced in the direction of the current (here again the technical direction of current is meant, see II.14).

III.47

If the directions of the forces produced by the magnetic fields coincide, they repell one another. If the forces are opposed, they attract one another (see Chapter II "Which Way Will the Needle Turn?").



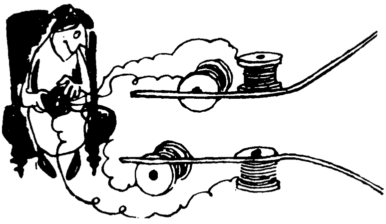
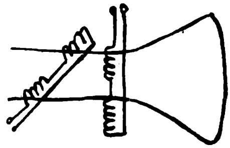
LEFT-HAND RULE

Above the electron the magnetic forces are opposed, while under it their directions coincide. In the case of such an interaction a charge will deflect upwards. The motion of a charge in a magnetic field is governed by the left-hand rule.

III.48

To set up fields for deflecting the beam, television tubes usually employ coils and not permanent magnets. A pair of coils arranged vertically near the neck of the tube deflects the beam in the horizontal plane. Another pair, arranged horizontally, deflects the beam up and down.

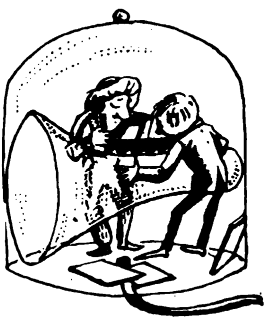
If the current in the coils reverses, the magnetic poles will also reverse, so that whereas formerly the beam has

moved upwards, now it will move downwards, being governed by the same left-hand rule (see III.47).

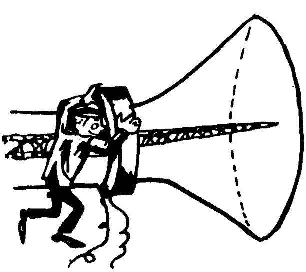
By supplying a "fast" *sawtooth* current to the vertical coils and a "slow" sawtooth current to the horizontal ones, *the beam can be made to scan* a picture (see III.39).

III.49



To place control plates inside a tube without upsetting its vacuum is not an easy job. The process of making snch tubes is a very complicated one. It is much simpler to manufacture magnetic-deflection tubes—there is no need for the coils to be fitted inside.

III.50



A coil fitted on the tube neck produces a magnetic field directed along the tube axis. Such a coil acts like a lense: it directs all the electrons to a single point on the screen, i.e. it *focuses the beam.*

Aerobatics

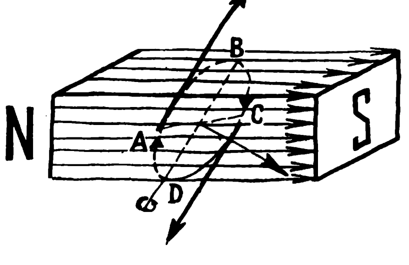
It is not hard to imagine how important it is for television to solve the problem of focusing the beam. Each of the electrons forming the beam does its best to repell its brothers flying along a parallel course and possessing a charge of the same sign. In its day this tendency of the electrons caused many difficulties for the developers of television.

Do you remember how the physicists who used the first cathode-ray tubes struggled against this phenomenon? They placed a small cylinder in the way of the electrons and applied a negative potential to it. The electrons were repelled from the cylinder walls and converged at the axis, thus forming a narrow beam (see I.19). But no sooner had they left the cylinder than they again scattered. The nearer they came to the screen, the farther away they repelled one another, the more scattered became the beam. To use such a "shaggy" beam for tracing a detailed picture is like attempting to paint a fine portrait with a brush used for painting fences.

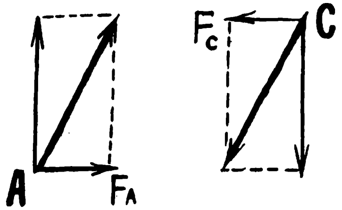
This means that it is necessary to develop such a system which would function like an optical lens and bring the beam into focus at the very screen.

This problem is solved by magnetic lenses. When current flows through the coil fitted on the tube neck, it sets up a magnetic field, whose forces are directed along the tube axis.

An electron flying along the lines of force of the field ignores the latter, because the forces of its aureole are at right angles to the direction of the magnetic forces. But what would happen if the electron were to decide to deflect from its course and fly, say, downwards?



At points B and D the forces will remain mutually perpendicular, but at points A and C the perpendicularity will be deranged. The forces of the aureole will be resolved into components acting in two directions, not only at right angles, but also longitudinally, along the lines of force of the magnet. The electron can no longer ignore the field: the longitudinal forces of its aureole (F_A and F_C) will interact with the forces of the external field. A repelling force will arise at point A and an attracting force, at point C.

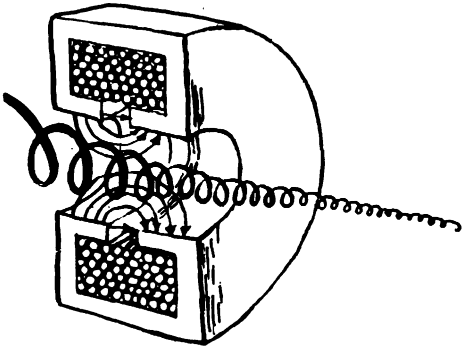


The aureole will turn to the left (viewed in the direction of the electron movement) and the electron will change its course. But as soon as it turns to the left, then there will also be an interaction at points B and D of the aureole.

Review all the considerations and you will see that the forces which arise here will turn the electron upwards. And since it is simultaneously moving both upwards and from right to left it is not hard to guess that its path is a circle.

Thus, deflecting from the course, the electron is subjected to a double influence. The anode of the cathode-ray tube continues to attract it towards the screen, while the field of the magnetic lens makes it describe a circle. What is there left for the electron to do? To fly on towards the screen, but not along a straight path but in a spin, like aircraft performing aerobatics. The flight path here is calculated with a high precision: with every turn the path of the electron is twisted tighter, the turns themselves become smaller and when it reaches the screen it will be right on the axis.

How tortuous is the path of the electron! No freedom of motion. It is subjected to the action of forces on all sides. The anode makes it fly straight towards the screen. The numerous colleagues flying alongside try to repulse it from the axis. But as soon as it leaves the axis ever so little, it finds itself subjected to the action of the magnetic field.



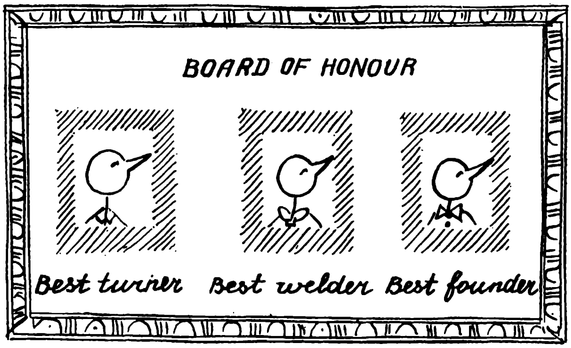
No independence whatsoever, whatever its wishes it has to go into a spin, making coil after coil.

And such is the fate of each of the electrons and all of them, spurred on by the field, strike the screen at the same point, forming a small shining spot.

THIS LIES AT THE BASIS

III.51

It is not only television that requires a focused electron beam. It proved to be an excellent cutting tool in processing metals.

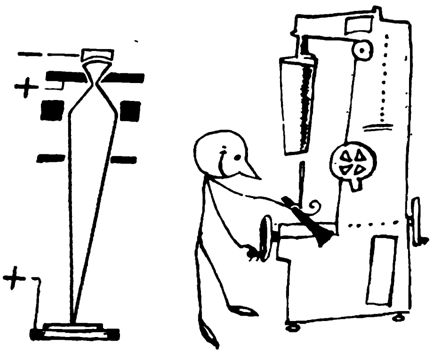


In recent years the electron has been mastering more and more allied professions. It should be noted that the electron has mastered the professions of the turner, grinder, welder and smelter in a very short time.

III.52

An electron gun, which we are now familiar with, and the metal to be processed are placed inside a vacuum chamber. For the beam to cut the metal, it should contain about 100 times more electrons than the beam of a cathode-ray tube.
What is more, it must be sufficiently sharp, wherefore its diameter is reduced to several microns through magnetic focusing. Such an enormous amount of energy is concentrated within this small diameter, that were there enough of such points to cover an area of one square centimetre it would equal the power of the turbines of the Krasnoyarsk

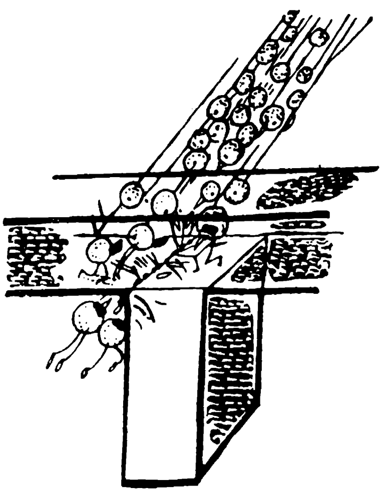
hydroelectric station! No wonder that at the point where the beam hits the metal a solar temperature of about 6000°C develops. With such a beam it is no harder to cut any metal, even the most refractory one, than it is to cut



butter with a knife. If the beam is stationary, then a hole is drilled (burnt through) in the metal, and if the beam is made to shift with the aid of a field, then it can successfully replace a milling cutter.

III.53

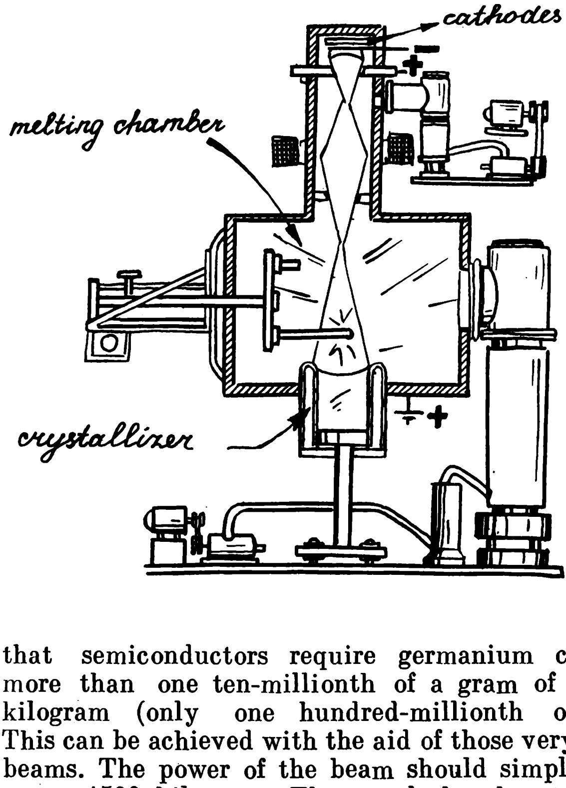
Metal is welded in a similar way. In welding, the power of the beam amounts to several tens of kilowatts. On striking the metal the electrons are abruptly retarded, and all their kinetic energy is converted into heat. In this case the beam yields such a concentration of energy at a depth of 0.001 to 0.1 millimetre, which is 100 times higher than that provided by any source of heat. The use of the electron beam revolutionizes the entire welding technology. For example, it is possible to weld metal at several levels or to make *T*-shaped joints straight through a sheet of metal.



By controlling the beam it is possible to make intricate welds with a precision which cannot be attained by a welder with a hand-held tool.

II.154

Electron melting has opened up new possibilities. It has made it possible to obtain extra-pure substances by melting and crystallizing. Such substances are required in rocket and atomic engineering, and electronics itself would not be able to do without them. It is an established fact

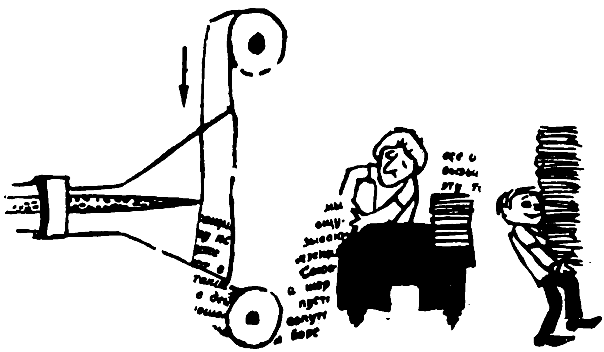


that semiconductors require germanium containing not more than one ten-millionth of a gram of impurities per kilogram (only one hundred-millionth of a percent!). This can be achieved with the aid of those very smae electron beams. The power of the beam should simply be increased up to 1500 kilowatts. The metal that has to be melted is put in the place of the anode. Melting, it drips down into a crystallizer, while the impurities evaporate and are deposited on the chamber walls.

This process is repeated many times until the necessary purity of the metal is achieved.

III.55

And now we see the electron beam in a totally different capacity—as a new means of printing books. The installation resembles a television receiver, only instead of the screen we have a ribbon of paper, which the beam scans line after line. The beam is modulated by the image of the printed text. On the paper it leaves a charge. Pulverized printer's ink and the electrified paper come together inside a chamber, the paper attracts the ink particles and the text



develops like a picture on photographic paper. Such an installation can make 25 impressions a second (the same speed as in television: 25 picture frames a second), or 1500 printed pages a minute, whereas an ordinary rotary press can make only 30 pages a minute.

Particle Or Wave?

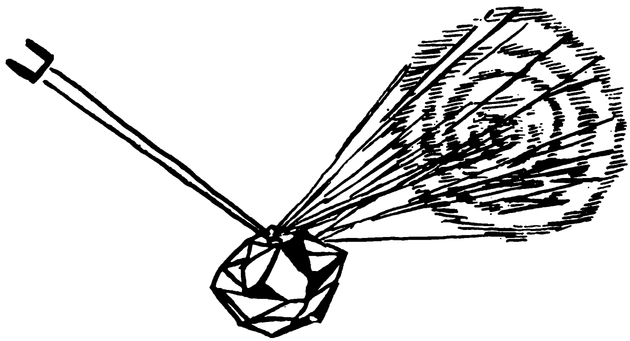
"The electron is as inexhaustible as the atom", said Vladimir Ilyich Lenin at the very beginning of this century. And all the subsequent development of physics has confirmed the wisdom of Lenin's words.

The discovery of the electron was only the first "nodding acquaintance" with this particle. To probe inside the electron, to learn what it is made up of—this is a problem that has yet to be solved.

So far we know only those peculiarities of its behaviour that can be seen by observing it from outside. And even here not everything is as yet clear.

In most of the known phenomena the electron behaves like a charged particle. But physicists know of cases when it behaves like a wave.

If light beams, reflected from a crystal, fall onto a screen, then one can observe a picture of wave interference on it. The explanation is simple: the waves reflected by tiny individual crystals merge. Where a crest comes together with another crest, the waves are intensified; where a crest



and a trough meet, a dark fringe is formed. Since the crystal possesses an ordered structure, a clearly defined sequence of dark and light fringes appears on the screen.

Such is the case with waves. But why are the same fringes formed by electron beams reflected from a crystal? Does this mean that the electron beam also has crests and troughs, and that it also consists of waves? Then what are the electrons, particles or waves?

In 1924 the answer to this question was given by the same physicist Louis de Broglie. The answer was most unexpected: the electron is simultaneously *a particle and a wave.* De Broglie proposed the famous formula with the aid of which it is easy to calculate the wavelength of the electron, by introducing into the formula the value of the mass of the electron and the velocity at which it travels.

Electron With A "Free Will"

Physicists have already got used to such a duality. Since light, which represents electromagnetic waves, also consists of photons, i.e. of material particles. This property is, evidently, inherent in various forms of matter. Nuclear fields consist of mesons. Universal gravitation is presumed to be of the same dual nature: on the one hand there is the gravitational field and on the other, an unknown particle, the so-called graviton.

But not everything can be approached with the same "yardstick".

Despite the similarity of their equations, the wave of the electron is not identical to the electromagnetic wave. The electron wave is a probability and not a physical wave, it is a mathematical one.

The dark fringes on the screen correspond to the troughs of probability waves. The probability that an electron enters this region is very low. The crest of the wave corresponds to the highest probability—most electrons strike those points of the screen, where the crests of the probability waves are. Everything seems logical. Yet at the same time...

Why do some of the electrons get at a point where the probability is high and others, where it is low? All the electrons are in identical conditions, are they not? Then why do they behave differently?

Some physicists explain this phenomenon in approximately the following way: the electron chooses its own path. According to them it has a "free will", in other words it can fly wherever it wants to.

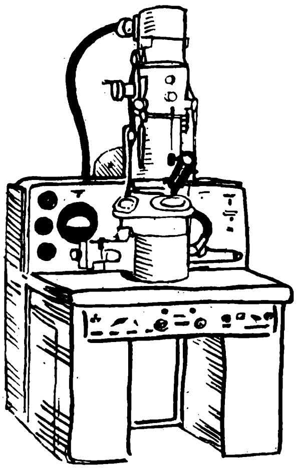
Such views should be regarded critically. The difference in the behaviour of electrons is the manifestation of statistical laws which govern the movement of an enormous mass of these particles.

There are laws of nature which man learns to apprehend and makes use of. Why talk about the free will of the electron? The whole history of electronics convinces us that the electron obeys the laws of nature; by making use of these laws, it can be made submissive to the will of man.

How Can A Molecule Be Seen?

Since electron waves exist in nature, this means that some use can be made of them too. These have one advantage compared to light waves: they are much shorter.

Have you ever watched the surf strike coastal rocks? Small rocks the surf does not seem to notice, it just runs on, leaving no trace. In the case of a large rock we have a totally different picture: the wave repelled by the obstacle runs



back against the next oncoming wave, and at the foot of the rock we can see the interaction of the oncoming and reflected waves.

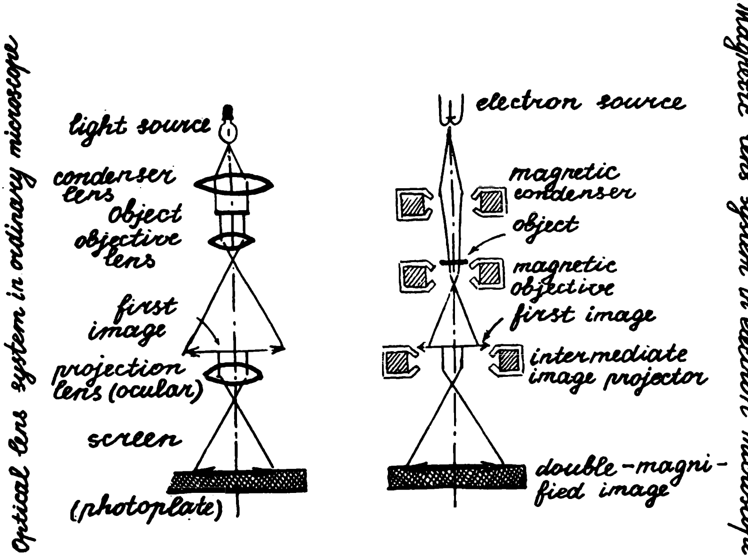
A light wave behaves in the same way. It is not reflected from objects whose size is smaller than the length of the wave. It is impossible to distinguish between two objects if the distance between them is less than the length of the light wave. This is the reason for the limited possibilities of optical microscopes: it is the light wave that passes through the system of magnifying lenses of the microscope.

The smallest object which can be seen here is commensurable with the length of the light wave. This wavelength comes to some ten-thousandths of a millimetre or, to be more precise, from 0.4 micron (violet light) to 0.7 micron (red light). For an image to become visible its size must exceed tenths of a micron. Only then it will be possible to magnify it to a significant size, say to several millimetres, i.e. several thousand times.

And this is all that an optical microscope is capable of.

Things are quite different with an electron microscope. Here we have to do with electron waves which can be even 100 000 times shorter than light waves. All that need be done is to accelerate the electrons to a certain velocity and they, obeying the formula evolved by de Broglie, will give birth to waves of the necessary length. True, no mean price has to be paid for this: to accelerate the electrons to the required speed, it is necessary to supply the anode with a voltage of the order of hundreds of thousands of volts.

The optical lenses of an ordinary microscope are successfully replaced by the magnetic ones we have already dealt with. Electron waves can discern objects 100 000 times smaller than light waves can. But still the microscope does not allow such objects to be seen, because magnetic lenses focus the beam worse than do optical lenses. The magnification of an electron microscope is only 100 times greater than that of an optical microscope.



"Only..." But this is not a trifle. At any rate it was only due to electronics that man could see a molecule, observe the reproduction of viruses and study the structure of proteins. And this knowledge allowed biology—the science of life—to make yet another big stride ahead.

What Does The Brain Radiate?

One of the laboratories of the RSFSR Academy of Sciences, headed by A. N. Sokolov, worked on a new and interesting problem: recording and interpretation of unpronounced words. What did the experiments bring to light?

It was found that several tenths of a second before we pronounce a word, the speech-forming organs receive a signal from the brain. If special electrodes are attached to the tongue or lips of the test person, it is possible to detect these signals, even in cases when the word was pronounced mentally and not aloud.

Is that mind reading? Partly yes. True, the recordings of these signals, the so-called biopotentials, are not easy to interpret. But something has already been achieved. It has been found that it is possible to read individual unpronounced sounds and that the biopotentials are directly related to the process of thought: the harder the question put to the person undergoing test, the higher the measured potential.

Of course, there could be no progress without electronics. To record the biopotentials an extremely weak signal has to be amplified. The signals are interpreted with the aid of an electronic computer.

But is it not possible to pick up the signals at the place where they originate? After all they are transmitted by the brain, and electronics allows the biocurrents generated by the brain to be recorded in the form of encephalograms. For this purpose electrodes are attached to various parts of the head, being filled with a special current-conducting paste which improves the contact. Current from each of the electrodes is fed to its own amplifier, from whose output the signal is fed to an electromechanical recording device or to a special screen. On the screen or the recorder tape one can see intricate and multiform curves, corresponding to various parts of the brain cortex—from 30 different points 30 different curves.

But if we take into account that each point includes millions of cells along which a multitude of different pulses circulate, then it is easy to see how hard it is to interpret such a signal. In exactly the same way, if you were to get connected to a common telephone cable that carries thousands of telephone conversations from one end of a town to the other, you would not be able to make out a single articulate word from among thousands of simultaneously pronounced ones.

No wonder that so far only the most general things could be understood: what frequencies does the signal sent by the brain contain, how to tell with the aid of an encephalogram whether the brain is vigilant or deeply asleep. As for interpreting words or thoughts, there is still a long way to go.

Is it not possible that there are other ways of solving this problem? Cases have been observed when mental information was transmitted directly from brain to brain. And in the electronic age it is unlikely that anyone is seriously going to attribute such phenomena to supernatural forces: if by modulating a carrier signal it is possible to transmit television pictures, then why visual images developing in someone's brain cannot be transmitted in a similar way. But if telepathy is possible, why can we not design a receiver that would be able to receive the radiations of a brain no worse than a telepathist?

Is it not possible that such a receiver can actually be designed? But to do this it is first necessary to understand the nature of signals carrying the thought in telepathy. And their nature is something out of the ordinary. For instance, it has been established that communication by telepathy is possible over any distances (within the confines of the globe, of course) and, what is more, it knows no obstacles. Attempts were made to place various shields impenetrable to electric and magnetic fields between the inductor (the one who transmits mental information) and the percipient (the one who receives). But they had no effect on telepathy. And this bewilders the scientists, for such properties are not possessed by electromagnetic waves of any of the frequencies investigated. This means that mental information is radiated by the brain with some other kind of carrier wave. But what wave? Nobody knows it so far. It is only possible to put forth hypotheses and then check them whenever possible. Now, in nature there is a particle possessing the same exceptional qualities. By this is meant the neutrino. The neutrino travels at the speed of light and has a zero rest mass. In this respect the neutrino is very much like a photon. But it also has features all of its own. In particular, there are no obstacles for this particle. The neutrino interacts but slightly with other particles and therefore nothing hinders its travel, including the whole mass of the globe and even a slab of cast iron having a thickness thousand million times the distance from us to the Sun! May it not happen that this is the neutrino that carries mental information? But can an image be transmitted "astride a particle"? It can. In the final analysis, radio waves also comprise particles. Einstein proved that such waves consist of photons. Then why can we not suppose that particles similar to photons form neutrino waves? True, such waves have not been observed. Well, and what of it? Radio waves were picked up at a much later date than they had been discovered by Maxwell. And how long radio waves were handled without even suspecting that they consisted of particles!

Is it not possible that the opposite will happen with neutrino waves? So far it is the neutrino particle that has been discovered, and then, may it not happen that the field of neutrino waves will be brought to light too?

CHAPTER IV. UP THE FREQUENCY SCALE

ABOUT HOW FROM YEAR TO YEAR MANKIND KEPT MASTERING EVER SHORTER AND SHORTER WAVES, AND WHAT ELECTRONICS HAD TO GO THROUGH WHEN MASTERING SUPERHIGH FREQUENCIES.

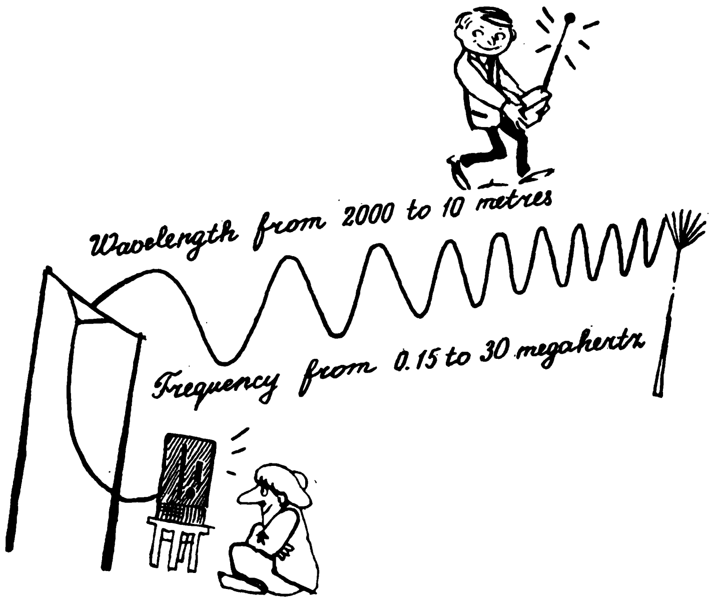
THIS LIES AT THE BASIS

IV.1

For various purposes modern engineering makes use of different wavelengths. The waves are provided by electronics. A multitude of electronic circuits have been developed for obtaining waves whose length ranges from several kilometres to some millionths of a micron.

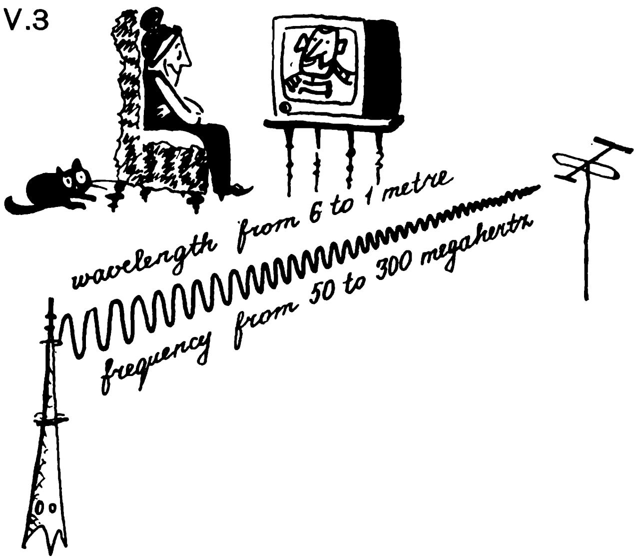
IV.2

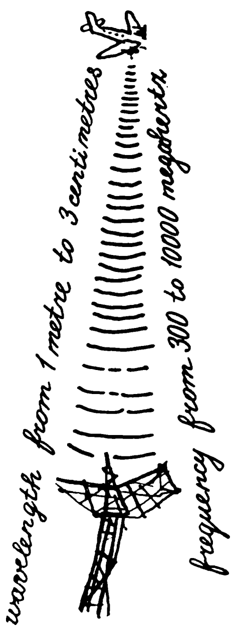
Wavelengths from 2 kilometres to 10 metres are used for radio communication.



From the formula given in Fig. III.15 it is easy to calculate that a wavelength of 2 kilometres corresponds to a frequency of 0.15 megahertz (or 150 kilohertz), and a wavelength of 10 metres, to a frequency of 30 megahertz.

IV.3





The radio wave band is followed by the television band. It makes use of wavelengths from 1 metre to 6 metres. This corresponds to frequencies from 300 to 50 MHz. Thus the width of the band used for television transmissions is 300—50 = 250 MHz.

IV.4

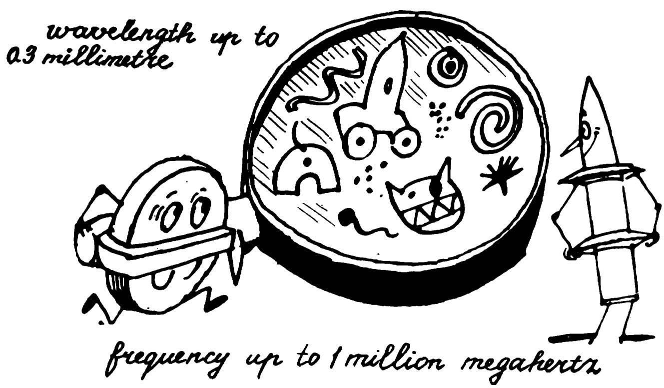
The television band is followed by the radar band. This employs wavelengths from several metres (usually less than one metre) down to 3 centimetres (from 300 to 10 000 MHz). The width of the frequency band in this case is 10 000—300 = 9700 MHz.

This band is so broad that there is room enough for all. At present it is being ever more widely used for radio communication. To increase the communication range use is made of relay stations installed on artificial satellites, for example.

Centimetre waves are obtained with the aid of special devices such as, for example, magnetrons, klystrons or travelling wave tubes.

IV.5

In recent years the numerous family of electronic devices has been augmented by new members—devices for generating millimetre and even shorter (submillimetre) waves.



There have been developed the dioctron, carcinotron, harmodotron, microtron, resnotron, and so on and so forth. All these are experimental devices, and it is not yet known which of them is fated to gain such popularity as is at present enjoyed by their elder brethren—the magnetron and the klystron.

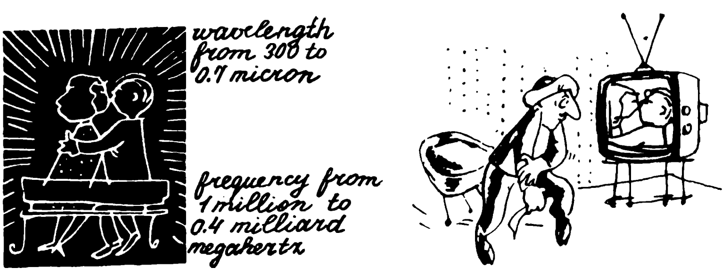
IV.6

The frequency band available for communication has broadened exceptionally with the development of quantum oscillators—lasers.

Lasers have extended the band to wavelengths of up to 0.4 micron, i.e. to frequencies of 750 000 000 MHz.

This band coincides with that of visible light rays (0.4-0.7 micron, i.e. 750 000 000 to 400 000 000 MHz). This is 30 million times wider than the range of frequencies contained in a television picture. This means that by using laser rays as carrier signals it is possible to simultaneously transmit 30 million television programs.

IV.7



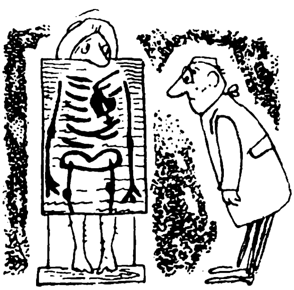
Proceeding up the frequency scale, we missed one step—the frequency band just below that of visible light: *infrared rays.*

"Infra" means below. The frequency of infrared waves is lower than that of rays of visible red light. Infrared rays cannot be seen with the naked eye. They occupy a band between millimetre and light waves, from approximately 400 000 000 MHz to 1 million MHz (wavelengths from 0.7 micron to 0.3 millimetre).

These waves proved very convenient for radar. No special oscillators are required to obtain them, since all bodies are "transmitting stations", radiating into space infrared thermal waves. Some objects radiate the heat received from the Sun, others their own heat (heat of the blood, heat of engines, etc.).

For such a radar only a sensitive receiver is required, and then even in total darkness it will detect the presence of such bodies.

IV.8



X-rays, whom everybody is acquainted with, employ waves 10 000 times shorter than those of visible light (up to hundred-thousandths of a micron).

The record in shortness of wavelength belongs to electron microscopy, where waves of some millionths of a micron are used.

IV.9

The shortest and longest of all known waves come to us from space. Among the waves that arrive from space some have been discovered with a wavelength of 30 million kilometres. Their period of oscillation lasts 100 seconds. Only five such waves are necessary to cover the distance from the Earth to the Sun.

At the same time cosmic rays contain oscillations with a wavelength of only 0.005 angström (ten-millionth parts of a micron)!

IV.10

To give a complete picture it should be mentioned that according to the latest scientific data waves from 8 to 14 microns are "olfactory waves" or "waves of smell". Perhaps in the future, when electronics masters such waves, it will be possible to convey smells, like pictures and sound are conveyed now.

From A Kilometre To Fractions Of A Micron

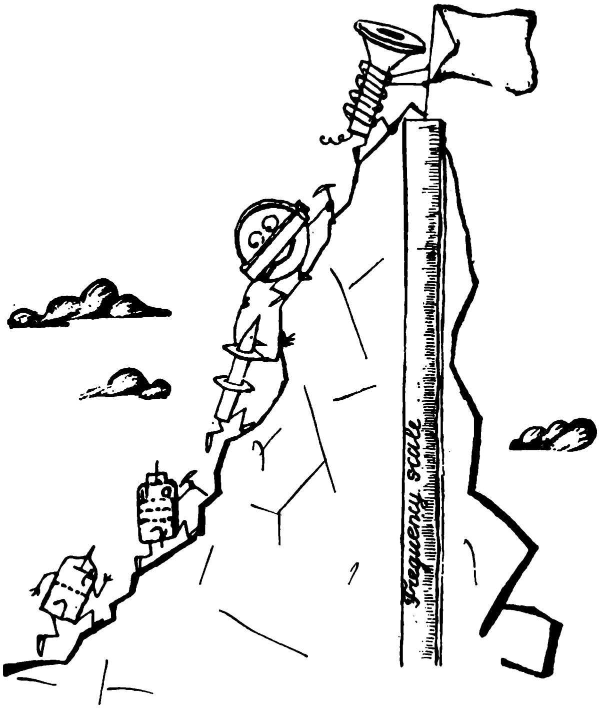
Much can be said about the history of electronics. But its essence can be expressed very briefly: the history of electronics is the history of the shortening of wavelengths.

Let us recall the stages in the development of radio communication. At first, long waves were mastered*. Then researchers discovered that short waves are capable of bouncing between the sky and the earth and in this way can be transmitted around the whole globe. So, short waves were taken up seriously. In several years they were shortened ten-fold, with a corresponding ten-fold increase in frequency.

By that time television was born. It required ultrashort waves. And again the frequency had to be increased ten-fold. And this is where the first complications set in: on extending into the ultrashort wave band the triode began to fail. It became necessary to introduce additional grids into the valve: thus tetrodes and pentodes appeared.

* It should be noted that radio waves first obtained by G. Hertz had a wavelength of the order of several tens of centimetres. But these waves were obtained not with the aid of electronic devices, but by means of a spark discharge and at first found no application in radio communication.

But these difficulties proved only the beginning. When radar demanded of electronics waves as short as 3 centimetres then all the equipment had to be developed anew. Valves of the usual design could no longer operate here, nor were the former LC tuned circuits of any good. And so, the family of electronic devices acquired new members. Instead



of valves with glass envelopes there appeared intricate configurations and combinations of ceramics and metal. The vocabulary of electronics became supplemented with such names as lighthouse tube and even more strange ones: klystron, magnetron and travelling wave tube.

Such is the fate of electronics: knowing no respite or breathing-space it must continue to clamber up the frequency scale. Clamber is, probably, the very best word because it reflects the difficulties encountered by electronics in the region of superhigh frequencies. New problems arose at each step and it is only the persistence and inventiveness of experts throughout the world that can explain the fact that, despite all obstacles, the frequency of radiations increased from year to year, as various allied fields required it of electronics for satisfying various technical needs.

The tradition is still maintained today. We are witnesses to yet another great stride into the region of high frequencies.

Utilizing instead of radio circuits the radiation of atoms and molecules, that branch of engineering, which at the very beginning of the book we called photonics in jest, is successfully mastering wavelengths as short as fractions of a micron.

This is very indicative of the successful development of electronics.

In half a century electronics has managed to "compress" waves several thousands of millions of times and, beginning from wavelengths measured in kilometres, to proceed to wavelengths of fractions of a micron.

What Do Short Waves Weigh?

—"Very well"—the reader might say,—"perhaps, increasing frequencies and shortening wavelengths was really not so simple. But was there any need in posing such problems and then applying so much effort to solve them? Radio got along quite well without short waves!"

Yes, it did. But the range of radio communication was limited. As for television, without ultrashort waves it could not function even over short distances. For transmitting many programs television requires still shorter waves. Why? This is why.

Television signals occupy a broad frequency band from several hertz to 6 MHz (see III.41 and III.42). When through modulation this signal is superimposed on the carrier signal, the band doubles and becomes equal to 12 MHz.

So, if the question of simultaneous transmission of several programs arises, then each program must be provided with its own channel having a width of not less than 12 MHz.

The ultrashort wave (very high frequency) band used by television covers frequencies from 50 to 300 MHz. How many programs can be transmitted simultaneously within this band?

The calculation is simple. The number of programs is equal to that of channels N, and

$$N = \frac{300-50}{12} \approx 20 \text{ programs}$$

This would seem sufficient, if television centres were to broadcast 2-3 programs. But really it's not enough. If we wish to set up a videotelephone network in a city, then the whole ultrashort wave band will be taken up by only 20 video subscribers!

And how many such channels can the centimetre wave band provide?

Let us estimate. Waves with lengths from 3 to 10 centimetres correspond to a frequency band of from 10 000 to 3000 megahertz. This can be easily ascertained: wavelengths are converted into frequency by the formula given in Fig. III.15.

The number of telechannels N is calculated as before:

$$N = \frac{10\,000-3000}{12} \approx 580$$

This already is much better. Five hundred and eighty videotelephones—this already smacks of video communication.

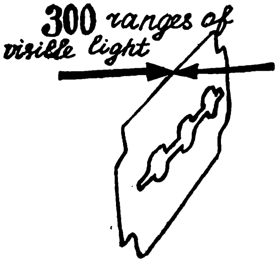
But, if the number of subscribers in the city approaches tens and hundreds of thousands? How is the problem of video communication to be solved?

Oscillations with frequencies below 50 MHz cannot serve as carriers: they will distort the "design". And the whole frequency band from 50 to 10 000 MHz (wavelengths from 6 to 3 centimetres) can accommodate only:

$$N = \frac{10\,000-50}{12} \approx 830 \text{ programs}$$

Where are the tens and hundreds of thousands of channels to be obtained if the city should be fully videotelephonized? Only one possibility remains: wavelengths must be shortened still more and frequencies raised.

But now we come to a very essential hitch: when wavelengths are compressed to fractions of a millimetre, then electronic devices become "exhausted", just like in the earlier stages of wave-shortening the triodes have become "pooped out". What is to be done about it? Give up all hope of ever having videotelephones?



By no means! Besides electronics there already exists photonics, and this is a job that it can easily do.

Getting somewhat ahead of our story, it can be said that photonic oscillators (lasers) generate light with wavelengths of 0.4 to 0.7 microns (frequencies from $4 \cdot 10^{14}$ to $7.5 \cdot 10^{14}$ oscillations per second, that is 0.4 to 0.75 thousand million megahertz).

How many television programs can fit into this band? Let us calculate:

$$N = \frac{(0.75 - 0.4) \times 10^{9}}{12} \approx 30 \text{ million programs!}$$

Now this is scope for you! But our ascent up the frequency scale has been so tempestuous that the reader must hardly have had the opportunity to perceive everything that has unfolded before him, when we have reached the peak—the optical frequency band.

Now we probably can take a short breathing-space and think about everything that we have met on the way.

All the light waves with lengths from 0.4 to 0.7 micron occupy a microscopic section of the scale. The length of this section is only 3 ten-thousandths of a millimetre. Nearly 300 such sections can fit on a razor's edge. And each of these sections can accommodate 30 million television programs!

At the same time the whole of the radio broadcast band with wavelengths from 1 to 2000 metres (two kilometres!) can barely accommodate 20 television programs! The first impression is that this is paradoxical.

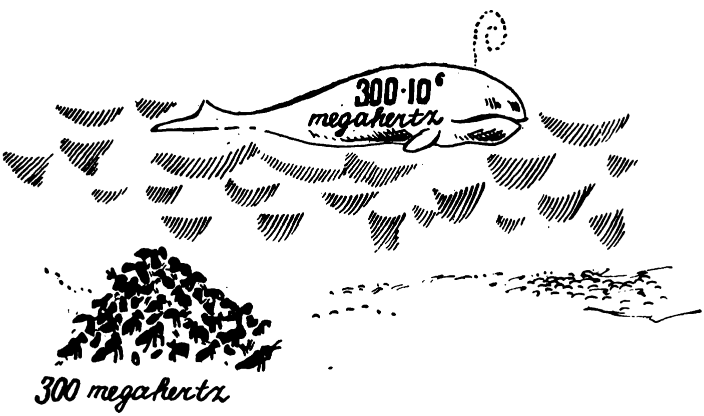
On the one hand we have a microscopic section of the scale only 0.3 micron long which accommodates all the light waves. And on the other, a distance that begins 1 metre from your doorstep and ends in another street two trolleybus stops away. This space accommodates all the wavelengths of radio waves used.

Why is it that an infinitesimally small section can contain a million times more information than a path stretching 2 kilometres?

The explanation is very simple. When evaluating the spectra of signals within the band of channels over which the signals are transmitted, it is not the scale of wavelengths but the frequency scale that is used

From formula III.16 it is easy to ascertain that the longest wave in the radio broadcast band ($\lambda = 2000$ metres) corresponds to a frequency of 0.15 MHz or 150 kilohertz.

The longest wave in the light wave band ($\lambda = 0.7$ micron) corresponds to a frequency of $0.45 \cdot 10^9$ MHz (0.45 milliard MHz). This frequency is $3 \cdot 10^9$ times higher than that of a signal with a wavelength of 2000 metres.



This is about how much an ant (weight—about 3 milligrams or 3 thousandths of a gram) is lighter than a medium-sized sperm-whale (weight—about 10 tons).

But here we must point out one circumstance. Perhaps, to many it may seem strange that the "sperm-whale" has turned out to be not the waves whose length is measured in kilometres, but those whose wavelength is some fractions of a micron. We are comparing a sperm-whale and an ant according not to their size, but to the weight. And the "weight" of radio waves increases with their frequency.

The highest frequency of light waves is approximately twice that of the lowest one; it is equal to $0.75 \cdot 10^9$ MHz. The light wave band, that is, a section of the scale which lies between the highest and the lowest frequencies is:

$$0.75 \cdot 10^9 - 0.4 \cdot 10^9 \approx 0.3 \cdot 10^9 \text{ MHz} = 300 \cdot 10^6 \text{ MHz}$$

And in the radio communication band the highest frequency is not twice, but 2000 times higher than the lowest one. And nevertheless, the frequency band is considerably narrower. It is only $300 - 0.15 = 298.85$ MHz, i.e. about 300 MHz.

And there is nothing strange in this. Two sperm-whales weigh 10 tons more than one whale. And 2000 ants are only $3 \cdot 10^{-3} \cdot 2000 - 3 \cdot 10^{-3} = 5.99$ grams heavier than one ant!

So it is with radio waves. Comparing the width of the radio broadcast band (300 MHz) with that of the light wave band ($300 \cdot 10^6$ MHz), we become convinced once again that the radio broadcast band "weighs" one million (10^6) times less than the optical band.

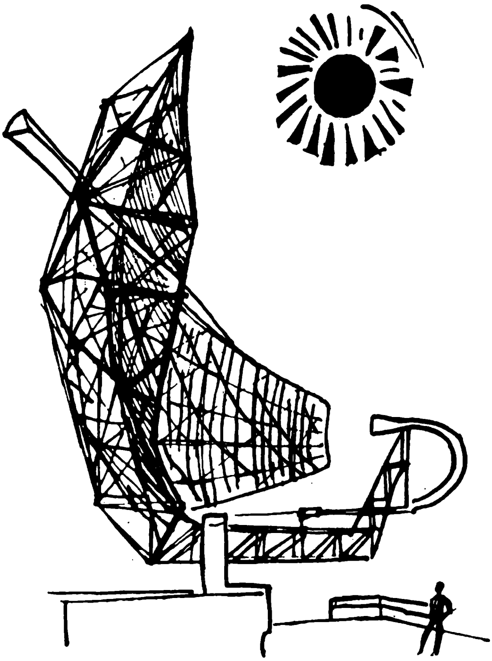
The Problem Of Narrow Beams

Now it is quite clear why electronics does everything it can to shorten wavelengths. Only in the band of the shortest wavelengths there is abundant space for communication and for transmitting any information.

The short, medium and long wave bands have long ago become too tight for radio communication. Now it is becoming too tight for television in the ultrashort wave band. Therefore radio communication has recently begun intensively mastering centimetre waves and in time television will, evidently, proceed into the light wave band. There it will have far more room. Red light alone has so many shades that the inhabitants of a whole city will be able to see one another by videotelephones operating with red rays only, without interfering with one another.

Lack of space is a significant factor that makes electronics shorten wavelengths. But there is yet another reason of no less importance. For solving a whole number of problems directivity of radiation is required: the waves must be radiated by the antenna not in all directions, but only in one and in a narrow beam.

This became especially important in radar. With the aid of the beam it is possible to determine the exact position of the reflecting object. In Alexander Pushkin's well-known story, the golden cockerel turned his head in the direction of the oncoming foe. A radar station indicates the direction



of the enemy by turning its antennas. The direction will be indicated exactly if the antenna of the station radiates waves in a narrow beam.

And to form such a beam it is necessary for the size of the antenna to considerably exceed the length of the radiated waves.

The first radar station (this was in the early forties) gathered metre waves into a beam with the aid of enormous antennas.

The beam intercepted the enemy's aircraft in the sky and indicated where the guns should be aimed at. Flyers could not put up with this for long. It became extremely urgent to equip aircraft with radar too. But how was this to be done? You cannot install an antenna two stories high on an aircraft! However, it is possible to decrease the size of the antenna many times without disturbing the condition of directivity of radiation, according to which the antenna must be many times larger than the length of the radiated waves. To do this we must approach the problem from the other end: instead of increasing the size of the antenna we can decrease the wavelength.

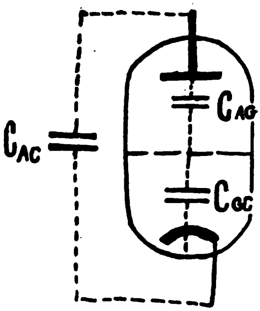
When wavelengths were decreased to the centimetre range it became possible to design compact and effective aircraft antennas.

What it cost to obtain centimetre waves, we shall discuss somewhat later. But now let us return to that stage in the history of electronics, when the development of television and long-distance radio communication demanded of electronics the mastering of short and ultrashort waves.

Grids Began To Multiply

At the first stage of the development of radio communication, the triode was coming to the rescue of electronics in all cases: it was helping to generate alternating currents, which could easily be converted into waves, to amplify, modulate, detect, convert signals into intermediate-frequency ones, in short, to do all the operations without which there could be no radio communication. But when life demanded the mastering of ultrashort waves, then there came to light that shortcoming of triodes which had not been noticed with lower frequencies. The thing is that the electrodes of a triode (anode, cathode, grid) are like the plates of a capacitor between which there exist definite capacitances C_{AG}, C_{GC}, C_{AC}.

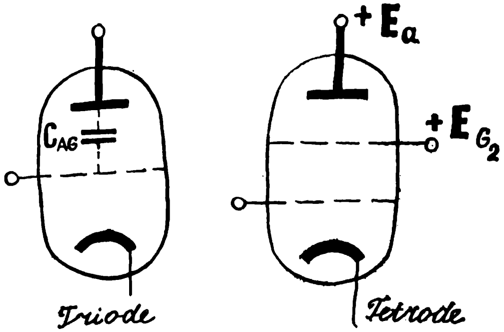
As you remember (see III.25) the higher the frequency of the signal, the easier it is for it to pass through a capacitor. On changing over to short and ultrashort waves, frequencies have become very high. As a result, the capacitance existing between the anode and the grid, which has no effect when the valve operates at low frequencies, has become a readily passable bridge for high frequencies. This bridge lets pass through some of the energy from the anode to the grid of the triode. In a triode oscillator such a bridge is



made on purpose: with its aid the necessary feedback is obtained to ensure oscillation (see Chapter III, "Why Do Rivers Flow?"). But if a triode has to operate as an amplifier, then such a "bridge" does nothing but harm. The undesirability of such a feedback (or coupling) can be judged by the name given to it by the specialists—it is known as parasitic feedback. Because of this feedback triode amplifiers operating at high frequencies generate their own oscillations, instead of amplifying the incoming signal.

How can this dangerous "bridge" be destroyed and the parasitic feedback eliminated?

It is possible to reduce the capacitance between the anode and the grid by decreasing their size or moving them farther away from each other (see III.21).



But both the one and the other deteriorate the electrical characteristics of valves. Designers have found another way out. They have introduced another grid into the valve and applied a positive potential to it. Around this second grid there develops a field which opposes the current flowing through the parasitic coupling.

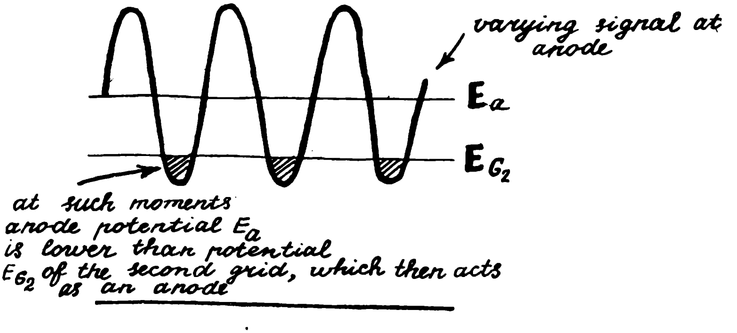
That is how tetrodes—valves with four electrodes (tetra in Latin means four)—have come into being. They have made it possible to design amplifiers intended for handling signals with frequencies up to tens of megahertz, without any fear that one fine day such an amplifier will become excited, in other words will begin generating a parasitic signal of its own. It would seem that the designers of valves have overcome the first difficulty caused by the change-over to ultrashort waves.

Nothing of the kind! When tetrodes have become operative, yet another trouble—secondary emission—has arisen.

Three Instead Of One

Secondary emission occurs in the following way. Since the anode is made of metal, it contains an "electron fluid" —free electrons which move between the atoms of the lattice (see II.10). Electrons coming from the cathode dislodge some of the free electrons of the anode. This is known as secondary emission (primary emission is the one occurring at the cathode).

The second grid of the tetrode also possesses a positive potential, therefore some of the electrons dislodged from the anode are attracted to it. This flow is especially intensive with the alternating anode current wave at its lower half. At such moments the potential of the second grid proves higher than that of the anode, thus causing the valve to operate in an "upside down" manner: the second grid begins to attract electrons as if it were the anode, while the anode functions like the cathode, radiating an undesirable electron flow due to secondary emission. This flow depends on the anode voltage, varies with the frequency of the anode current and distorts the amplified signal. Why does this effect become noticeable only in tetrodes? Don't the electrons in the



triode strike the surface of the anode? Does not secondary emission occur there?

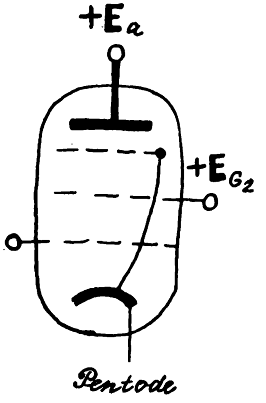
All this does occur. But in the triode secondary-emission electrons bother no one, and that is why they were not noticed. And indeed, an electron dislodged from the anode has nowhere to go, because in the triode, besides the anode, there are no other electrodes with a positive potential to attract it. Under the action of the field of the anode the electron is forced to fall back onto the latter. That is why before the introduction of the second grid into the valve the secondary-emission effect really bothered no one. But in the tetrode it turned into a problem, an obstacle, that had to be immediately eliminated.

It was eliminated with the aid of the third (suppressor) grid which barred the way for secondary-emission electrons between the anode and the positively charged grid, and thus a five-electrode valve, the pentode, was born.

The pentode has helped radio communication to amplify short waves. In particular, with its aid it is possible to amplify a signal carrying a television picture. And all this has become possible because the third grid has enabled the harmful effect of secondary emission to be eliminated.

It should be mentioned, incidentally, that electronics has developed such devices in which secondary emission produces a very useful effect.

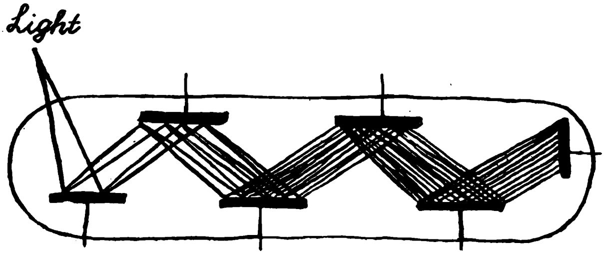
The stream of electrons produced through the action of light because of the photoemissive effect is usually very weak. But by directing this stream at another special electrode it is possible, due to secondary emission, to obtain a much stronger stream. Then the secondary-emission electrons are directed towards a third electrode, which, being "bombarded", emits in its turn secondary-emission electrons. Then they are aimed at a fourth electrode, etc. The result is an "avalanche" which at each stage becomes more and more powerful. Thus, a few "stones"—electrons dislodged by light from the first electrode—give rise to a whole



Pentode

"landslide" owing to the secondary emission of several anodes disposed in their way.

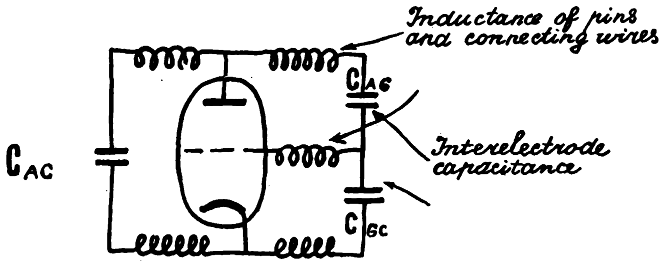
That is how the photomultiplier—a device which enables a small current caused by the photoeffect to be converted into a powerful signal—operates.



Causes Of The Second Crisis

Diseases of growth are an inevitable phenomenon. Any branch of science and engineering in the course of its development must go through a number of crises, when it becomes necessary to thoroughly revise the former methods and ideas.

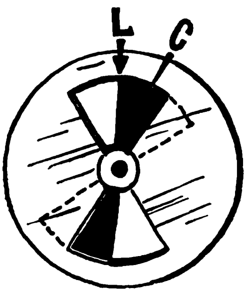
The result of the first crisis experienced by electronics was the birth of multigrid valves.



The second crisis came at the moment when radar set the task of mastering centimetre waves.

What was the cause of this crisis?

Let us recall an ordinary *LC* tank circuit. Its natural frequency is the lower the higher the value of the capacitance *C* and the inductance *L* (see III.7). But the triode oscillator circuit including our tank has, in addition to the tank capacitance, parasitic capacitances we have already dealt with: C_{AC}, C_{GC} and C_{AG}. And if the effect of the "parasites" is already noticeable with ultrashort (metre) waves, then what is to be expected in the case of waves which are 100 times shorter still! Now any part of not only the electronic circuit, but even of the valve itself becomes a "parasite". A short piece of wire begins functioning as an antenna, because its length is commensurable with that of centimetre waves. The pins of valves, via which voltage is applied to the electrodes, also become "parasites": they possess an inductance which is quite noticeable at such high frequencies. And together with the interelectrode capacitances the pins form parasitic tank circuits.



The valve has become all "overgrown with parasites", each of them possessing its own natural frequency and preventing the oscillator from producing oscillations of the required frequency. And indeed, it is not so simple to tune the anode circuit to a frequency of, say, 10 000 MHz. To raise its frequency it is necessary to decrease its capacitance and inductance. It is possible to disconnect the capacitor completely and to wind off all but two-three turns of the coil. In essence there will be nothing left of the tank circuit, and yet due to the effect of "parasites" its natural frequency will be much lower than 10 000 MHz. For example, for waves from 39 centimetres to several metres (i.e. for frequencies below 1000 MHz) a tuned circuit, known as butterfly circuit, has been developed. The wings of the butterfly form a small capacitor. And instead of the coil there has remained a short jumper—merely a single incomplete turn!

And still the natural frequency here is not high enough; to generate centimetre waves it is necessary to raise the resonance frequency 10 times more. In addition, with an increase in the frequency another shortcoming of the butterfly circuit becomes manifest. When the wavelength is shortened to the size of its jumpers, the latter become like antennas. The oscillatory energy of the circuit begins to be radiated uselessly into space and the circuit efficiency sharply falls.

The solution to this problem demanded a lot of ingenuity on the part of the specialists. As a result of their efforts new tuned circuits looking like cups had made their appearance and, finally, there was developed a ... triode.

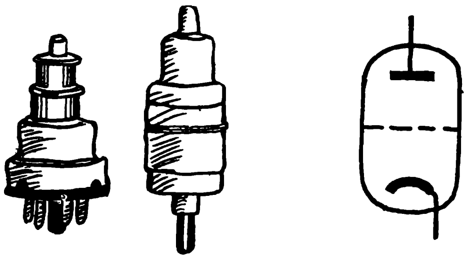
You needn't be surprized, it was not a tetrode, nor a pentode, but a triode. But this triode was specially developed for superhigh frequencies (SHF) and it is only vaguely reminiscent of the earlier low-frequency triode.

A DIFFERENT KIND OF TRIODE

THIS LIES AT THE BASIS

IV.11

You see before you two representatives of a large family of electronic devices designed for superhigh frequencies (SHF). Inside these valves one can find all the elements of ordinary triodes: anode, cathode, grid, heater. But their



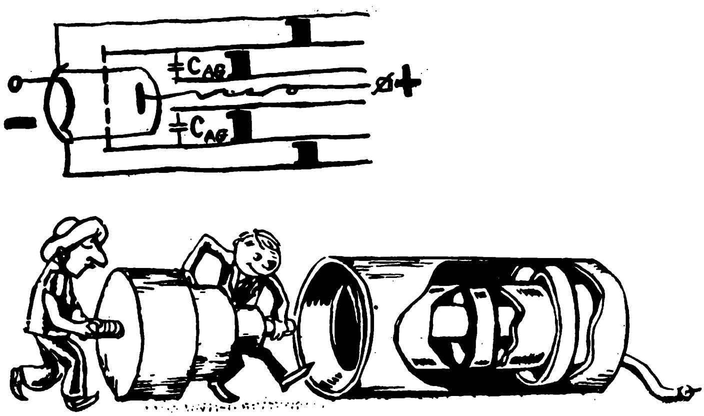
outward appearance is totally different from that of the former valves. And inside them a good deal is different from the earlier triodes.

The envelope of the valve at the right is made up of a set of metal cylinders, and its ends are closed with ceramics. These valves are known as metal-ceramic valves.

The left-hand valve is of the lighthouse variety; its envelope is stepped and is reminiscent of a lighthouse. The odd shape of SHF triodes will become quite understandable after we get familiar with the SHF oscillators in which these triodes are used.

IV.12

In an oscillator employing a lighthouse triode you will not find an ordinary tuned circuit consisting of *LC* components. Here the tuned circuits are shaped like cups and are fixed directly to the disk terminals of the valve. The valve merges, as it were, with the tuned circuit, that is why no pins can be seen and, consequently, there is no parasitic inductance. As for the parasitic capacitance (for example, C_{AG}), it is connected to the tuned circuit and becomes an integral part of it.



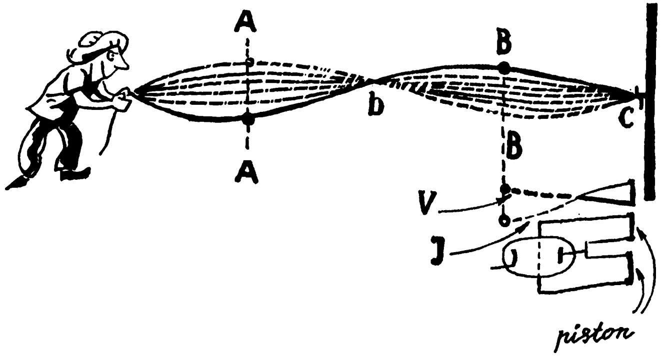
IV.13

Tuned circuits of this type are called *cavities.* Inside them standing waves develop.

These waves are somewhat similar to the waves formed by a cord one end of which is secured to a wall and the other, uniformly moved up and down. The wave will travel to the wall, will be reflected and then begin returning. And the crest of a new wave travels forward to meet it. As a result of superposition of the forward and reflected waves the cord will form standing waves. At some points (*AA*, *BB*, see page 204) loops will be formed: here the cord oscillates with the greatest swing. At the same time other points (*a*, *b*, *c*) remain motionless, despite the presence of waves: they are known as nodes of the standing wave. Point *c*, where we have secured the cord will be the first node.

The waves in the cavity are, of course, of a different nature: here oscillations of magnetic and electric forces occur.

But once again we see that waves of different nature have common properties: in the cavity there are also loops and nodes. The piston of the cavity serves as the wall to which the cord is tied: that is just where a voltage node is formed. After all, a piston is a short-circuit: in this place the resistance (and, consequently, the voltage) will equal



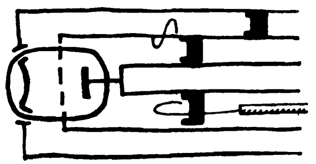
zero (see the voltage curve V). But where resistance is low, current is large. That is why a current loop is formed precisely here (see curve I). Shifting of the piston causes the voltage node and the current loop to move together with the piston—the length of the standing wave varies.

Much in the development of the theory of cavities should be put to the credit of the Soviet scientist M. Neiman.

IV.14

To generate oscillations feedback is necessary. This feedback is obtained with the aid of a special coupling loop which transmits energy from the anode circuit to the grid circuit.

Another loop allows some of the energy of the anode circuit to be transmitted to the antenna and radiated into space.



Where there is the current loop (i.e., at the piston), the magnetic field is also intense. That is why the coupling loop is placed precisely here.

The same energy can be taken off via a capacitor. The capacitor must be placed as close as possible to the voltage loop, i.e. to the place where the electric forces are concentrated.

By shifting the piston to the left and right, the length of the standing wave is changed, thus tuning the oscillator to the necessary frequency.

Electrons Are Too Slow

What a hard nut to crack the SHF range was one can judge by the very appearance of the new oscillators. Everything had to be developed anew: circuit arrangements, valves and tuned circuits.

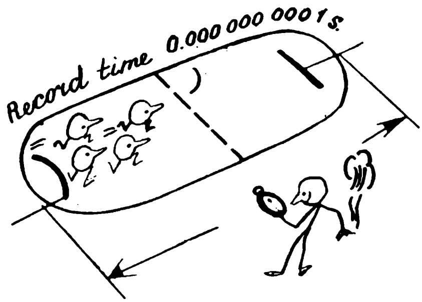
One would think that in the newly designed valves everything is provided for. Nevertheless, oscillators employing these valves cannot ensure frequencies of even 3000 MHz. At such a frequency the wavelength is 10 centimetres. And radar requires wavelengths three times shorter still. It needs wavelengths of 3 centimetres, i.e. frequencies of up to 10 000 MHz. Even the new valves cannot operate with such frequencies, although they have been especially designed for SHF. But why? The valves and the tuned circuits are an integral whole, you know, and the parasitic capacitances which had formerly been an obstacle have now merged, as it were, with the tuned circuits. There are no inductances—the pins have turned into disks, and the disks have also merged with the tuned circuits. Now what prevents obtaining oscillations of the highest frequencies?

The whole trouble is in one circumstance: in these valves the electron emitted by the cathode takes too long to reach the anode. What has happened to the electron here? What has become of its mobility and lightness which formerly had been admired all the time?

The electron has remained just as mobile. And the time it takes it to fly from the cathode to the anode is only one ten-milliardth of a second—this is 10 000 times shorter than a microsecond. But in the range of SHF oscillations even milliardth parts of a second also become decisive.

The trouble is that this is the very time (one ten-milliardth of a second) a full oscillation period lasts at a frequency of 10 000 MHz. While the electron is flying from the cathode to the anode, the voltage across the tuned circuit has had time to reach its maximum value, decay and then build up again. So we see that indeed, in comparison with the speed of variation of the voltage, the electron flies rather slowly. Even it has proven too slow for such high frequencies. In the time scale that we are accustomed to a ten-milliardth of a second cannot even be called a twinkling. But for SHF valves this twinkling is too long—they are far more sensitive to time than we are.

Up till now we have considered that in an oscillator everything occurs instantaneously: a signal develops at



the anode, passes through the feedback circuit to the grid and immediately gives a "push" to the anode.

But in the SHF region the concept "immediately" acquires a different meaning.

A signal has developed at the anode. Through the feedback circuit it has gone to the grid. The potential at the grid has increased and pushed a "slowish" electron towards the anode.

But while the electron is flying from the cathode to the anode, a positive half-wave at the anode has been replaced by a negative one. The arrival of the electron is most untimely. This is the same as if someone, who wants to increase the swing of a pendulum, tries to change the direction of its movement not at an extreme point of its path, but somewhere halfway. In this case, before giving the pendulum a push, it is necessary to stop it each time, as a result the oscillations will not increase their swing, but will be damped.

The same thing occurs in the triode: the flight (transit) time of the "slowish" electron is commensurable with the period of SHF oscillations, and produces a phase difference between the oscillations at the anode and the grid (see III.12), hence the feedback voltage begins operating "out of step".

How can the transit time be decreased? This may seem very simple—just shorten the path of the electron. That is indeed what has been done. In the triodes developed for SHF oscillations a gap commensurable with the thickness of a rasor blade accommodates the cathode, grid and anode. One cannot help recalling the master smith, as described by the Russian writer Leskov, who was able to make metal shoes for a flea.

But here it is not a technological difficulty to be overcome. A modern smith could have made a still smaller gap, if this would not worsen the quality of the valves.

The anode voltage of the valve is high. If the cathode is too close to the anode, a spark can flash between them. Yet another danger has to be taken into consideration: the closer together the electrodes are, the larger the parasitic capacitance (see III.21). And when the parasitic capacitance is large, even cavities cease to operate. What is the way out? If you move the electrodes farther apart, the transit time increases. If you bring them closer together, the parasitic capacitance increases.

Now this is a real crisis! A real vicious circle!

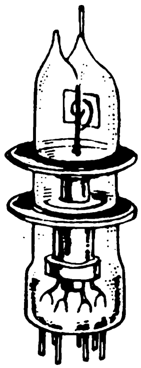
Should not an attempt, perhaps, be made to reduce the area of the grid, anode and cathode, while retaining a small gap? Then the capacitance will decrease, but the transit time will not increase. But, no, this is not the way out either.

A cathode with a small area will not provide the necessary amount of electrons! An anode with a small area will not be able to carry the necessary current!

All this has been taken into account when developing metal-ceramic and lighthouse triodes. All the dimensions here are not casual. The electrodes cannot be brought closer together—the parasitic capacitance will begin to interfere. Their area cannot be reduced—the current in the valve will be decreased and so will be the valve power. And radar requires powerful pulses for distant targets. As a result, these triodes have begun to be used for amplifying and generating waves longer than 10 centimetres. For producing waves with lengths of 3 centimetres, new ways have had to be sought.

Tuned Circuit As A Traffic Light

In the first SHF oscillators designed, the tuned circuit merges with the electronic valve. Is it not possible to go still farther—to design such an electron valve where the tuned circuit will be an integral part of the valve itself? It has been found to be possible. Such is the design of oscillators of 3 centimetre long waves—magnetrons and klystrons.

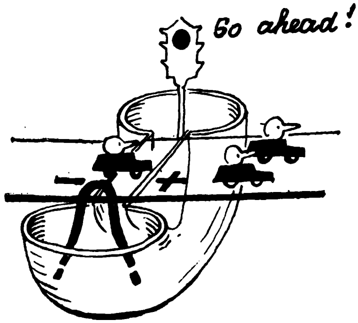


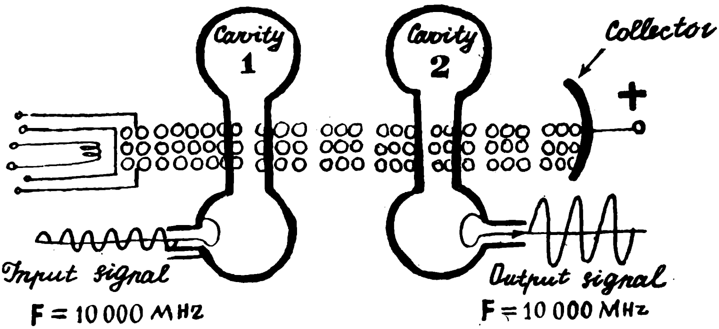
The klystron again makes use of the electron gun that we have already become acquainted with. The electron beam pierces the space inside the klystron and runs against a collector electrode to which a positive potential is applied. Two resonant cavities are installed in the way of the beam. They look like doughnuts. The holes of the "doughnuts" are covered with grids through which the electrons can freely pass. Inside the "doughnuts" there is an alternating field—the same standing waves as in the cavities in Sections IV.12 and IV.13.

Both cavities are tuned to a wavelength of 3 centimetres, i.e. to a frequency of 10 000 MHz.

Along the path from the start to the finish the electron first encounters cavity No. 1. Oscillatory energy with a frequency of 10 000 MHz is supplied here with the aid of a loop. During each period these oscillations act upon the electrons in different ways, and thus the electron beam undergoes bunching.

Something of the kind occurs in thoroughfares which are equipped with automatic traffic lights. As long as the light is green, drive along at full speed, catching up with those who are ahead. But, if you are out of luck, and the light has turned red, then step on the brakes and wait while the rest catch up with you. When the traffic light has turned green again you can continue on your way in the cluster or bunch of cars formed in front of the red light. On passing several traffic lights, all the cars are distributed into groups—some will wait at the light for those who are behind, others will catch up with those who were ahead.





Nearly the same thing occurs in the klystron: the electrons are cars, and the resonant cavities act like traffic lights. But the traffic light only shines a signal, according to which the drivers adjust the speed of their cars. In the klystron it is different. The cavity itself adjusts the speed: the electrons flying through its grids are either accelerated or retarded, depending on the sign of the voltage half-wave which is active in the cavity at the given moment.

If there happens to be the plus sign at the right-hand grid of cavity No. 1, and the minus one at the left-hand grid, the electric field will accelerate the electron which is between the grids. At the next moment the signs of the grids are reversed and the electron that then happens to be between the grids will have to slow down—the field will brake it. As a result there will be bunches of electrons, nearly the same as of cars on a thoroughfare.

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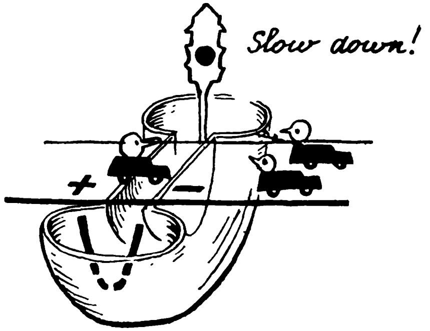
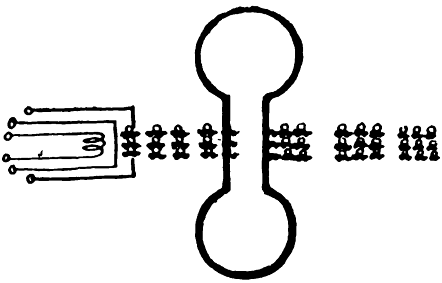
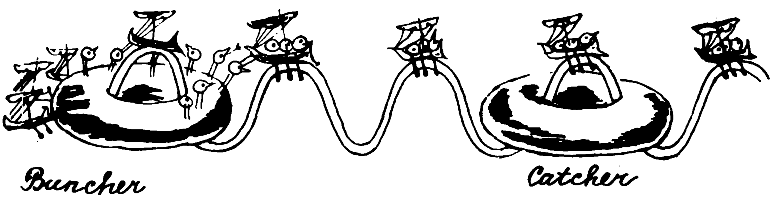




Klystron Means Surf

The word "klystron" was borrowed from the Greek. It means surf.

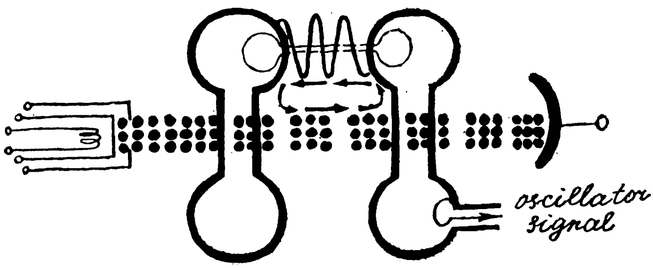
This name reflects well the principle of its operation. The electrons bunched by the first cavity act upon the second



cavity like the surf does on a floating wharf. One after another the bunches of electrons move past cavity No. 2, and each of them gives cavity No. 2 a push. How many such pushes are repeated every second?

The bunches develop at cavity No. 1—"traffic light". Electric oscillations applied to cavity No. 1 serve as the traffic light signals. The green signal of the traffic light (i.e. the accelerating half-wave of the voltage) alternates with the red light (the retarding half-wave) with a frequency of 10 000 MHz. This means that the bunches follow one another with the same frequency. These "surf waves" push the second cavity (it is called a catcher) 10 000 000 000 times a second, i.e. in step with its natural frequency.

And so, the electric oscillations applied to the first cavity (it is called a buncher) are conveyed by a stream of electrons



to the second cavity, both cavities being tuned to resonance. In the second cavity the oscillations will have a significantly greater amplitude. For they are born of electrons and the electrons preliminarily acquire a high energy from a static field. This field, formed by the collector and the accelerating electrodes of the electron gun, accelerates the electrons to very high speeds. In this respect the klystron is similar to any other amplifier: it amplifies oscillations at the expense of the energy of a d.c. source.

An amplifier can readily be turned into an oscillator: for this purpose feedback should be provided. If a loop is used to couple the catcher with the buncher, some of the energy of the catcher will be fed back along this circuit. This energy will be sufficient for the buncher to produce bunches, and a "surf" will develop inside the klystron. The waves of the surf will drive the catcher, and again some of the energy will return to the buncher—thus a closed circle is formed. The klystron will begin oscillating. The frequency of the oscillations will be equal to the natural frequency of the cavities.

But why is it necessary to couple the cavities of the klystron with a special loop to obtain the feedback? After all, the cavities have grids. The openings of the grids let pass through the whole stream of electrons. Then, why shouldn't the wave seep through the catcher to the buncher, thus ensuring the feedback?

The trouble is that the waves developing here have a length of about 3 centimetres, while the openings of the grids are far smaller. The wave will "not notice" such small openings. If waves and electrons possessed the power of sight, then for the electrons the grid would seem transparent, and for the waves, a blank wall.

Time Became Necessary

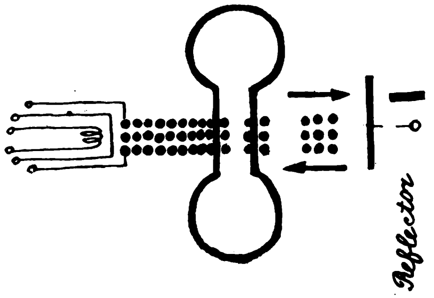
A frequency of the order of 10 000 MHz proved too much for the triode. But the klystron could easily cope with it. Why? Again we return to the transit time, i.e. the instant when the electron has already left the cathode but has not yet reached the anode.

With the change-over to the SHF range the triode has changed its appearance. In the new designs it became possible to do away with the difficulties which are connected with the effect of parasitic inductances and capacitances. But there remained too long a transit time, a deeply hidden, inherent and incurable defect.

How is this problem solved in the klystron? Most singularly: if for the triode the long transit time is a defect, for the klystron it is simply a must. For it is in this instant that the processes, on which all the operation of the klystron is based, must occur. During their transit the electrons should have enough time to group into bunches and excite on their way the catcher, from which a powerful, amplified signal is taken off.

And what is to be done with parasitic capacitances? After all, the cavities have grids through which the electrons fly. If the grids are brought close together they form a large capacitor. It may happen that its capacitance will not allow the cavity to be tuned to a frequency of 10 000 MHz. This means that the grids should be moved farther apart. The path between the grids will become long, and so will the transit time.

What an interesting picture there will be, if the time of transit between these grids becomes equal to the period of the SHF oscillations. While the electron is flying between the grids, the positive half-wave of the oscillations will be replaced by the negative one. And the wave, which at first has driven the electron will then begin to retard it. Acceleration, deceleration, acceleration, deceleration—and we see all the electrons flowing in a steady stream, without any



bunches. As if the traffic light has flashed the red signal for an instant and then the green one again, passing the stream of cars.

What is the way out of the situation? If the grids are brought closer together, the capacitance is high. Move them farther apart, and the cavity no longer bunches.

Only one circumstance comes to the aid. The thing is that the electron gun of the klystron accelerates the electrons to very high speeds. The overall transit time in this case remains significant—for it is a long way from the cathode to the collector. But the short distance between the grids the electron covers very quickly, even if they are spaced far apart. Consequently, the grids can be safely moved farther apart, thus decreasing the harmful capacitance, while operating with signals of the highest frequencies.

Again the advantage is on the side of the klystron, and the triode must own up once again that in the range of SHF oscillations it cannot hope to compete with the klystron. Especially after the klystron, when generating SHF oscillations, has become able to manage with one cavity instead of two.

In this klystron (it is called a reflex klystron) the following idea is embodied: if, to ensure oscillation, it is still necessary to use a loop for coupling the catcher with the buncher, then is it not possible to use one and the same cavity both for catching and for bunching?

This is exactly what has been done. With the aid of a cavity the electrons are bunched and made to fly towards a reflector—an electrode possessing a negative potential. The reflector is surrounded by a field from which the electrons bounce like a ball from a wall. On bouncing, the electrons fly back in the same bunches to the cavity and give up all their energy in the form of pushes which follow one after another.

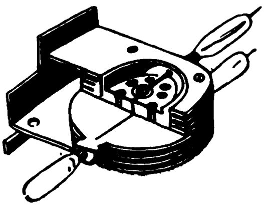
The frequency of the pushes (and consequently, the frequency of the oscillations) will necessarily coincide with the natural frequency of the resonant cavity, because the cavity has combined all the functions: the bunching, the catching of the energy and the feedback.

The first models of reflex klystrons were developed in 1941 by V. Kovalenko. Independently of him similar designs were developed by N. Devyatkov and I. Piskunov.

But the general idea of a klystron came up much earlier: it was suggested in 1932 by one of the pioneers of Soviet radio engineering D. Rozhansky.

THIS LIES AT THE BASIS

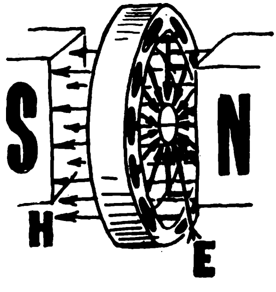
IV.15

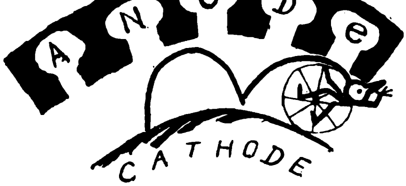


And here is yet another representative of the family of electronic devices intended for generating super-high frequency oscillations. It is called a magnetron. It was invented back in the twenties, but gained popularity considerably later when radar set the task of mastering centimetre waves. It was then that the Soviet engineers N. Alexeyev and D. Malyarov, headed by M. Bonch-Bruyevich, developed the first multisphere magnetron.

IV.16

We have already dealt with the behaviour of the electron under simultaneous action of electric and magnetic forces (Chapter III, "Aerobatics"). In magnetic lenses the forces of the magnetic field are directed along the path of the electrons. In the magnetron they act crosswise. Nevertheless, even in this case the electron under the action of magnetic forces has to master the techniques of aerobatics. Here it moves along an intricate curve known as the cycloid. The same curve is described by any point on the rim of a rolling wheel.

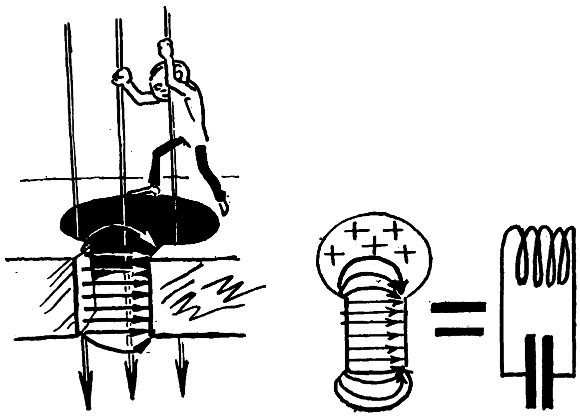




At the same time the anode tends to attract all the electrons, to tear them out of the embrace of the magnetic field. Here we have, as it were, a peculiar competition: the electric field of the anode makes the electron fly straight, while the magnetic field tends to twist it as hard as it can.

If the magnetic field is intensified, the twisting increases. If the field of the anode is intensified, then the convolutions of the cycloid begin to straighten out. The forces of such opposing fields in the magnetron are selected so that the convolutions of the cycloid would not reach the anode and the electron would not get onto it.

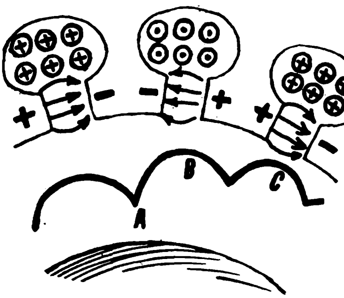
IV.17



In addition to the static fields, the electron is subjected to the action of a variable field which develops in the cavities of the magnetron. These cavities are disposed directly in the anode, and they are the very spheres, because of which the device was called a multisphere magnetron. The spheres concentrate the magnetic forces, while the electric forces act in the slots. The slots form a sort of capacitors of tuned circuits, whose coils are the cavities.

IV.18

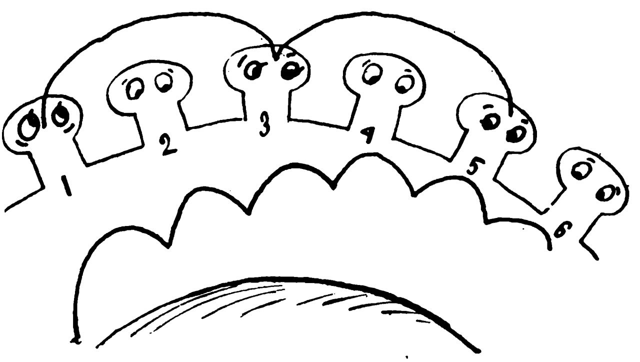
Like in the klystron the field of the tuned circuit may accelerate or decelerate the passing electron, depending on the sign of the half-wave of oscillations which is active



in the sphere at the given moment. On entering a decelerating field produced by one of the spheres the electron yields it some of its energy. Therefore it loses its force before having enough time to return to the cathode, and at point A its speed becomes equal to zero. But here it is picked up by the fields of the adjacent sphere, gathers strength anew and begins the next convolution at the same point A. This brings it to the next sphere (point B).

IV.19

The spheres are interlinked by means of special couplers in such a way that, if the spheres are numbered, all the even ones will be interlinked and so will be all the odd

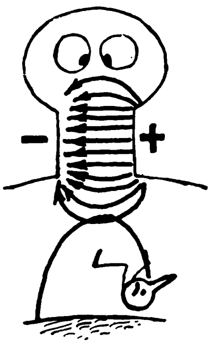


ones. Therefore at a given moment of time one and the same half-wave acts in all the even (or all the odd) spheres.

In the adjacent spheres the oscillations are in antiphase: at the moment when the field of sphere *1* decelerates the electrons, the field of sphere *2* accelerates them. But while an electron is moving away from the 1st sphere and approaching the 2nd one on the second convolution, exactly half a period of the oscillations has passed. The signs of the half-waves in the spheres have reversed, and now a decelerating field is produced in sphere *2*.

Everything here is calculated precisely: flying past all the spheres in succession, the electron arrives at exactly those moments, when the decelerating half-wave is active in the sphere, causing the electron to give up some of its energy. Finally, the electron will have given up all its energy to the spheres and will fall onto the anode.

IV.20



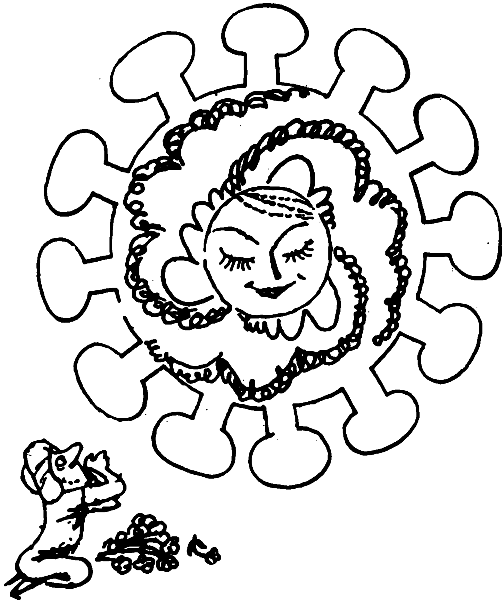
A different fate awaits its unlucky fellow, if the latter is a tiny bit late and approaches sphere *1* at the moment when the accelerating half-wave is active there. Having acquired additional energy from it, the electron will fly on, completing the convolution of the cycloid, and will reach the cathode before its velocity is equal to zero. On striking the cathode, it will give up the rest of its energy and will then be out of the game.

In its wake all the electrons which happen to be out of phase with the alternating voltage across the spheres will fall down onto the cathode and since they give up the rest of their energy to the latter, it is not cooled, but heated by the "electronic rain". The heating may be so intense that the heater of the magnetron is often switched on only at the beginning of the process and then is cut off after the magnetron begins oscillating.

IV.21

The electrons which are in phase with the voltage interact with the field of the spheres differently, because at the moment when the decelerating half-wave of the voltage is active they happen to be in different sections of the cycloid.

The faster an electron flies, the more intensively it is decelerated. The slower electrons catch up with the faster ones, forming bunches, and these bunches revolve like the spokes of a rotating wheel.



IV.22

The energy given up by the electrons in the bunches sustains the oscillations in the cavities (spheres) of the magnetron.

The frequency of these oscillations is equal to the natural frequency of the cavities and may reach 10 000 and even 100 000 MHz. A loop introduced into one of the spheres takes off the oscillatory energy and feeds it to the antenna for radiating centimetre or millimetre waves.

IV.23

If the magnetron is compared to the klystron, its advantages become obvious: in the klystron each of the electrons interacts with the cavity only once, while in the magnetron the electron, spinning round in its cycloid, acts upon several cavities simultaneously. It is forced to spin round under the action of a magnetic field.

Owing to the repeated action of the bunches, powerful oscillations develop in the magnetron cavities: the pulse power comes to hundreds and thousands of kilowatts. These pulses are fed to the antenna of a radar station, which directs them towards the target (aircraft, rocket).

Regardless of how complex are the processes taking place in the magnetron, they are based on the very same principle we find in all electronic devices: the interaction of charged electrons with the forces of static and variable fields.

Naivety And Ingenuity

Even the first brief acquaintance with the basic types of superhigh-frequency electronic devices makes it abundantly clear how multifarious are the principles and designs born of the SHF range. But one feature makes related all the devices examined: in all cases use is made of the resonance phenomenon. And this, if you care to put it that way, is their weak point: all of them are fine as long as the signal frequency coincides with the natural frequency of the tuned circuit. But if the oscillation frequency needs changing?

In the klystron the reflector voltage is changed for this purpose. But this allows the frequency to be varied merely within narrow limits: as long as the signal is capable of driving the cavities. And this is only possible if the frequency of the "pushes" is close to the natural frequency of the cavity (see III.8 and III.9).

To vary the tuning of the cavity is quite a complicated matter. The same problem is encountered in receivers: in order to amplify signals of other frequencies it is necessary to retune their circuits.

For a long time this could be born with. It seemed impossible to invent anything new: all devices suffer from the same defect. At some frequency they operate wonderfully, but there is no way of varying the frequency within broad limits or amplifying such signals as contain a multitude of oscillations of different frequencies.

And then came an inventor who, on encountering the problem, posed a number of naive questions.

Why necessarily a tuned circuit? Why necessarily the resonance?

His naivety is understandable. How could the Austrian architect Rudolf Kompfner be aware of all the difficulties that had to be overcome in designing electronic devices intended for superhigh frequencies?

But electronics was in luck. Of course, it had to be an architect and not a physicist who would think up such naive questions. Perhaps, it was just this naivety that the designers of electronic devices lacked, being too much used to turn in most cases to tuned circuits for aid.

The path chosen by Kompfner was a most unexpected one: he decided to do away with the cavity and to obtain interaction between bunches of electrons and an electromagnetic wave travelling alongside.

But how can a wave and a stream of electrons be made to run side by side. The wave travels at the speed of light and electrons, 10-15 times slower. A particle cannot catch up with light—this was proved long ago by Einstein. But as the saying goes, if the mountain cannot come to Mohammed, then, perhaps, Mohammed can approach it?

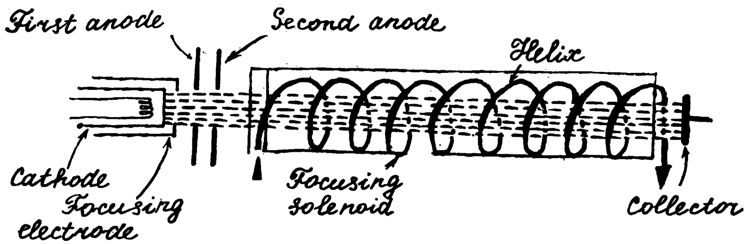
The electron, does it lag behind the wave? Fine.

And why not reduce the speed of the wave? Another question that the specialists would consider naive. A wave can only travel with the speed of light, and no one can change it.

But Kompfner was not only naive. Having posed a naive question, he was able to answer it imaginatively. If travelling waves cannot be decelerated, then, perhaps, their path can be lengthened? And he made the wave travel along a helix. The wave travels along the turns of the helix at the speed of light. But how soon will it reach the next turn? This can be readily seen: the wave will travel from turn to turn so much slower as the distance between the turns is less than the length of the turn itself.

And alongside it travel the electrons. At first they outstrip the wave a bit, then it begins to decelerate them. In this case energy is transmitted to the wave. And whereas in the klystron and magnetron the electron gives up its energy to the cavity during a brief moment while it is flying past, in this case the electrons and the wave interact all along the path. Therefore, the amplifying effect is much more tangible: the klystron amplifies signals ten-fold, and the device developed by Kompfner, a million times. And what is more, without any cavities, without any retuning! The tube can operate within a very broad range of frequencies.

For this device the architect Kompfner was awarded the title of Doctor of Physics, and the device itself is known as a *travelling wave tube*.



Pulses and Buratino

The possibility of varying the oscillation frequency within very broad limits is a great advantage of the travelling wave tube. (For generating oscillations use is usually made of the backward-wave tube, in which the wave and the stream of electrons move counter to each other.) But another possibility is probably even more important: the travelling wave tube can amplify signals which contain a multitude of oscillations of different frequencies.

We have already come across one signal of this kind: that is a signal which carries a picture, i.e. a television or video signal. It contains oscillations with frequencies from the lowest to fairly high ones—up to 6 MHz (see III.41). They can be amplified by a pentode.

But for radar, where the frequencies of the carrier signals are tens of times higher and the frequency band, tens of times broader than in television, the travelling wave tube has proven a very valuable device.

To understand why the frequency band must be so broad, it is necessary to know just what a radar signal is like.

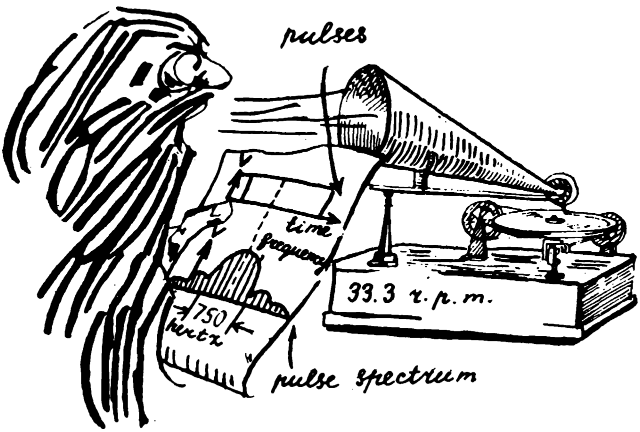
The antenna of a radar station radiates pulses into space, i.e. very short bursts of centimetre waves. The radiation of a pulse must cease before the previous pulse sent towards the target returns. Otherwise the next powerful pulse of the transmitter will be superimposed on the pulse returning from the target, and since in travelling there and back the latter pulse has spent nearly all of its energy, the transmitter pulse will drown it out, making it impossible to notice it. Everyone has come across such a phenomenon: an echo in the forest repeats all your phrases, but you can hear only the last syllable.

The pulse does not travel long. It flies at the speed of light and covers a distance of several hundred metres in millionths of a second. During this time the next pulse must be radiated. Hence, the duration of the radiated pulse should not exceed millionths of a second. For transmitters this is convenient: it is possible to concentrate in a narrow pulse a large amount of energy, while the power of the d.c. supply sources can be quite low. But then many problems arise in connection with the reception and amplification of the echo pulses, because the narrower the pulse, the broader the frequency band of oscillations it contains. Ask an engineer how to explain such a strange property. In reply he will suggest that you "fish out" one by one all the oscillations of different frequencies contained in the pulse by means of a variable-frequency "sieve" (see III.9). Or he will advise you to resort to mathematics, expressing the pulse as the sum of simple sine waves by using Fourier transformations. But that which seems convincing to a specialist will hardly satisfy the person who has posed this question for the first time.

Therefore we shall approach the question in a different way—we shall consider a simple example.

Probably, most of you have heard children's broadcasts in which Buratino takes part. However, not everyone knows how the actor playing the role of Buratino can imitate the voice of the small wooden boy, so unlike the voices we are accustomed to.

It turns out that the actor is assisted by electronic equipment. Any recorded voice can be made into the "voice of Buratino" by increasing the reproduction speed. That is just what is done at the radio studio. The actor playing the part of Buratino pronounces all the words very slowly, drawling on purpose. This is recorded on a tape and reproduced at about double the recording speed. The phrases which have been pronounced slowly gain the normal speed,



while the voice becomes unnaturally high. Why? Because by doubling the speed of the tape, we also double the frequency of each of the oscillations contained in the signal. And indeed, if formerly 800 sound wave crests a second have passed the recording head, at double speed it will be 1600 crests that will pass the playback head.

You can do the same with any 33.3 rpm record by playing it at a speed of 78 revolutions per minute. This will turn a bass into a soprano, and you will hear funny "dolls" voices.

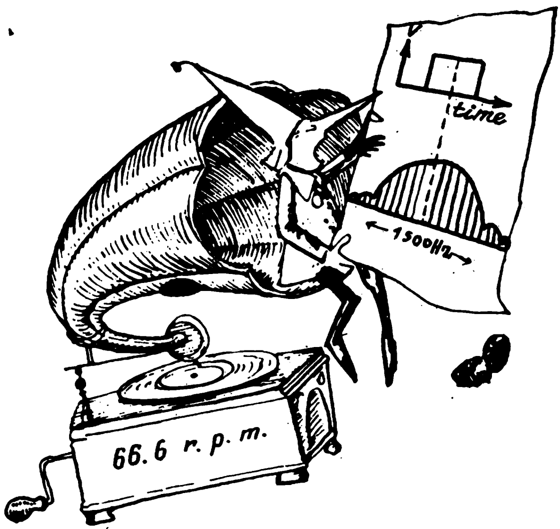
All right, but what have pulses to do with it?

Well, isn't a record tantamount to a pulse? The duration of the "pulse" is the time necessary to hear the record from beginning to end. A medium-size 33.3 rpm long-playing record plays about 10 minutes. In this case 10 minutes is the duration of the "pulse". If we make the record turn with a speed of 66.6 revolutions per minute, the "pulse" will become twice as short. And the frequency of all the oscillations contained in the sound recorded on this record will be doubled, and the sound which has formerly occupied a band from 50 to 800 Hz, will now occupy a band from 100 to 1600 Hz.

At 33.3 rpm the band width is 800 — 50 = 750 Hz.

At 66.6 rpm the band width is 1600 — 100 = 1500 Hz.

The band has become twice as broad because now the pulse lasts only 5 minutes instead of 10.

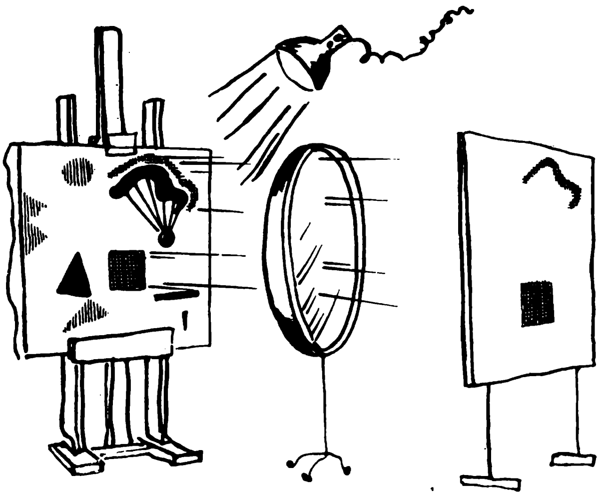


In radar a pulse lasts millionths of a second, but here also the same regularity is valid: if the pulse is made twice shorter, the frequency band will become twice broader.

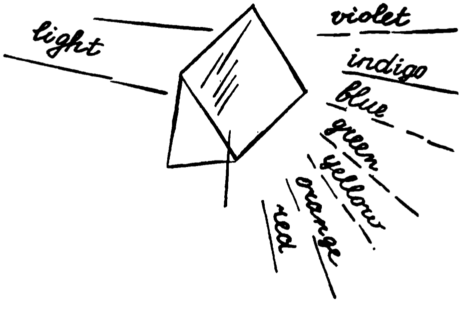
Everyone knows that with the aid of colour filters from a beam of white light it is possible to single out by turns red, blue and green light. In electronics the role of such a "colour filter" can be played by a narrow-band *LC* circuit (see III.9). A set of such circuits is similar to an optical prism: here the incoming signal is broken down into a multitude of "colours".

In his days Isaac Newton wrote in a book on optics that with the aid of a prism he was able to obtain a "colour image of the Sun". For the word "image" Newton used the

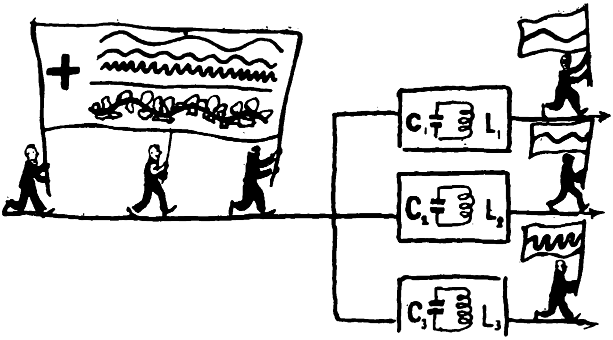
Latin "spectrum". In electronics the set of all the frequencies of oscillations contained in a complex signal is now also called a spectrum, although it is impossible to obtain a "colour image of a pulse". True, if our eyes were able to



see radio waves like the waves of the optical range, then every signal would appear as an intricate design with a multitude of tints and, at times, even with a whole gamut of colours.



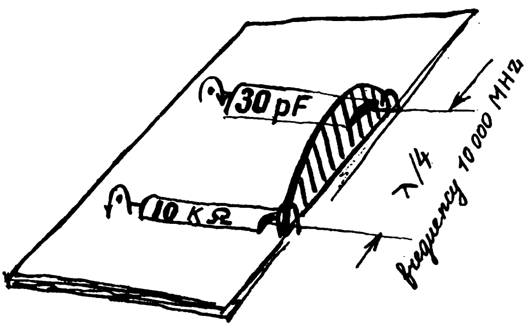
The "design" which reaches a receiver "astride the carrier signal" is not simply a design on a curtain lace, but rather the multicoloured ornament of a tapestry. The amplification of complex signals possessing a very broad spectrum is



one of the most important and difficult problems in electronics. In many cases this problem is solved with the aid of the travelling wave tube.

Waves Travel Through A Tunnel

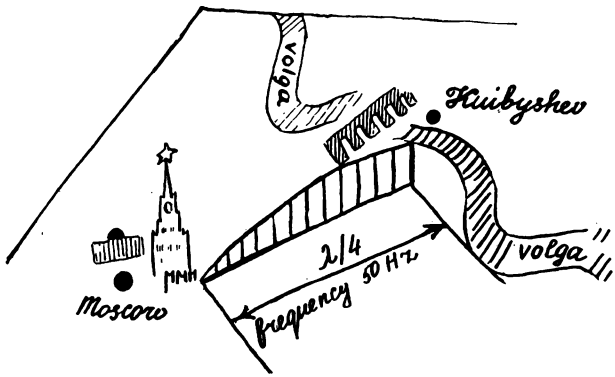
You see, it was no easy matter for electronics to obtain centimetre waves. Highly sophisticated amplifier and transmitting valves and tubes had to be developed.



In addition, the reception of pulses of centimetre waves involved the pass-band problem. And even the feeding of signals from the oscillator to the antenna and from the antenna to the receiver input proved a problem that was not so easy to solve.

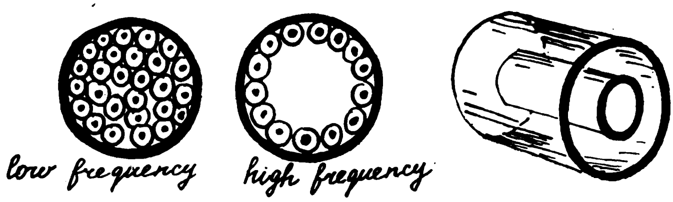
Until the change-over to the SHF range, the signal was fed by wire. But all the usual conceptions become useless as soon as superhigh frequencies are concerned.

Compare the current produced by SHF oscillators with the ordinary commercial current. Both of them are sine-wave currents, but the SHF current makes 10 000 000 000 oscillations per second, while the current supplied to your flat, only 50-60. The same difference is true for the waves—those of the SHF oscillator are 3 centimetres, and of your



a.c. supply mains, 6000 kilometres long. Only a quarter of such a wave can fit into the entire length of the power transmission line connecting the Kuibyshev Hydroelectric Station with Moscow! But in the case of SHF oscillations a piece of wire only a few centimetres long can accommodate several waves. A wire 7.5 millimetres long (quarter-wave section) already operates like an antenna, dissipating the SHF energy into space. In addition, with an increase in the frequency of SHF oscillations, the losses in wires also rise.

Since Faraday's time it is known that as soon as a charge starts moving, it immediately becomes surrounded by an aureole (see III.46) with magnetic forces acting therein. The more intense the motion, the more powerful the field of the magnetic forces. Making 10 000 000 000 oscillations per second, the electron develops such a powerful field that it begins to ostensibly stand in the way of all the other electrons near by, for they too are oscillating and each of them has its own aureole. Inside a wire the electrons become too cramped, so they move away from the axis to the surface layer where there is much more room: at any rate no one crowds them outside the wire.

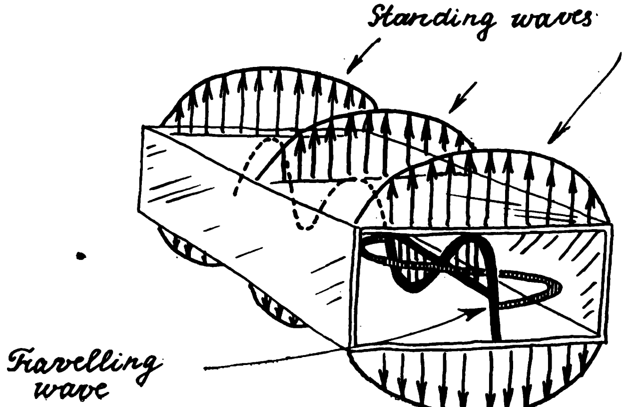


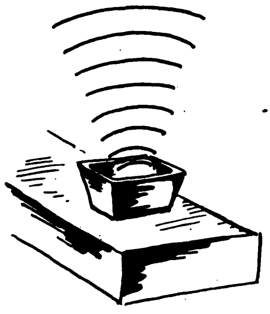
Hence a very important peculiarity: superhigh-frequency currents always flow through a thin outer layer at the very surface of the wires. Of course, in this case they have to overcome a greater resistance: it is one thing for water to flow through a wide pipe, and quite another for it to flow through a narrow gap between two pipes. Due to the high resistance, the energy of SHF oscillations is spent in heating the wires. In short, wires are unsuitable for transmitting SHF oscillations. Therefore, the SHF oscillatory energy is transmitted without wires.

How?

Directly through space.

However, the space must be limited, otherwise the waves will spread in all directions, their energy will be dissipated, and only an insignificant amount will reach the destination. For this not to happen, the wave is transmitted along a special channel, similar to a tunnel of the underground. This channel is called a waveguide.





The field inside the waveguide is of a complex nature. Standing waves develop across the waveguide, and the energy is carried along the waveguide axis by a travelling wave. A slot whose dimensions are commensurable with the wave length can serve as an antenna. Sometimes a horn is attached to the slot to gather the waves into a narrow directed beam.

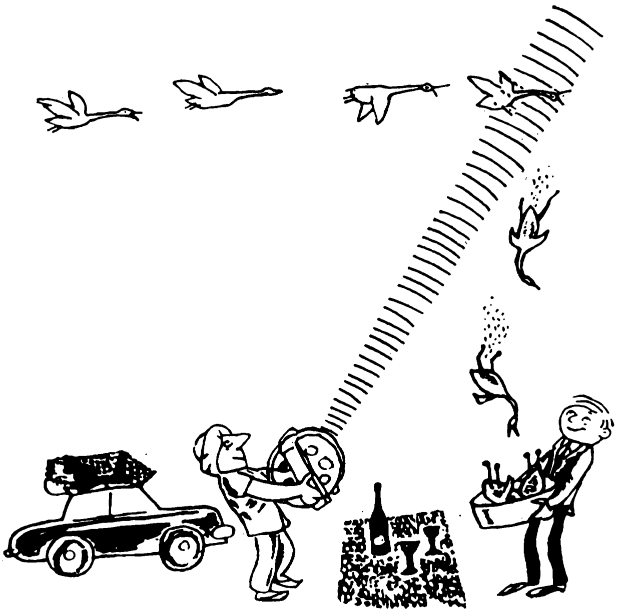
The theory evolved by Maxwell makes it possible to predict the behaviour of the waves and to calculate the dimensions of the walls of the waveguide itself and of the antenna for producing narrow beams.

THIS LIES AT THE BASIS

IV.24

How long does it take for a duck to roast? About an hour. But it can be roasted in 6 minutes. For this purpose miracle-ovens have been developed. They have neither firewood, nor gas or red-hot spirals. What is it then that roasts the duck?

Magnetrons!

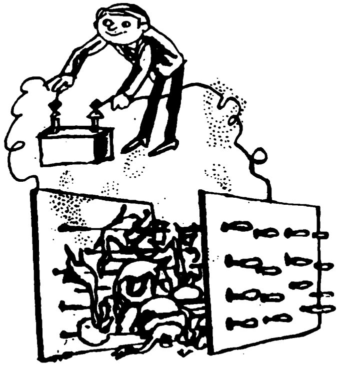


IV.25

If the plates of a capacitor are interleaved with a material of an infinitely high resistance (perfect insulator), no current will flow through it.

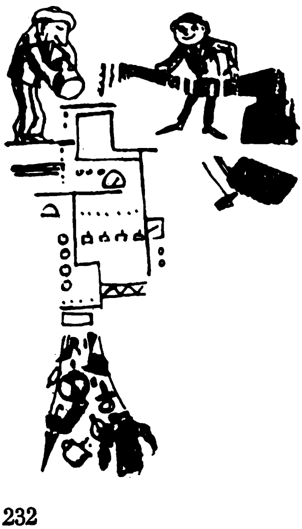
But there is nothing absolutely perfect in nature. All insulators (including the body of the duck) have a finite resistance and the action of an electric field will cause a current to flow through them.

All insulators are poor thermal conductors, therefore it takes an ordinary fire a long time to heat them up, and non-uniformly at that: the duck may burn on the outside and remain raw inside. An insulator (the duck) placed in a varying field is permeated through and through, and



the current developing in it produces heat. The higher the frequency of the oscillatory energy, the greater the amount of heat produced. The source of such oscillations can be a magnetron.

IV.26

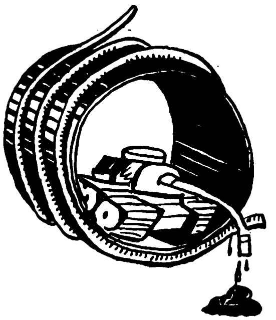


The high-frequency "cold flame" has found wide application. It is used to soften glass to give it the necessary shape, to form plastics, to vulcanize rubber, to dry cotton and wool.

This "flame" is widely used in the food industry. It is employed to smoke ham, dry tobacco, destroy the larvae of flour worms.

Most original is the design of an electronic "sewing machine". Two edges of plastics or rubber sheets are drawn between the plates of a capacitor. Under the action of a field the edges are fused together, forming a seam. A seam without any holes—what can be better for making inflated mattresses, boats, floating toys, waterproof covers and coats!

IV.27



Whereas insulating materials become heated through the action of an electric field, eddy currents are produced in metal due to the action of magnetic fields. In order to obtain these fields powerful oscillators generate alternating currents which circulate through the turns of enormous coils encircling induction furnaces. Such furnaces can melt tons of metal, because their power is as high as thousands and thousands of kilowatts.

The ability of a magnetic field to penetrate inside metal has allowed melting to be done so quickly that the metal has no time to become oxidized, and this greatly improves the quality of the melt.

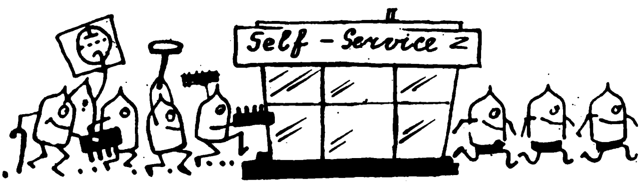
IV.28

Very often it becomes necessary to increase the strength of the steel parts of various machines and devices. For this purpose they can be hardened with the aid of ultrahigh-frequency currents. At such frequencies current circulates only in the outer layer of the metal. Its surface becomes heated while inside it remains cold and retains its elasticity. By applying in turn water and the "high-frequency flame" we obtain the best-quality parts—the ones that are highly strong on the outside and resilient inside.

IV.29

And here are examples of self-service: the use of techniques developed by electronics for the needs of electronics itself. The glass-to-metal seal between the envelopes and bases of valves is made by means of high-frequency fields.

To obtain a high vacuum in a valve it is necessary to remove gas from its parts. For this purpose the valve is placed between the turns of a coil. The field heats the parts inside the envelope red-hot, the gas escapes from them and is then exhausted from the envelope.



Pure silicon and germanium for the production of semiconductor devices are also obtained by melting their crystals in a vacuum with the aid of high-frequency fields.

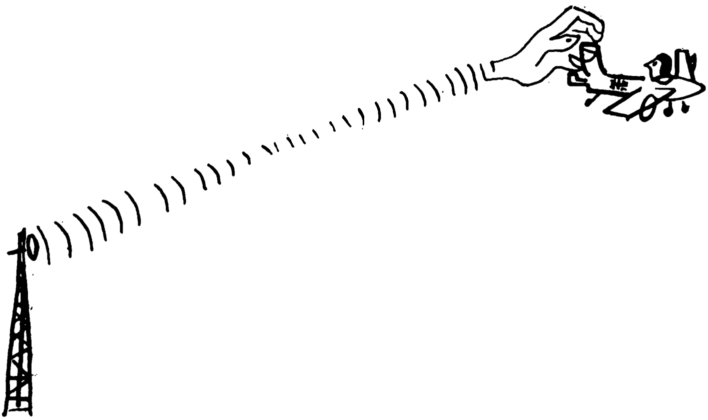
Episodes Of The Last War

So far we have only dealt with the peaceful "occupations" of the electron. But it is well known that pulses of centimetre waves, gathered into a narrow directed beam by a radar antenna, were a very effective weapon in the past war. So it was not by pure chance that it was exactly in military radar equipment where the magnetron, klystron and travelling wave tube received their start in life and their first baptism of fire. But the radar station is only one side of the medal. And the other...

One dark February night of 1942 two German battleships, "Scharnhorst" and "Gneisenau" and the cruiser "Prince Eugen" left Brest, which was blocaded by the British fleet, and passed through the English Channel. Not one of hundreds of British stations could detect them—the radar screens were "blinded" by German jamming stations.

This marked the beginning of the great battle of electronics which continued throughout the whole of the World War.

Two decades have passed since the end of the war, but memories of the great battles are still alive in the minds of its contemporaries. Even those who did not take part in it can picture to themselves the scope and ferocity of the battles, thanks to films, literature and the tales of war veterans.



But then those who actually participated in the war do not all have a clear idea of another kind of battle—the invisible and unending battle of electrons and waves.

But the outcome of most operations depended greatly on the skillful use of electronic equipment. Here are a few episodes.

For guiding their bombers to British cities the Germans set up special radio beacons on the occupied territories in Belgium, the Netherlands and France. The narrow beam of the beacon helped the German pilot keep on the right course.

The attempts to jam these signals were unsuccessful: as soon as one beacon was jammed it was replaced by another beacon operating at another frequency. Then the British chose another antidote: they built on their territory stations capable of receiving and relaying the signals of the German beacons. The "tint" of the signal did not change but the direction indicated to the German pilot by the narrow beam of the relaying station guided him off the track, away from the target. There was even one case, when the false signal made the German pilot land in England on an airfield in Devonshire, and to the very end he was perfectly sure that he had come down on his own airfield in France.

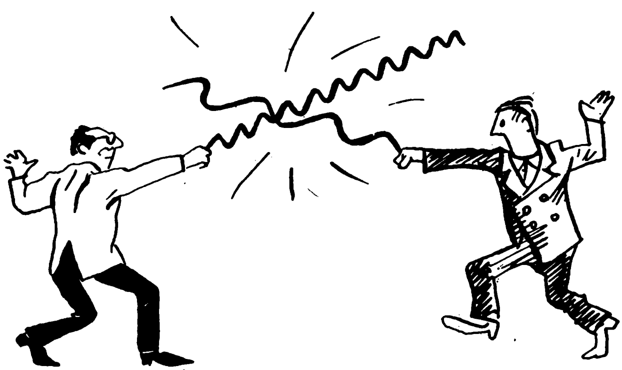
Sometimes the false signal made the Germans drop their bombs not on the target, but on a wasteland or into the English Channel. Finally the German pilots stopped believing their own or any other beacons.

Then the German high command resorted to a war stratagem. German radio stations began transmitting propaganda broadcasts to Britain. The inhabitants of London soon noticed a strange coincidence: every time just before the arrival of the "guests" from Germany the voice of the German announcer sounded louder. At the same time in the environs of London the voice became barely audible. This, of course, intrigued the secret service, but for a long time the explanation escaped them. It turned out that the propaganda was only a camouflage and the purpose of the station was quite different. It guided the German pilots to London. To this end, shortly before take-off the mode of operation of the station was changed: instead of an ordinary antenna, a directional antenna was put into operation, radiating the waves in a narrow beam. The beam was directed at London, that is why the signal became stronger in London and disappeared in the suburbs.

When the ruse was unravelled it became easy to counter it. Relay stations were used anew and the German bombs began falling again into the English Channel.

Electrons Fight Battle

The gun volleys and the bomb explosions have long died down. People are fighting for peace. The World War is over. But the electronic war has not ended. It is being waged



without respites, cease-fires, nor any declaration of war for many years on end. Experts in electronics need no battle fields, they fight their "battle" in laboratories and factory shops. The struggle is being carried on for the accuracy of the equipment, for its reliability and rapidity and each new achievement is one more victory in the continuous "electronic war".

The means that are used by electronics in this war are distributed according to its "fighting arms". There are means of defence and attack, of reconnaissance and of camouflaging beams. A radio beam can be very dangerous. True, it does not carry death in itself but may be the harbinger of death. If it is allowed to "feel" freely through space, it will direct a shell or a bomb straight at the target. Hence the conclusion: the beams must be fought against.

How?

Many means have been found.

Materials absorbing radio waves have been developed. If the target is coated with such a material, the beam will not be reflected from it, and the pulse will not return to the radar station, or it will be so attenuated that the target will not be seen on the radar screen.

There is another way of solving the problem. Let the pulses be reflected, but it will be impossible to get a fix on them, if simultaneously with the reflected signal a more powerful interference signal is sent to the receiver of the radar station. The frequencies of the interference signals must coincide with the operating frequency of the enemy's receiver. And the receiver is tuned to the frequency of the radiated pulses. To determine the tuning, it is necessary to study the radiated signal. It is for this purpose that reconnaissance is conducted: special reconnaissance receivers catch, record and analyze the radiated signal.

Radio camouflage renders reconnaissance difficult: among many camouflage signals radiated at various frequencies, the dangerous one cannot be detected. If the signal has been deciphered, the enemy will use special stations radiating interference signals within the range of the operating frequencies. However, even in the case of interference the radar station can operate normally, if special means have been provided for differentiating between the radiated and interference signals. By modulating the signal by special codes, such systems can be developed as will be able to detect the targets, fix their positions, aim the guns, control rockets and ensure communication in the presence of the enemy's interference signals.

Thus, in the compex interaction of electronic circuits and devices is born the tactics of the electronic war.

Among the many "professions" of the electron the military one, unfortunately, plays by no means a minor role in our anxious days. And we, people who are striving for peace, should remember this and be well aware of the role in the defence of our country that the electron should play.

Double-Edged Weapon

One cannot imagine a modern army without electronic devices. Electronics has become an integral part of its organism, its nervous system, if you want to put it that way. Electronics provides communication between the subunits and headquarters. It helps detect the enemy's targets and ensures firing accuracy. And then there are pilotless aircraft, tanks which fight battle without tankmen, rockets which change their course on command from the ground.

It is already impossible to wage war without electronics. But the designers of modern military equipment must always bear in mind that electronics is a double-edged weapon.

Most of the equipment used for military purposes radiates waves into space. Where is the guarantee that these radiations will not be put to good use by the enemy?

The enemy can overhear a command transmitted by radio. The code used for maintaining it secret can be deciphered by the enemy. By the radiations of control systems and radar stations it is possible to tell where the units are located and what they intend to do. Knowing the nature of the signals it is possible to produce interference in the operating frequency range.

That is why a whole branch of electronics is occupied with the development of reconnaissance devices which cannot only detect signals, but also record them on a tape, analyze them, determine their purpose and "colouring", i.e. investigate their spectral composition.

It is known that radio-controlled rockets were first used by the Germans in the last war. They transmitted to their base signals for monitoring speed and height. The British reconnaissance devices not only received these signals but also deciphered the commands which controlled the rockets. The British experts developed equipment for radiating false commands which caused the rockets to descend before they had reached the target. The radio countermeasures were so

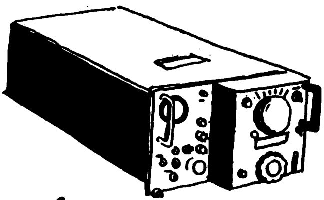
effective that the Germans had to reject the radio control and rely on the gyroscope.

The outcome of a war depends to a great degree on the available information about the radio equipment of the enemy. The high command of the armed forces of contemporary America is striving regardless of cost, to find out

the characteristics of the electronic systems and devices which the armies of the socialist countries possess. At the present time the National Security Council of the USA is maintaining 2000 interception radio stations installed on board ships, in aircraft and bases, and 8000 operators carrying out reconnaissance.

Many of you, evidently, remember how at one time the Americans attempted to conduct reconnaissance with the aid of radio equipment installed on balloons. Now balloons have been replaced by satellites.

In recent years a number of American firms, including such a giant as General Electric, are specializing in the



ferret receiver, USA

development of miniature devices intended for espionage. And what do they not have in their list!

Miniature television cameras and tape recorders that can be hidden in furniture, pictures, and in walls. Tapping receivers built into a tube of lipstick, a fountain-pen, the case of a watch. There have been developed microphones in the shape of a thin plate that can be easily slipped under a door.

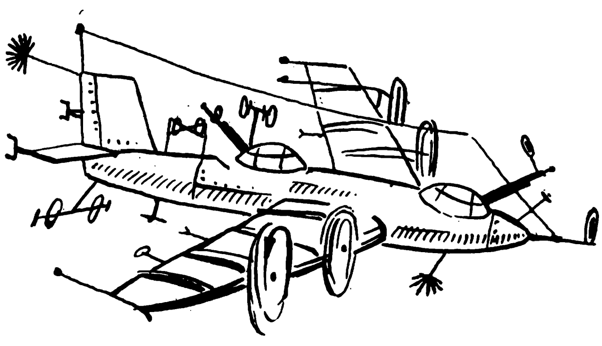
There is a big demand for such articles: they are supplied to state agents, smuggled deep into the territories of other states, as well as to the security service agents and private people who spy on the citizens of their own country. Realizing that at any moment the "other edge or end of the weapon" can hit the one that is using such devices, the firm "Clifton", at the end of the list of novelties it has developed prints this warning: "Be careful! In many countries there are laws prohibiting the use of some of the above-listed equipment. It is the buyer's (and by no means the seller's) business to ascertain how these laws may be applicable to the use of any of the purchased articles".

"Be careful! ..." A most timely warning. Unfortunately, it was unheeded by those who installed the latest equipment in the "Lockheed U-2" aircraft that on May 1, 1960, piloted by Francis G. Powers, trespassed the USSR frontier, when he made his unlawful flight. His aircraft was equipped with special transmitters that radiated interference signals, a multichannel reconnaissance receiver for all the "used" ranges of radio waves (from 2.5 centimetres to one metre). Paired antennas made it possible to establish just where the signal was received from. All the signals were recorded on magnetic tapes in the hope that subsequently the deciphered recordings would help determine the purposes of all the signals and to determine the range of operating frequencies.

Luckily the plans of the American intelligence service were foiled: flights over foreign territory with the aim of reconnoitering are also a double-edged weapon, you see.

Signals Versus Signals

The input of a radar receiver is something like a throat. The antenna of the receiver is like an open mouth. If the frequency of an interference signal is within the tuning



band of the antenna, the receiver will as readily "swallow" both its own and the strange signal. The station will "choke" if the interference signal is much more powerful than its own echo (reflected) pulse.

Suppression of enemy radar stations by powerful interference signals was often practised during the last war.

To protect Bremen from bombing raids, the Germans used antiaircraft batteries controlled by gun-laying radars of the "Würzburg" type.

Allied reconnaissance established that the carrier frequency of these radar stations was 560 MHz. In the summer

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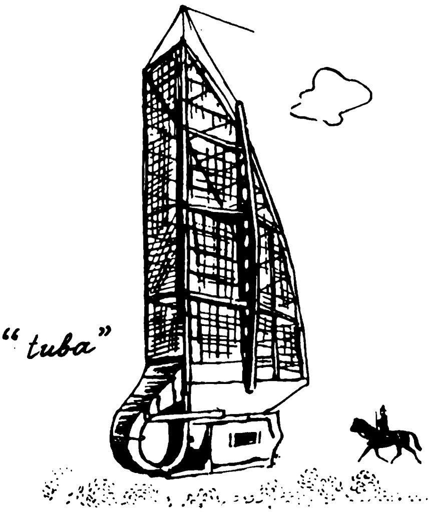
of 1943 bombers of the 8th American Air Fleet were equipped with the "Carpet" type transmitters. The transmitters radiated interference signals with a spectrum of an average frequency of 560 MHz. In October of 1943 the first results became known: half as many "Carpet-equipped" aircraft were shot down as other types.

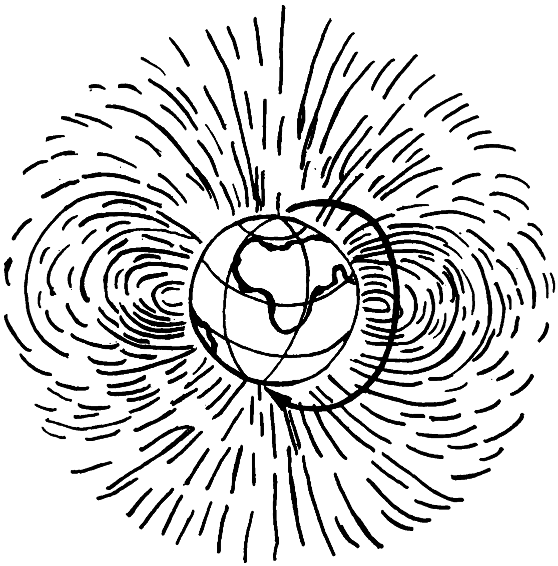
Interference is a very effective method. If radio can be compared to the nervous system of an army, then interference is a means capable of almost fully paralyzing



this system. Having understood this, the Allied armies made use of various counter measures in the last war. On the basis of the B-29 "Flying Fortress" the Americans built up a whole "combine" for producing all kinds of interference. The "Flying Fortress" carried 18 transmitters, reconnaissance receivers, and, as for antennas, so many of them were mounted, that the aircraft came to be known by the nickname of "porcupine".

However, in electronics there are no methods against which new defence measures cannot be found.

A double-edged weapon is a fairly trivial case. One can recall stories with a multitude of various "edges". The "first edge" of one such story was the equipment of German flighter planes with radar stations that provided for aiming



and interception. The "second edge" the English made immediate use of: they caught the signals and determined their frequency range. This was followed at once by the "third edge": British bombers were equipped with jamming stations. Do you think that was the end of the "edges"? Nothing of the kind! The German pilots learned to guide their fighters by the jamming signal, as if it were a radio beacon!

Again the balance was tilted in the fighters' favour and again a counter-measure was found.

Since the jamming signals transmitted by the bomber helps the enemy, this means that they should be transmitted from the ground. Enormous American "Tuba" transmitters were set up all along the southern coast of England. Their powerful signals "blinded" the German fighters while still in Europe, and the British bombers, freed of their pursuers, flew safely home across the English Channel.

Under contemporary conditions jamming has become so effective that it is not so easy to find the "third edge" of the weapon. The explosion carried out by the Americans on Johnston island in August 1958 interrupted communication between Tokyo and California within the 5 to 25 MHz range. Communication was only restored 18 hours later.

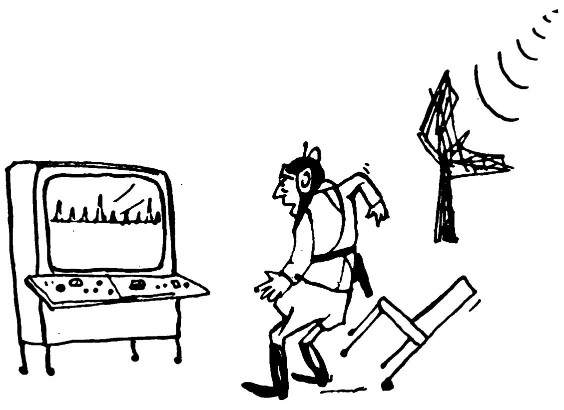
A nuclear explosion gives birth to an enormous quantity of electrons in the form of fast beta particles. In the earth magnetic field the electrons behave in the same way as in the field of a magnetic lens—they "go into a spin" and move along the lines of magnetic force*.

Knowing the structure of the earth magnetic field, it is possible to direct into any area the huge mass of beta particles formed during such an explosion.

The sons of Earth have now concentrated so much energy in their hands, that compared to it the Earth seems a meek old woman covered with a transparent veil of the magnetic field and innumerous radio waves. The old woman is very worried: what if the children, carried away by their dangerous games, go too far?

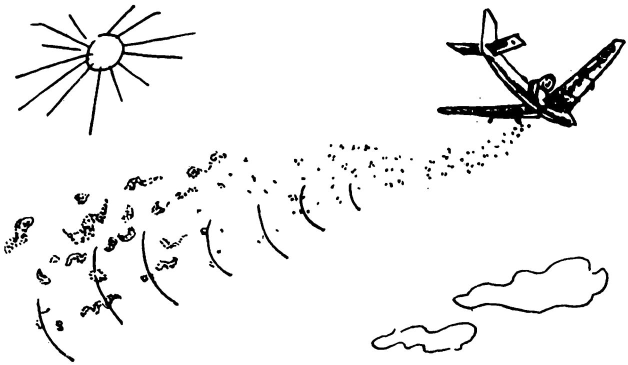
Target For Distraction

A great effect can sometimes be achieved by very simple means. A simple conter-measure is the use of reflectors, for example, of ordinary foil.



An aircraft drops pieces of metallized tape and a spurious target appears on the radar screens. The "eyes of the artillery" begin to track the spurious targets and, following the "eyes", the barrels of the guns turn automatically in the direction the mirrors of the radar antennas are turned.

* See Chapter III, Section "Aerobatics".



Hence, a spurious target cannot only distract the "eyes" but also "deflect" the shell.

A ribbon of foil is not very heavy. Each of the aircraft can carry enough of it to make a false impression of a mass raid on the radar screens.

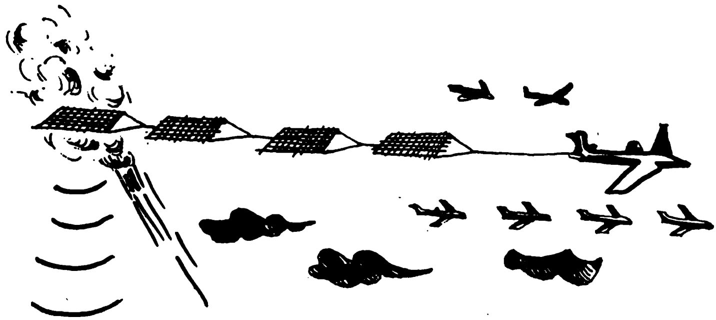
During the previous war a single aircraft managed to produce up to 700 false targets! Just try and figure out which of the 700 targets should be fired at. The simplicity of this method contributed to its popularity: throughout the war about 20 000 tons of foil were dropped over the territory of the fascist Germany!

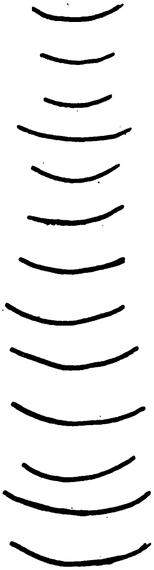
For effective reflection use is made of angular reflectors of various sizes and shapes. In the war years to lead astray the airborne radars of bombers the whole "unexisting cities" were built with the aid of such reflectors.

Special nets made up of such reflectors were used. The net reflected a greater part of the energy and the gun-laying stations automatically aimed the guns at this false target. One aircraft "caught into nets" the shells of the enemy, thus clearing the way for all the rest.

Electronic means were used on a large scale in the summer of 1944, during the landing in Normandy, when the second front was opened.

Preparing for encountering the landing force, the Germans concentrated a large number of detection stations along the northern shores of Europe, which monitored all the surrounding space and every inch of land. By means of artillery fire and air raids the Allies destroyed 80 per cent of the





German stations before landing and to suppress the remaining means of the enemy about 700 jamming stations were set up.

A grandiose mystification was begun: allied planes kept flying over the English Channel, producing false targets now here, now there with the aid of reflectors and special signals. The nonplussed German pilots were exhausted to the extreme by the multitude of false alarms.

With the aid of innumerous false signals the Allies for over four hours imitated the movement of a landing force in the direction of Boulogne and finally got the Germans to concentrate their forces in the Boulogne and Calais areas. In the meantime the allied troops landed in Normandy, where the German defences were so weakened that of the 2127 ships taking part in the landing they were able to sink only 6.

Rockets And Electronics

In the years that have passed since the utter defeat of the fascist Germany, a giant leap forward has been made in the development of electronics. Whereas formerly military electronics was being used on the ground, on ships and in aircraft, now devices for many types of rockets have to be developed.

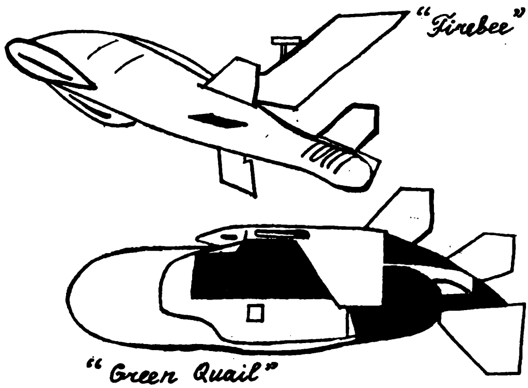
These devices must be light and compact, because the space in a rocket is limited and extra weight of the equipment reduces the range of the rockets several times. And, in addition, the devices should be especially reliable: during the acceleration at blast-off not a single component should fail. The problems of the measurement accuracy and of high-speed processing of data are of great importance here because of the enormous velocities of the rockets. Sometimes it is not so simple to make a device combining all these qualities. But then in recent years electronics itself has provided the designers of such devices with many new remarkable means.

Whereas during the last war the equipment mostly employed valves, now nearly all military equipment makes use of semiconductors. And as far as the circuitry is concerned, great progress has been made, especially in the field of logical and controlling computer techniques.

All the latest achievements are utilized in the development of new types of rockets. And the experience of the years bygone is also taken into account. Old tactics is assuming a new form. For example, for jamming ground stations and producing false targets use is made of those very rockets. Here are two such rockets which at the present time are adopted by the US Army. These are rockets of the "Green Quail" and "Firebee" types.

They are launched from an aircraft and controlled either by radio or by means of their own computers. Having outstripped the aircraft that has launched them, they jam stations by transmitting interference signals and, should the need arise, can serve as spurious targets, attracting the enemy's fire to themselves. On completing the operation such rockets "commit suicide"—they explode to keep secret everything they have aboard.

False radar targets are also used by modern electronics for ensuring the action of inter-continental ballistic missiles.



In particular, the USA are investigating the methods of surrounding the warheads of missiles with a cloud of metal splinters forming a false target.

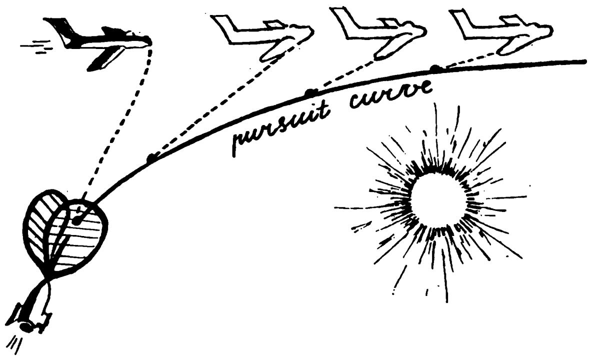
But how are these splinters to be delivered out into space?

You can't load them into the missile! For each gram carried by the rocket is paid for at a high price.

A very simple way out has been found.

The carrier rocket, having brought the warhead on its course, has fulfilled its main task. Now it can be used as a false target. After the warhead is on its course and separated from the carrier rocket, the latter blows up, turning into a cloud of splinters. At high altitudes the atmosphere is rarefied, therefore the splinters accompany the missile, moving at the same speed. The size of the cloud can be anything up to hundreds of square kilometres. The little warhead is completely lost in this vast cloud and it is no easy matter to detect it with the aid of a radar.

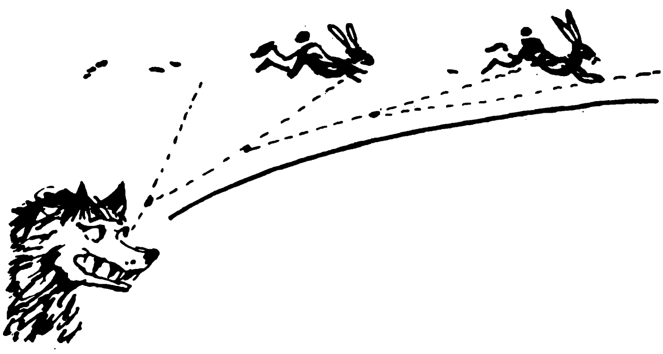
It was already during World War II that homing missiles and torpedoes were being used. Two antennas which radiated signals at an angle were mounted on the missile head. As long as the missile kept flying straight to the target, the signals of the two antennas remained equal. Should it deflect a tiniest bit, a difference signal appeared, causing an automatic device to put the missile back on the course. As a result, it flies along a path which the mathematicians call a pursuit curve. Hunters know that this is the very way a wolf catches a hare. As long as the hare is unaware of danger, it runs along a straight line, but as soon as it sees that it is being pursued, it begins to wind. But the



wolf, just as the missile with an electronic head, watches the target continuously.

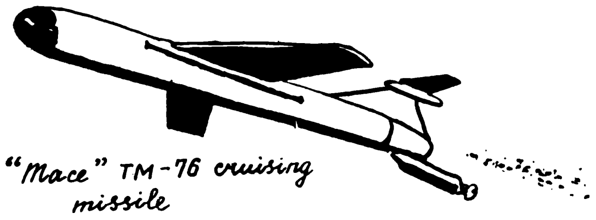
Norbert Wiener, the father of cybernetics, narrated the following episode. One day he was in a laboratory of the War Department. He was all alone in the room, but he could not get away from the feeling that somebody was continuously watching him. And then he noticed that the blunt nose of a torpedo suspended from brackets kept turning in the direction where he went. It was a far from pleasant feeling. It seemed that next to him in the room a merciless predator was hiding, in whose head instead of the brain there was a deadly charge.

Incidentally, a charge without any brain is not the worst thing imaginable. When cybernetics supplied shells, missiles and torpedoes with "artificial brains", the predators became much more dangerous, and relations with them, much more awe-inspiring.



Here is a novelty of the same kind.

The "Matador" cruising missile (USA) carries the "Atran" guidance system that is protected against jamming. Its principle of operation is most interesting. A map is introduced into its memory beforehand. The same area over which the missile is flying, is mapped with the aid of panoramic radar devices. An electronic circuit compares the two maps and, contrasting the main landmarks, produces course correction signals for the autopilot.



During tests 6 jamming stations failed to deflect from its course a cruising missile furnished with such an equipment. It behaves like a person with an ideal memory: if he knows the lay of the country, individual false landmarks will not lead him astray.

Modern radar techniques have acquired many new possibilities.

And what possibilities lie dormant in still shorter wavelengths? What prospects will open up if wavelengths are shortened another 100, 1000 and 100 000 times?

True, this is not so easily done. Magnetrons, klystrons and travelling wave tubes of the old designs—that glorious arsenal of devices for the centimetre range—are no good for generating micron waves. No wonder that for nearly 20 years the "ceiling" for electronics were centimetre waves with frequencies of not higher than 10 000 MHz.

But science and technology never stand still. Lasers have come into being and technology has made (for God knows which time!) another leap up the frequency scale. It is not without reason that we have begun this chapter with the words: the history of electronics is the history of making waves shorter.

THIS LIES AT THE BASIS

IV.30

Recently the mastering of the light wave band, whose wavelengths are only fractions of a micron, has opened up new possibilities before radar and communication techniques.

How are micron waves produced?

We have seen that in decimetre- and centimetre-wave oscillators a definite part of the standing wave must fit into the length of the cavity (see IV.13). Hence, the cavity must be shorter than the radiated waves.

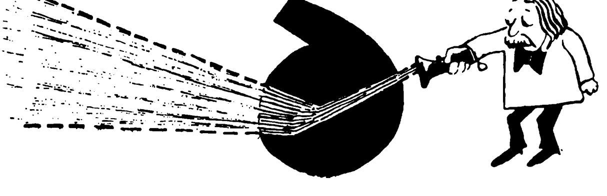
If we wish to obtain with the aid of a cavity waves 1000 times shorter than millimetre ones, we shall have to make a cavity that would be seen only under a microscope. The problem is practically insoluble. Fortunately, nature has provided us with another possibility. It has resonators which are "tuned" to very short waves. Such resonators are the *atoms* of various substances.

IV.31

Under ordinary conditions the atoms of gases or crystals absorb light energy.

In 1916 Einstein established theoretically that with the aid of light it is possible to bring the very same atoms into a state of excitation, so that they will begin radiating light waves of a different frequency. There develops a peculiar "induction of light": atoms of gas or crystals will, as it were, amplify the light falling on them.

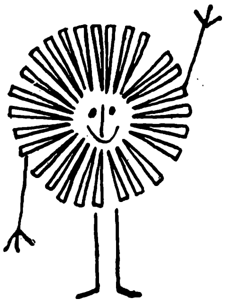
In 1940 the Soviet physicist V. Fabrikant described



experiments which have brought success in achieving the intensity of the radiated light in excess of that of the incident rays. In 1951 V. Fabrikant, F. Butaev and M. Vudynskaya were granted an Author's Certificate testifying their invention of "A Method of Amplifying Electromagnetic Radiations (ultra-violet, visible, infrared and radio waves)".

In 1954 N. Basov and A. Prokhorov of the USSR developed the first quantum oscillator.

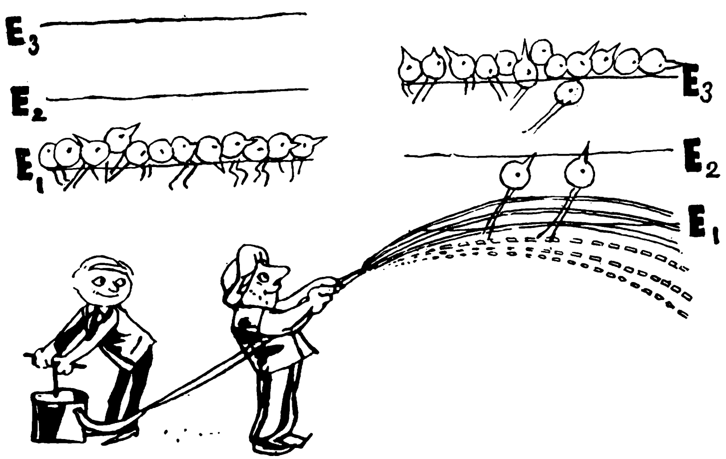
V.32



The operation of quantum oscillators is based on the processes of absorption and radiation of particles of light—photons (that is why we have given this field of electronics the name of photonics).

The photon is a quantum (the smallest portion) of light energy. In nature there exist other quanta: a quantum of the invisible electromagnetic field (i.e. of radio waves), a quantum of sound energy (it is called a phonon), a quantum of gravitation (graviton) and that of the nuclear field (meson).

IV.33



If an atom absorbs a photon, the energy of the atom will be increased: one of its electrons will make a transition from its normal orbit, where it has had energy E_1, to a higher one of energy E_3.

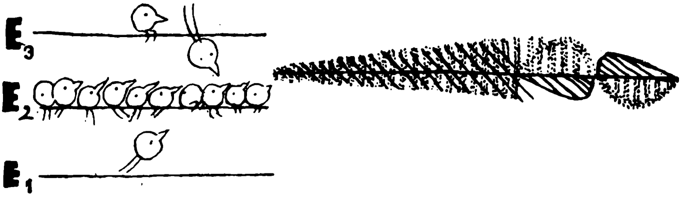
By irradiating certain substances with a special "pumping signal", it is possible to make many atoms transit from level E_1 to level E_3. Such a process is known as the excitation of atoms.

The photon absorbed by the atom possesses just so much energy as is necessary for the atom to "step" from E_1 to E_3.

The frequency of the pumping signal consisting of these photons is determined by the same "step": the higner the "step" ($E_3 — E_1$) the higher must this frequency be.

IV.34

Unlike the stable state, to which energy level E_1 corresponds, the excitation state is unstable: the atoms easily transit from level E_3 to a more stable level, for example, E_2 (to be more precise, their electrons "jump" from the higher orbits corresponding to energy level E_3, to lower ones). In this case each atom radiates one photon, while together they produce a stream of electromagnetic energy—they radiate light.



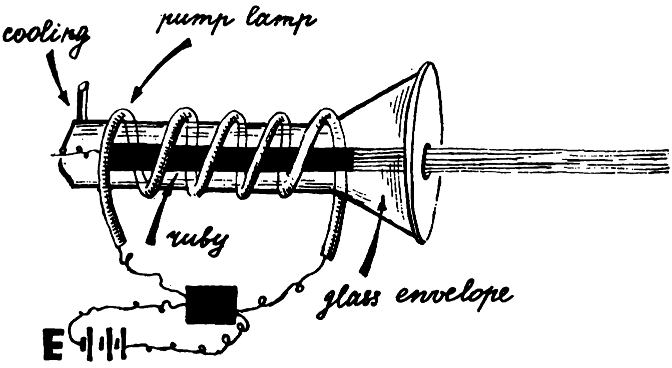
The radiation will continue until all the electrons leave level E_3, i.e. go $E_3 — E_2$ "step" down.

Pumping will again cause them to transit to this level and this will be followed by the radiation of a pulse of light. The time spent in pumping is several times that of the radiation.

The pulses radiated by modern lasers usually last thousandths of a second. During a long pumping time the excited atoms accumulate much energy, which then, during thousandths of a second, is radiated from the crystal in a straight bright beam.

IV.35

The radiation frequency of the laser depends on the difference between the levels $E_3 - E_2$, i.e., on the "step" by which, having radiated a photon, the atom must go down (see IV.33). And the frequency of the pumping signal is determined by the difference $E_3 - E_1$ (see IV.33).



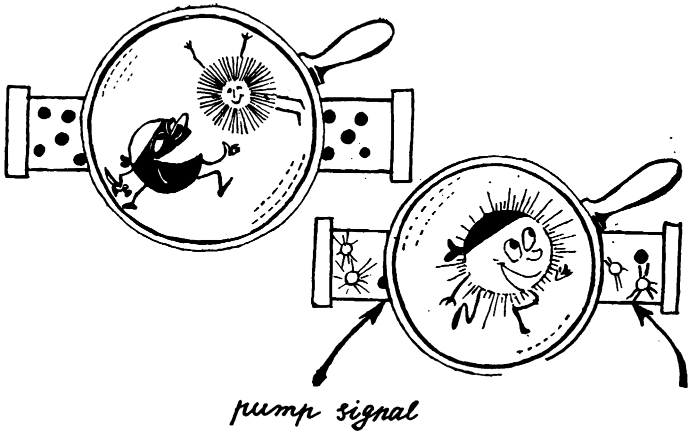
The ruby laser emits red light, the pumping signal being usually produced by green light. The frequency of red light is lower than that of green light. Consequently, the "step" $E_3 - E_2$ is smaller than the "step" $E_3 - E_1$.

Unlike an ordinary tuned circuit, the dimensions of which may change with time due to external effects, the "atomic tuned circuit" or "molecular tuned circuit" possesses an exceptionally high stability.

If the oscillation frequency of such "tuned circuits" is used for measuring time, then the divergence between such a timepiece and the astronomical clock will not exceed one second in three thousand years!

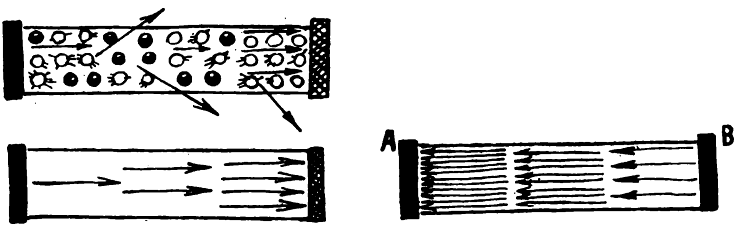
IV.36

Prior to application of the pumping signal all the atoms of chromium in the ruby rod are on the lower "step", i.e. in a stable condition. The pumping signal supplies the ruby rod with photons and, having excited its atoms, makes them transit to step E_3.



IV.37

An excited atom may emit a photon at any moment. This photon will reach another excited atom and, having "pushed" it down to level E_2, will carry along a new photon.



The two photons will immediately turn into four, the four—into eight, etc. Thus, an "avalanche" of photons develops and what is more, all the photons "march in step", in the same phase and at the same frequency.

Some photons may deflect from the axis of the rod (in the drawing their paths are shown by arrows). They very quickly leave the crystal, without meeting any atoms on their way. But then those that are moving along the axis will continue to meet time and again more and more new excited atoms which they will continue to bring back into the stable state, taking along new photons.

Thus in the direction of the crystal axis a mighty stream of photons will be formed.

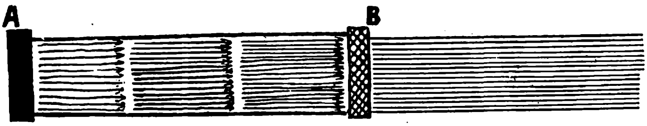
IV.38

The avalanche rolls down the ruby rod becoming ever more powerful, thanks to the new photons it has picked up on the way. On reaching mirror *B*, set up at the right-hand end face of the rod, the stream will be reflected and will rush backwards, continuing to grow.

At the left end face of the rod the stream impinges against mirror *A* and, on being reflected, again rushes towards mirror *B*.

IV.39

Unlike mirror *A*, mirror *B* has a certain transparency, but the first stream of photons was too weak to break through it. With every run back and forth the avalanche becomes



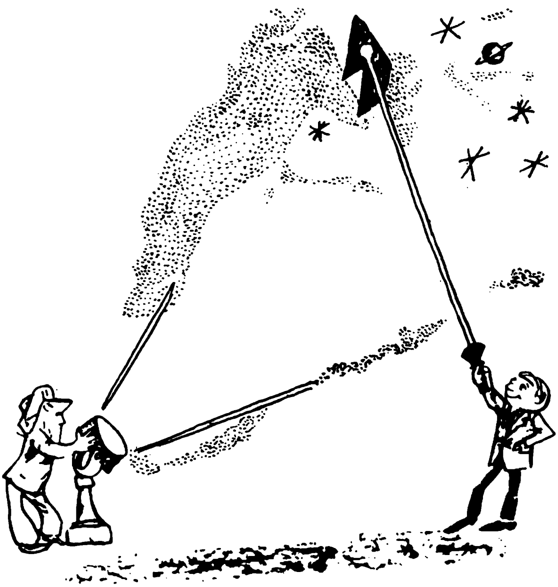
more powerful and finally, having gained enough strength to break through the half-silvered mirror *B*, a narrow beam of photons will pierce the space.

IV.40

The laser-emitted light differs from ordinary light in that it is excited by a special signal and therefore all its photons, as it were, "march in step", in the same phase and at the same frequency.

Herein lies the main advantage of the waves borne of photonics: ordinary light "disperses" in all directions, while the laser light is emitted in a single direction in the form of an even and straight beam.

A light spot produced on the moon by a laser equipped with a telescopic lense will be only three kilometres in diameter. The beam of an ordinary search light at such a distance would become so broad that it could cover 11 lunar discs.



Since The Hyperboloid Was Created

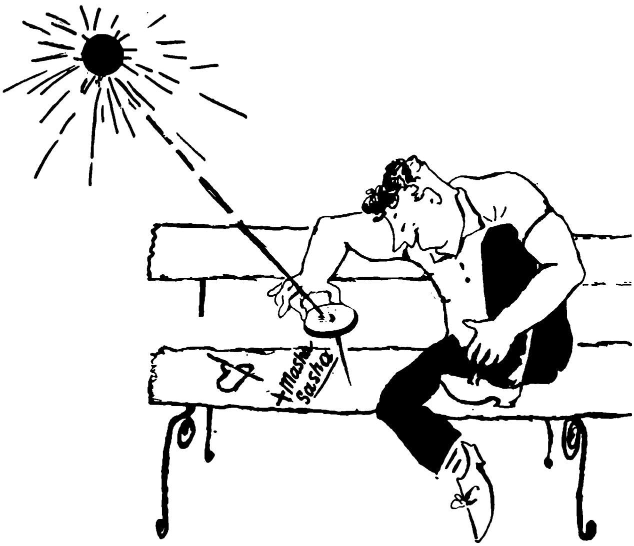
About 40 years ago in a science fiction book by Alexis Tolstoi there appeared a fine word—hyperboloid. The inventor of the hyperboloid whose name was Garin obtained a beam of light of an unprecedented power and decided to conquer the world with its aid.

In our childhood each of us had his own small "hyperboloid"—an ordinary magnifying glass. Its beam did not possess the same fantastic power, but in principle, its action was the same as of the device developed by Garin: the rays of the sun concentrated on a small spot could leave a trace on wood or on a bench, or burn one's hand.

But then lasers made their appearance and Tolstoi's fantastic idea has become a reality. The light spot produced by the laser beam harbours a menace that cannot be dismissed: the spot is illuminated with the intensity of a thousand suns! This causes metal to evaporate and a graphite plate to heat up to a temperature of 8000°C in five thousandths of a second.

17 Зак. 15299

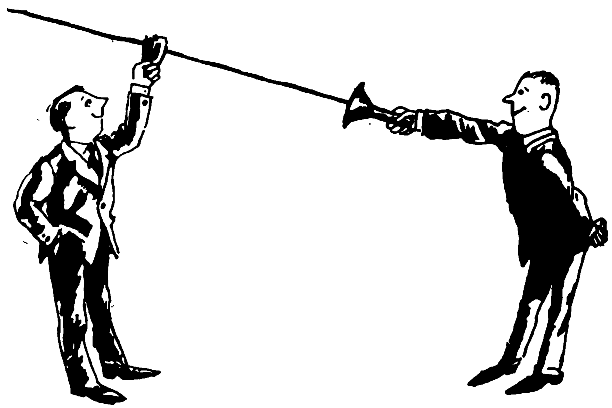
At first the developers of the laser introduced a peculiar method of evaluating the power of the beam and the degree of its concentration. They measured these magnitudes by the number of ordinary safety razor blades. If the beam is directed at a blade a hole will be burnt in it. A laser is capable of burning holes through several blades at once and sometimes even through several scores of them.



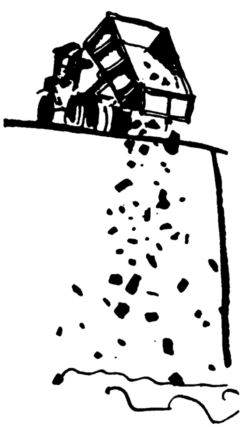
In what way is this different from the hyperboloid? Hardly anyone would risk getting in the way of such a beam!

But why is it that the hyperboloid has finally appeared in the form of the laser? The laser emits photons, i.e. ordinary visible light. But then there are other sources of light besides the laser. Why cannot they be used for the same purpose?

Unlike the laser-emitted light ordinary light possesses a very broad spectrum of frequencies. In other words, it is made up of waves of different length. Imagine that someone has dumped a lot of different stones into a lake. Some of them are large and others, small, and they form waves of different lengths which are superposed on one another. But instead of a uniform sequence of crests and troughs, complex ripples will appear on the surface of the lake.

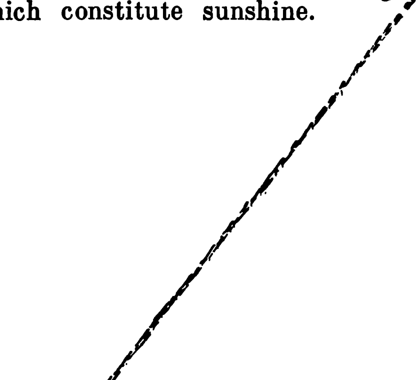


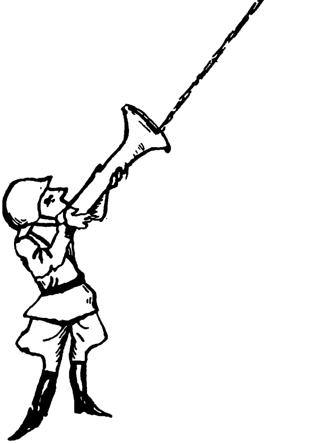
It is impossible to form directed beams out of ordinary light, because the waves of such a light act on one another differently: either the crests or the crests and the troughs coincide. The resultant picture is even more complicated than that on the surface of the lake into which a large number of different stones has been thrown. That is why specialists call the laser-emitted light a signal, while ordinary light, say, that emitted by an electric lamp, for them is nothing other than noise. Of course, no one has ever heard the noise of an electric lamp, but all the same the lamp can be called a generator of noise, because from experts' viewpoint noise is any signal of a random amplitude and broad frequency spectrum. (For information on the spectrum and its decomposition see Section "Pulses and Buratino", Chapter IV.)



The filament of the electric lamp is heated to white heat by electric current. The excited atoms of the filament are at different energy levels. Rolling off the higher to the lower "steps", they emit an enormous mass of photons. But since the "steps" are different, light emitted by each of the atoms has its own wavelength. And together all the atoms produce a broad radiation spectrum, a multitude of waves of different lengths.

The Sun is also a generator of noise. Each square centimetre of its surface sends to the Earth a signal having a power of the order of 7 kilowatts. But if we wish to separate out with the aid of a filter a frequency band of 1 MHz, then at the output of the filter only 0.00001 watt power will remain—the power will be decreased 700 million times! This means that the share of a band of 1 MHz is only one seven-hundred-millionth of the energy, the rest falling to the share of other frequencies of the spectrum, other numerous waves which constitute sunshine.





With the aid of a prism which differently refracts these waves it is possible to create a "colour image of the Sun", i.e. to single red, orange, yellow, green, blue, indigo and violet light out of white light.

The laser beam has but one colour. It consists of waves of a single length. And this is its main advantage: it possesses directivity, its waves do not diverge and do not quench one another, but travel in a single direction and in a narrow beam.

The laser beam can be made still narrower by focusing. This does not require enormous reflectors nor lenses. The length of light waves amounts to several ten-thousandths of a millimetre (from 0.4 to 0.7 micron). Even a very small lens will be much larger than the length of the radiated waves.

By producing a directed beam with the aid of a laser and employing focusing it is possible to "bombard with light" any distant object.

The laser light is emitted in the form of very short bursts lasting thousandths of a second. The power emitted during bursts is several thousands of watts. The Associated Press Agency has already reported that America has begun developing a quantum oscillator capable of destroying a flying aircraft or other target at a distance of two kilometres. The same beam in space will have a range of several hundred kilometres, as there is no atmosphere to attenuate light rays. The weight and size of this oscillator will be quite impressive. Whereas Garin carried his device about in a suitcase, the projected American device will weigh about 14 tons.

And what kind of lasers will appear in 20 year's time? Of course, they will be lighter and more effective. And will it be possible to aim a "light spot" at a rocket and burn a hole in it? For at the rocket's enormous speed it will take only a tiny hole to make the rocket lose control and dive down to earth. It is not so simple to solve this problem.

For the "light spot" to burn a hole, the beam must be fixed on the fast flying rocket. And to do this the beam must be instantaneously refocused following the course of the rocket.

What should the "light spot" be like? The German scientist Tierring made the following calculation. To melt the body of a rocket within one minute, a power of about 800 kilowatts is required. Even if the divergence angle of the focused beam is only one angular minute (for comparison, let us say that the disc of the rising Sun is seen at an angle of 10 minutes) at a height of 50 kilometres the "light spot" will be about 200 times wider than the cross-sectional area of the rocket nose. The rocket will receive only 1/200 part of the energy of the laser. This means that during a whole minute the radiation power of the laser should be

$$800 \times 200 = 160\ 000 \text{ kilowatts.}$$

And the radiation power of a modern laser is on the average only several milliwatts. The conclusion is not very encouraging. For the beam to destroy a rocket, the power of the laser must be increased 100 million times! The calculation is simple but convincing. It is unlikely that in the nearest future a "hyperboloid" will be developed that will prove an effective weapon against rockets.

How Can Light Be Modulated?

A most attractive idea—to turn the directed beam of a laser into a carrier signal! Carrier light signals could have carried 30 million TV programs.

However, to transmit any kind of information with the aid of a laser, it is necessary to learn to apply "designs"—code pulses, television pictures, a spectrum of audio frequencies—onto the "canvas".

This is where a problem arises. Really, how can light be modulated? The "crooked mirrors" of electronics cannot solve this problem; the "mirrors" are based on the action of the field of the control grid on a stream of electrons. But how are photons to be acted upon? They carry no charge, so fields mean nothing to them. How is this difficulty to be overcome?

Having paid attention to various cases when field exerts influence upon the optical properties of matter, physicists have immediately got on the right trail.

Here is the thread of their thoughts and actions. Sounds, pulses, images are converted into an electric current. The current produces a field. The field acts on a crystal changing its optical properties. The laser beam can either pass through a crystal or be reflected by it. Hence, if the crystal is subjected to the action of a varying field, the intensity of the beam will vary and the necessary "design" will appear on the carrier laser signal. In this case the term "crooked mirror" is no longer a figure of speech, because to modulate light real mirrors are required. And they really must be "crooked"—under the action of the field they distort the light.

Physicists know of various phenomena (or, as they like to put it, effects), which make it possible to act upon light with a field. For example, the Faraday effect, which in essence consists in that under the action of magnetic fields the polarization of light is changed. (The reader was earlier made familiar with polarization in Chapter III—see III.18.) Or the Zeeman effect: an external field causes the spectrum of a beam of light passing through a crystal to vary. In this way frequency modulation of the laser signal is effected. Or take the Kerr effect (refraction of a beam and variation of polarization under the action of an electric field), which makes it possible to modulate carrier light signals, converting the modulating signals into variable electric fields.

Light can be modulated by sound. In this case the sound waves deform the crystal lattice, thus changing the optical properties of the medium through which light is propagated.

Finally, in the laser itself it is possible to vary the intensity of the pumping, thus influencing within certain limits the intensity of the light signal and its frequency.

And now the modulated laser signal has reached the receiver. As you know, here we need to detect the signal, i.e. to separate the "design" from the "canvas". This can be done by making use of the photoelectric effects, wherewith the current through a photocell depends on the intensity of illumination. The detection comes to a simple phenomenon: the intensity of the modulated beam varies, thus changing the current in the photocell circuit.

The same effect is used for converting the frequency of a light signal. The signal of the transmitting laser is mixed in a photocell with the signal of a local laser oscillator (the role of the local oscillator was described in Chapter "Electrons, Waves, Fields"—Section "Kingdom of Crooked Mirrors"), the difference frequency being produced at the output. The rest of the circuit does not differ from that of ordinary superheterodyne receivers (see circuit diagram on page 143), because as a result of the conversion the frequency of the light signal is lowered down to a radio frequency.

Today extensive research into the modulation and detection of light signals is under way. Physicists are carrying out experiments. The results are being compared. The suitability of the above described methods for various signals and modulating frequencies is being evaluated. The scientists are faced with enormous work on the problems of the modulation of light, so as to find for various practical purposes the most "effective effect" of those that are known.

On The Agenda

A new patient is admitted to the clinic. The X-ray shows that urgent surgical intervention is necessary. The surgeon is ready to begin the operation. But what he is holding in his hand is neither a cutting nor a piercing instrument, but some unusual device. Then he carefully examines the X-ray pictures, thoroughly measures on them the distance from the surface of the patient's body to the site of operation and adjusts his device accordingly. Then he depresses a button and the patient's body is pierced by a narrow beam of light.

The operation is over, but on the patient's body there is not a trace of blood and, in general, no traces of the operation. It turns out that the beam has penetrated inside the body without causing any harm and has only cauterized the place at which it has been focused, i.e. the site of operation!

Fantastic? As of now, yes. But in the nearest future this will evidently become a reality.

Because the radiation power of the laser can be selected in such a way, as to be harmless everywhere except the point whereat the beam is focused. This point will be something like the point of a sharp needle. What is more, this needle need not pierce the patient's body—the "point" will appear exactly where the affected tissue has to be cauterized.

Similar experiments have already been conducted: a laser beam has been used to "fuse" detached retina in the eye without harming the sensitive tissues of the pupil.

There is no limit to the possibilities opened up by lasers for science and technology. The photon has proven to be a formidable rival of the electron not only in radar and communications, but also in the field of production. With the advent of lasers metals and other materials can be processed not only with an electron, but also with a photon beam. In addition, the narrow laser beam makes it possible to "sound" microscopic parts, obtaining their image on a photographic plate and determining precisely their size.

But this is not all: it has been found that under the action of such a beam the molecules of certain substances gain in chemical activity. By varying the frequency of the radiations one can excite the molecules of different substances. This means that the necessary corrections may be introduced into complex chemical processes, accelerating some reactions without affecting the others. The same beam can be used for breaking the bonds between molecules, i.e. to change the structure of various substances according to your own will.

And here is another prospect: the transmission of energy without wires. And indeed, a narrow beam is actually a conductor, it concentrates all the energy which can be delivered to the destination without losses.

And there are other projects. Light exerts pressure—this was proven 70 years ago by the Russian scientist Lebedev. But whereas the pressure of ordinary light can be detected with very sensitive instruments only, what will it be like in the case of a powerful and narrow beam? It has been calculated that the pressure in a laser beam is of the order of several million atmospheres.

With the aid of such a beam, just as if it were a gigantic pointer, it would be possible to change the path of artificial satellites directly from the ground.

With the advent of lasers a new trend in technology—holography—was born. What is this?

Roughly, it is something like three-dimensional photography. The object to be photographed and a special plate are illuminated by a laser beam directed by a system of special mirrors. On the plate there remain the traces of the interaction of beams (holograms). Do not seek for the image of the original on the hologram—there is only an interlacement of quaint lines that have nothing in common with the outlines of the object just photographed. But if the object is removed and the laser beam is passed through the hologram, the object appears again. No, not the object, but only its "wave copy"—it is incorporeal and has no weight, but it does have a definite volume. You can step behind it and look at it from there; if there are two objects on the hologram (for example, two chess pieces), then when viewed at certain angles, just as it is in reality, one object will hide behind the other.

In this respect the "portrait" in holography differs from any stereoscopic pictures produced till now. The most that can be achieved with them is an illusion of volume and perspective, but here we are dealing not with an illusion, but with a real "cast" made from the original, the sole difference being in that it consists not of any substances, but of waves.

One can suppose that with its development holography will firmly establish itself in stereoscopic TV and stereoscopic motion pictures.

IV.41

Many fields of technology will find use for the narrow, concentrated, sharply directed light beams produced with the aid of lasers. Wide use will be made of lasers for maintaining communication with objects in space. True, direct communication between the Earth and space is always made difficult because light is dispersed by clouds, fog, snow and rain. The laser will have to be installed in the satellites, while ordinary radio stations will keep up communication between the satellite and the Earth.

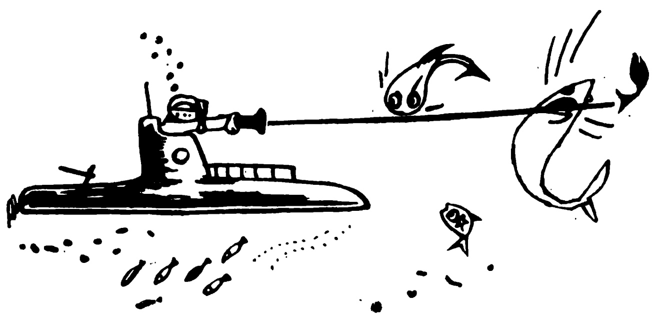
IV.42

A beam sent into space by a laser will travel straight to its destination.

For communicating with Mars an ordinary radio station must have a power amounting to millions of watts, whereas in the case of the laser, one watt power is sufficient, i.e. less than the power of a pocket electric torch or flashlight!

IV.43

Lasers can be of great service not only in space, but also under water. Ordinary radio waves are greatly attenuated

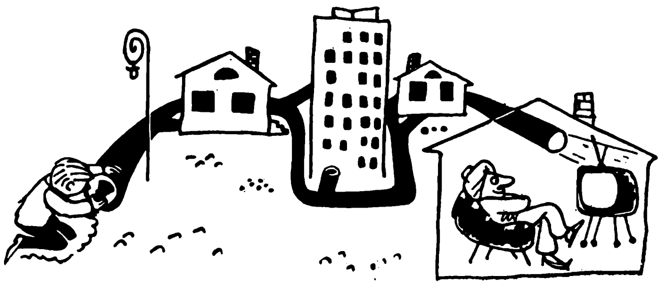


(weakened) in water, therefore ultrasound is now being used for underwater communications. Light is also poorly propagated through water, but light waves whose length corresponds to blue and green colours freely pass through sea-water—hence the specific colour of sea-water.

Communication and radar under water are now realized by means of radar beams of the "sea-water colour".

IV.44

Light signals, which will be used as carrier signals for sound and television communication, should be protected from the effect of the atmosphere. Most likely, special tubes will be developed for these signals, and to change their direction use will be made of mirrors.

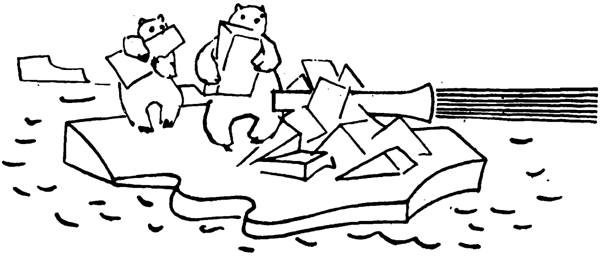


IV.45

In electronics the stage of "diseases of childhood" has long been passed, but with photonics it is only beginning.

Do you remember how difficult was the change-over from spark transmitters to continuous wave radiation? Something of the kind is now happening with the laser. Pumping is effected flashwise. After every flash of the pump lamp the laser emits a pulse lasting several thousandths of a second. The development of continuous pumping is a difficult problem: if the pumping power is increased, the laser will become excessively overheated and therefore cooling will have to be employed, involving the construction of bulky and complex systems.

Recently it has become possible to develop several types of lasers with continuous wave radiation.



IV.46

Of great help in space studies are molecular and paramagnetic amplifiers. In many ways their principle of operation is similar to that of the laser. Just as in the case of the laser the molecules of a substance are excited at the expense of external energy and "go step E_3—E_1 up" (see IV.33).

But whereas in the laser this is followed by the atoms spontaneously making a transition to a lower level and radiating photons, in the amplifier (molecular or paramagnetic) a new impulse is required to produce this effect. Just such an impulse is provided by the signal that is to be amplified.

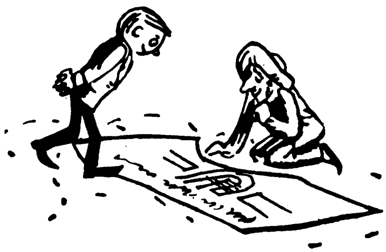
The frequency of the amplified signal must correspond to the magnitude of the "step" (E_3—E_2) from which the molecule of the substance will "fall" under the action of the impulse. It turns out that the oscillatory circuit of the amplifier (i.e. the molecule) is tuned to resonance with the amplified signal.

Both in molecular and paramagnetic amplifiers the excited state of the medium (crystal, solution, gas) is reached through the action of electromagnetic fields.

And the differences spring from the fact that the excitation is conditioned by different physical processes. Whereas in the molecular amplifiers electrons, on being excited, make a transition from orbit to orbit, in the paramagnetic amplifiers the electrons during excitation remain in their former orbits, but the magnetic state of the molecules of the irradiated paramagnetic substance is changed.

IV.47

The main advantage of quantum mechanical amplifiers is the absence of internal (intrinsic) noise. In the case of valve amplifiers internal noise is caused by the thermal motion of the electrons. Paramagnetic amplification, on the other hand, is realized at very low temperatures—minus 269 degrees Centigrade—which is nearly equal to absolute zero. At such a temperature the thermal motion practically ceases. What is more, each photon has so little energy that



even when moving chaotically they are incapable of producing noise of their own. That is why paramagnetic amplifiers can amplify a signal to an extent hundreds and thousands of times greater than do valve amplifiers without any fear of the signal being "drowned out" by noise. And whereas a modern receiver can provide 10^{14}-fold gain (a hundred trillion times), a receiver with a quantum mechanical amplifier can amplify signals to a level thousands of times higher.

Universe Calling!

In recent years specialists in electronics have been more and more frequently worried by problems on a cosmic scale.

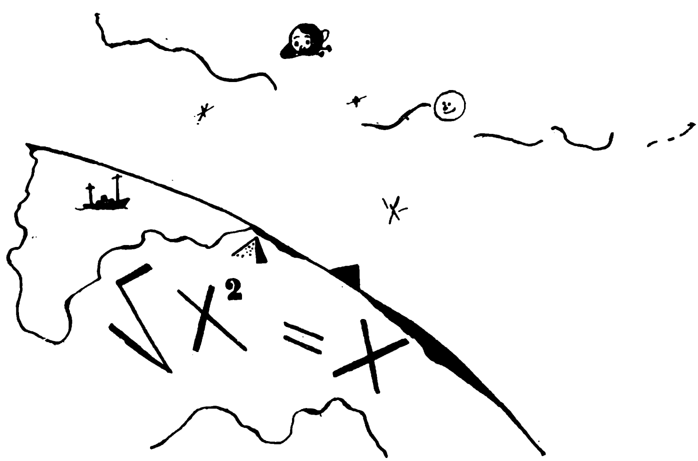
And this is only natural: for progress in every branch of science and engineering has always given an impetus to developments in the allied fields.

In connection with the exploration of space there have been developed super-sensitive receivers and reliable electronic circuits which ensure the launching of spacecraft into orbit and communication between the spacecraft and the Earth.

Having mastered with the aid of electronics an enormous range of wavelengths from a micron to kilometres, man puts himself the question: is it not possible to utilize these waves for communication with the inhabitants of other worlds? After all, in the infinite depths of the universe there must be beings as intelligent as we are, who know how to transmit and receive signals no worse than we do!

Can there be any doubt how interesting it would be to get in touch with a civilization which has, perhaps, outstripped ours by, say, several thousand years!

In the future it may be even possible to visit the inhabitants of neighbouring galaxies, but in the meantime it would



be very tempting to get but a short message, some signal in response. Something like a message: we know about your existence and are willing to be friends with you.

This dream has been born long before the advent of electronics. At that time various means of communication were discussed. Some wanted to construct an enormous mirror that could produce a light spot on Mars. The authors of this idea thought that the mirror should be used for burning some mathematical symbol on Mars. There were other projects: for example, it was suggested to make a gigantic sign on the Earth. The mathematician Gauss believed that Siberia would be very convenient for this purpose. He suggested that the sign should be made of planted yellow wheat which would contrast against the background of the green taiga. Others believed that the sign should be made in the Sahara desert.

None of these projects have ever been realized. The advent of radio gave a new start to the old dream. Now it is radio messages that are being expected from the inhabitants of the universe. And then...

A sensation! Signals from space! The American engineer Carl Yansky has caught messages that are repeated exactly every 23 hours 56 minutes!

Alas, disappointment has awaited the investigators of these signals, who have been so eager to establish an interplanetary communication. It has been found that these signals are not at all transmitted by beings endowed with reason. Electromagnetic waves are radiated by the Moon and the Sun, Mercury, Jupiter and Saturn. We have managed to receive radiations of natural "radio stations" removed from us by thousands of millions of light years.

The thirst for contact with inhabitants of the universe has remained unsatisfied. But now there has appeared a new field for the application of electronics—radio astronomy.

"This Is Earth Calling! How Do You Hear Me?"

Well, if our brothers-in-reason are in no haste to send us a report, maybe we should let them know about us?

In 1960 a signal with a wavelength of 21 centimetres was sent from America. Having travelled a distance of 100 trillion kilometres, this signal should reach stellar systems in the constellations of Cetus and Eridanus in 11 years. And if the inhabitants of one of these systems should catch our signals and wish to contact us, we would receive the reply in 1982. Even a short "conversation" with the inhabitants of the universe would, as you see, last quite a time: in 22 years one answer and one reply.

What are the chances of starting such a conversation? If there are thinking beings, do they have sensitive receivers? Will they be tuned to this wavelength?

It is hard to forecast anything. But selecting a wavelength of 21 centimetres, the scientists pursued a definite aim. The thing is that this is the wavelength of the signals transmitted by the hydrogen atoms. This occurs each time when the particles inside the hydrogen atom change their magnetic moment. In every atom this phenomenon is repeated on the average once every 11 million years. But the amount of hydrogen dispersed in space is so great that this rare phenomenon takes place every moment somewhere and, therefore, from any part of the universe continuously come signals with a wavelength of 21 centimetres.

Hydrogen is present in the entire interstellar space. Receiving the signals of hydrogen atoms astronomers keep an eye on what is going on around us. In particular, they have been able to observe a catastrophe of two gigantic galaxies—it has been surmised that "antiworlds" have collided.

All very well, but what has this to do with other civilizations? Why have the scientists decided that these civilizations will hear us at precisely this wavelength?

They have reasoned this way: any civilization that has reached the same level of development as we have or, what is more, that has outstripped us, must take an interest in the universe and catch hydrogen signals with a wavelength of 21 centimetres. This means they must have receivers tuned to this wavelength. Suffice it to modulate the signal to give it a corresponding "tint" and it will become easily distinguishable. "Those people" will understand that this is a call and will begin to reply.

Will these conjectures be confirmed? We shall wait and see. And we do not have to wait very long, only about 9 years.

Astronomy's Second Wind

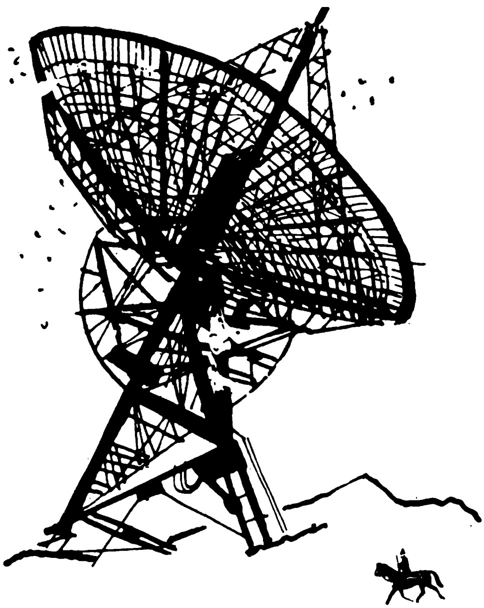
In the life of sportsmen there are moments when it seems that all their strength has been exhausted. And then comes what is known as the second wind.

A similar situation occurred in astronomy. All that can be seen with the aid of optical telescopes was studied thoroughly. But the infinite depths of the universe attracted man by the abundance of undisclosed secrets. But what is to be done if all the possibilities of telescopes have been exhausted and one cannot look farther. And then came astronomy's second wind, or rather, second sight.

The radio telescope came to the assistance of the optical telescope.

Space proved saturated with radiations of various frequencies. Innumerable natural ratio stations transmit these signals. Waves from 8 millimetres to 12 metres long are emitted into space by the Sun. Our Moon "operates" with a wavelength of 1.25 centimetres. Gigantic accumulations of hydrogen continuously transmit signals with a wavelength of 21 centimetres. All waves from 1 centimetre to several metres long pass through the Earth's atmosphere.

Giant mirrors of radio-telescope antennas with diameters of up to 100 metres continuously sound space, watching everything that is happening around. The appearance of these mirrors may seem strange to many: what kind of a mirror



is it, if it consists of only holes?! To make these mirrors lighter they are actually made up of lattices. Then why do the received waves not seep through the openings of the lattice?

You and I are used to handle ordinary mirrors intended for reflecting optical waves. The waves caught by the antennas of radio telescopes are several hundred thousands of times longer. Since the size of the holes in the mirror is less than the length of these waves, for them this mirror will be just as smooth and even as an ordinary mirror is for optical waves with lengths of several fractions of a micron.

The mirror reflects the arriving waves, focusing them on the antenna. With the aid of such systems it has become

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possible to discover a multitude of unknown galaxies at distances from which it takes light 6 milliard years to reach the Earth!

Radioastronomy has not only a long sight, but also the ability to look through.

There are parts of the universe which are hidden behind a layer of cosmic dust impermeable to light rays. For electromagnetic waves this curtain proved to be transparent.

With the aid of radio telescopes formerly unknown clusters of stars were discovered in the centre of our Galaxy, and the Galaxy itself was found to have a shape close to that of a spiral. Incidentally, such a structure had been forecast theoretically before it became possible to observe it.

An enormous role in the development of radioastronomy has been played by quantum mechanical amplifiers (molecular and paramagnetic—see IV.45 and IV.46). They make it possible to receive very weak signals that arrive from the depths of the universe. Actually, it is only such purposes that they are suitable for. For ordinary radio communication they are far too... good.

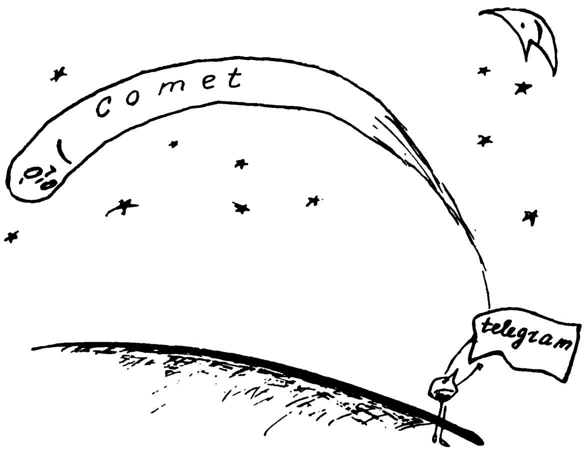
This sounds somewhat paradoxical, but this is exactly the conclusion that the experts have arrived at. The thing is that these amplifiers are so sensitive that for them any body radiating thermal (infra-red) waves is a source of quite a noticeable interference. Only when the antenna of the receiver looks out into cold space can their amplification be effectively utilized.

In San Fernando, USA, a radio telescope was erected for observing extinct stars, which are invisible with ordinary telescopes. It proved so sensitive that it "noticed" all the insects flying by because of the heat radiated by their tiny bodies. Within a radius of 15 metres one could not light a cigarette without disturbing reception.

Those cosmic objects that do not send their own signals can be "sounded" by means of reflected waves. Radar has proven to be capable of coping with this problem, despite the remoteness and unusual nature of the targets. It has become necessary to develop special stations, transmit signals at longer intervals, but make them much more powerful. Such signals have helped establish more accurately the composition of the Moon and Venus and also to measure the distances to them—this is precisely what radar is for: to determine the distances to very remote objects to an accuracy within several kilometres. The Lebedev Physics Institute developed a special laser for radar sounding of the Moon at the Crimean Astrophysical Observatory.

On The Tail Of Meteors

Electronics has helped astronomy. And astronomy has not left electronics unanswered. In particular, it has helped investigate the conditions of propagation of electromagnetic waves through the atmosphere depending on the state of the



Sun and other heavenly bodies. And it has made certain suggestions concerning reliable communication over great distances. It has been established that outer space continuously bombards the Earth with a hail of meteoric particles. On entering the atmosphere, the particles soon burn out, but for a certain time they leave an ionized trace. If a meteor weighs even a hundred-thousandths of a gram, the trace will be sufficiently dense for reflecting radio waves.

Is it not possible to receive radio waves reflected from these traces? Will such a communication be continuous or will it be necessary to wait until another meteor can be "caught by the tail?"

The meteoric rain is continuous. Every day about 10 milliard meteors weighing several hundred-thousandths of a gram burn out in the atmosphere.

But not every missionary from outer space is suitable for communication. They may fly in any direction and their paths will determine the position of their tails. It is necessary to wait for such a tail that will reflect the waves in the direction of the receiving station.

While the conditions are unsuitable, the long-distance communication station automatically records the messages on a magnetic tape, watches the state of the atmosphere and waits until a trace suitable for communication appears in the sky. When it appears, the station hastens to transmit all the messages it has stored up. Instead of a hundred words a minute an ordinary radio station transmits, such a station in the very same minute transmits about 1500 words. Such a high speed makes it possible to transmit in a short time all the messages stored up by the station while there were no suitable meteoric tails.

Beyond The Restriction Line Of Television

We have already seen that outer space can help electronics in the solution of many terrestrial problems. Among them is the problem of long-distance television. The horizon range limits the reception range of television signals. The horizon is the restriction line. How is this line to be overstepped?

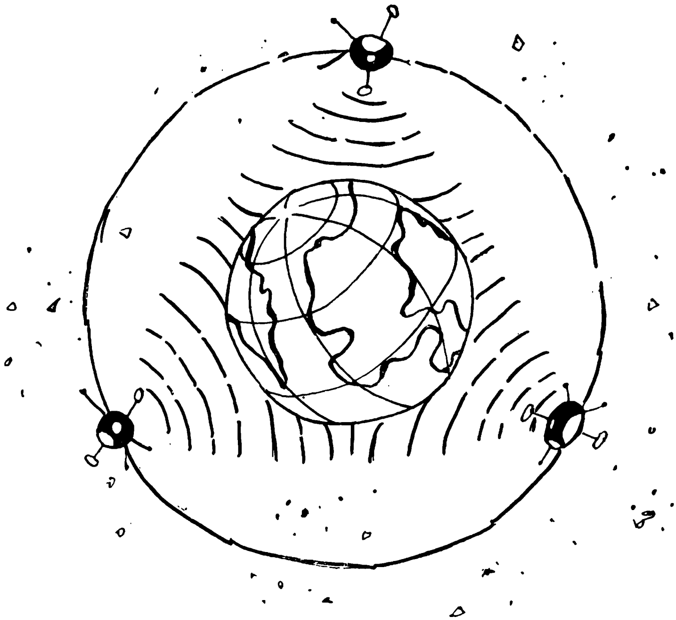
Relaying is quite a reliable method. Relay stations which receive the signal and then retransmit it are set up at the distance of direct vision from one another.

It is quite obvious that this costs dear: every 100 kilometres—a relay station, over a distance of 10 000 kilometres—about a hundred stations. And this is all very well on a dry ground, but what if there is an ocean in the way?

The signal can be sent by cable, but in the cable it quickly loses its energy. Then amplifiers have to be set up along the way. And whereas relay stations are set up every 100 kilometres, the amplifiers in the cable line have to be installed every 25-30 kilometres. Again this is costly, and the reliability of such a communication line is low.

To increase the range the antenna of the relay station can be set up higher. Then the distance of direct vision will become somewhat longer, the horizon will recede, and the station will become able to service a larger area. It is not by chance that the French use for relaying the highest structure they have—the famous Eiffel Tower.

Italy and Switzerland communicate over the Alps: the relaying antennas are set up on the summits of Jungfrau (4166 metres), Monte Generoso (1701 metres) and in the town of Chasserelle situated at an altitude of 1609 metres above sea level.



The Americans tried to solve the problem of long-distance television in another way: by creating "an artificial ionosphere" with the aid of special rockets. An explosion made at an altitude of 100 kilometres produced a cloud of atomic potassium. This cloud ionized by the sun rays reflected television signals for one and a half to two hours. Clearly, in special cases this method is quite acceptable. But it can hardly be used for daily transmissions of television programmes, the more so as the ionization of the cloud by the sunbeams is not constant either—the Sun has set and there is no communication.

But with the aid of satellites this problem can be solved radically! Relay stations installed in three satellites spaced 120 degrees round the Earth will ensure world-wide television communication. If the orbit is chosen correctly (design altitude 35 800 kilometres), each of the satellites will be "tied" to a certain point of the equator: the number of revolutions of the satellite will coincide with that of the Earth.

In 1963 the American rocket "Thor" launched into orbit the first satellite for relaying "Intervision" programmes, the "Syncom-2". With the aid of this satellite pictures were transmitted from the port of Lakehurst, New Jersey, to the ship "King's Port" that was steaming towards Nigeria to the African island of Lagos.

The Soviet satellites "Molniya" allow television broadcasts to be relayed from Moscow to the Far East.

When implementing "Intervision" through satellites, a number of as yet unsolved problems were encountered. For instance, how can an evening broadcast be transmitted to some area of the globe where the dead of night reigns.

The programmes are first recorded on a magnetic tape and then transmitted later, at daybreak.

Satellites can help not only television but also ordinary radio communication. The thing is that the wave range from 10 to 2000 metres is becoming more and more cramped every year. Hence the natural desire to extend the radio communication range down to centimetre wavelengths. But there is one drawback: waves shorter than several metres are not reflected by the ionosphere, and for them the horizon is a line they cannot "overstep". This is where satellites come to the rescue. By installing a relay station in a satellite it is possible to receive a radio broadcast at centimetre waves and direct it from the satellite to a distant point of the Earth...

Up the frequency scale stride not only electronics but also those fields of technology that are connected with electronics: radio has begun mastering centimetre waves, while television wants to make use of lasers and operate with waves several tenths of a micron long.

CHAPTER V. ELEMENTS OF "WISE" MACHINES

HOW SIMPLE ELECTRONIC CELLS ARE EMPLOYED TO ASSEMBLE COMPLEX CIRCUITS OF "WISE" MACHINES.

THE TWO SCALES OF A BALANCE

THIS LIES AT THE BASIS

V.1

Ever since it was born, since its early childhood, one might say, the triode has become famous. But its fame at that time was one-sided: its main merit was considered to be the ability to serve as an electronic key. If you recall, at first it was

even considered inconvenient to call it a valve, and it was known as a "vacuum relay." With time the "talent" of the triode has proven much more versatile: it has become an amplifier, an oscillator, modulator, detector, mixer — in short, it has coped with all the tasks (within a definite frequency range) put by radio communication.

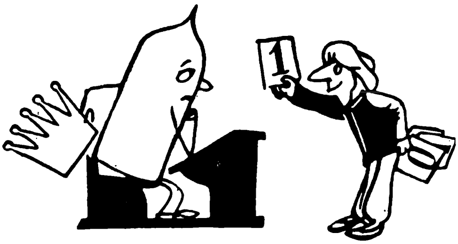
With the advent of pulse techniques, the triode-keys had to be recalled again. And now all radar circuits include triodes. And in electronic computers hundreds of thousands of triode-keys are employed.

V.2

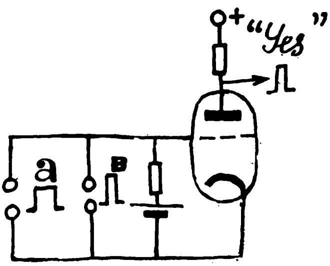
Every one knows that the electronic computer is the forebear of the class of "wise" machines. That is why it also needs "wise" keys. So as not to lag behind the times, the triode has had to learn: it has mastered logic and the binary number system.

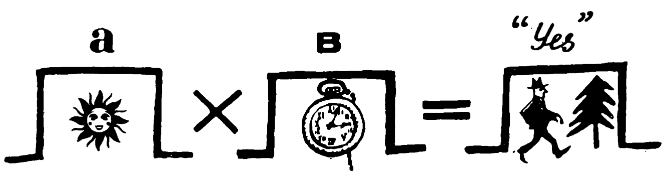
The logic of the triode is simple: it is either conductive or cut off. In the first case it answers "yes" and in the second, „no".

Let, for example, the triode be cut off. Then two pulses (*A* and *B*) are simultaneously applied to it (to its grid).



It is rendered conductive and gives the response "yes". In this way it confirms that the pulses have actually been applied, and both of them at once: *A* and *B*. And what will happen if only one of the pulses is applied? It all depends on





the electronic circuit. In our case it is designed in such a way that separately neither of the pulses can render the triode conductive. This is achieved by applying a negative potential to its grid.

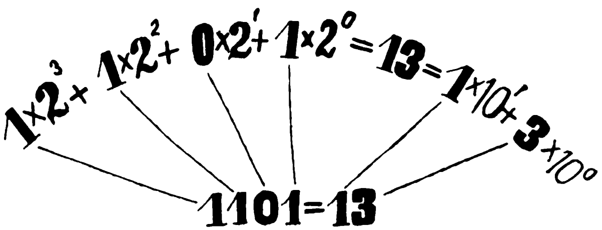
The pulses may represent anything, i.e. any events *A* and *B*. For example, if the weather is fine (*A*) and there is time to spare (*B*), then it is possible to go for a walk ("yes"). If one of the conditions is not fulfilled, then there can be no walk ("no").

In automatic electronic circuits triodes usually solve other problems. Suppose a workpiece is set correctly on a lathe (*A*) and a cutter of the appropriate shape is brought near to it (*B*), then the lathe is switched on ("yes").

With a circuit including many triodes it is possible to foresee many different conditions and, if they match, to obtain at the last triode the general response "yes". Thus with the aid of the very same triode-keys it is possible to elaborate executive programs for automatic devices and electronic computers.

V.3

When a triode is used for computing, its conductive state is regarded as unity (or bit) and the cut-off state, as zero. Bits and zeros can make up any number in the binary number system. The principle of the binary system is quite



simple. Unlike the decimal system, the basis of which is the number 10, in the binary system the basis is the number 2.

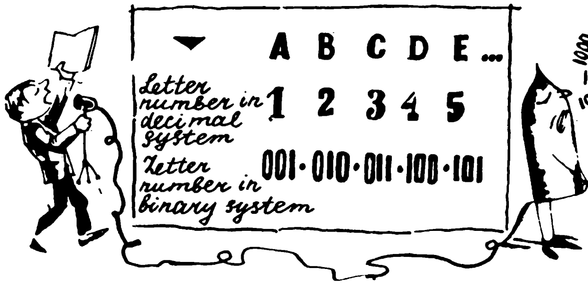
In the decimal system any number is the sum of tens raised to different power, for example: $1307 = 1 \times 10^3 + 3 \times 10^2 + 0 \times 10^1 + 7 \times 10^0$.

The same number can be expressed as the sum of twos raised to different power: $1307 = 1 \times 2^{10} + 0 \times 2^9 + 1 \times 2^8 + 0 \times 2^7 + 0 \times 2^6 + 0 \times 2^5 + 1 \times 2^4 + 1 \times 2^3 + 0 \times 2^2 + 1 \times 2^1 + 1 \times 2^0 = 10\,100\,011\,011$.

And this is what number 13 looks like: $13 = 1 \times 2^3 + 1 \times 2^2 + 0 \times 2^1 + 1 \times 2^0 = 1101$.

V.4

By assigning binary numbers to all the letters of the alphabet, any text can be converted into a sequence of bits and zeros.

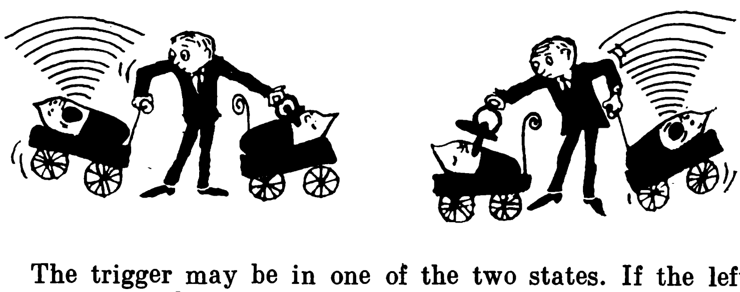


Being rendered conductive and non-conductive, the triode can recite Pushkin's verse or Turgenev's prose in its own "valve language".

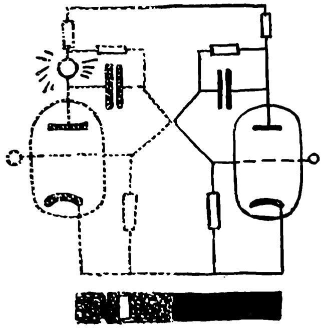
V.5

Very convenient for the binary system has proven a circuit employing two triodes, which is known as *trigger*.

At first the trigger circuit was used in radar, but in recent years it is being used in enormous quantities in the electronic computer circuits.



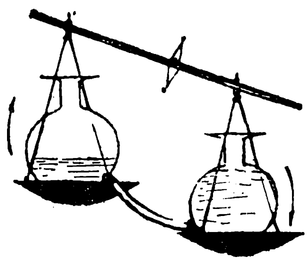
The trigger may be in one of the two states. If the left triode is conducting, the right one is necessarily cut off. In this case the lamp included in the anode circuit of the left triode will light up, which denotes the number "1".



In the other state the right triode conducts, and the left one is cut off. The lamp does not light, thus denoting "0".

V.6

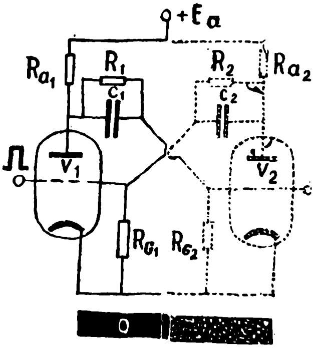
The operating principle of the trigger is somewhat reminiscent of a balance with two communicating vessels, filled with a very mobile liquid, put on its pans. By giving a downward



push to the right pan of the balance we cause it to descend, and all the liquid will flow into the right vessel.

This position will be very stable, because all the weight of the liquid will press on the right pan of the balance. To bring our system out of this state it is now necessary to give a downward push to the left pan. By inertia it will pass through the position of equilibrium, and the liquid pouring out of the right vessel will begin to fill the left one. Now the liquid will press on the left pan. The balance will assume a new position, which will also be very stable. To change it a new impetus is needed.

V.7



Something of the kind takes place in the trigger: the vessels are the electronic valves, and instead of the mobile liquid we have electric current which is even more mobile. In the cut-off valve there is no current—this is the empty vessel.

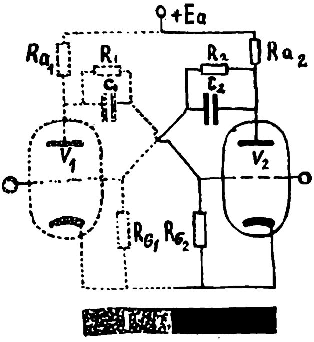
Suppose that initially the left valve V_1 is cut off—the trigger is in the "0" state. At some moment a positive pulse arrives at the grid of V_1—our "balance" is given a push. While valve V_1 has been cut off, the current has flown past the valve, via the circuit consisting of resistors R_{a_1}, R_1 and R_{g_2}. This network is a voltage divider. A definite part of the anode voltage $(+E_a)$ falls across each of the three arms of the divider.

The pulse has rendered conductive the left valve V_1, which is connected in parallel with the lower arm R_{g_2} of the divider, and the positive voltage across this arm drops considerably (since the resistance of the conducting valve V_1 is low), in other words, the positive voltage between the grid and the cathode of valve V_2 decreases. Valve V_2 starts getting cut off. And since valve V_2 is connected in parallel with arm R_{g_1} of the second voltage divider (circuit R_{a_2}, R_2, R_{g_1}), the voltage across this arm will increase. Therefore the positive potential at the grid of valve V_1 will also increase and the valve will become still more conductive.

V.8

One might think that a kind of mutual aid exists between the valves: they both help each other to change over to a new state. As a result, the left valve is now conducting and the right one is cut off: all the "liquid" has flown from the right "pan" to the left one, the balance has "turned" and will wait in this state for a new impetus. This state corresponds to the number "1".

Obviously in this case it is not the weight of the "electron liquid" that is acting upon the "pan of the balance" (the weight



of electrons is negligible), but its electric charges. When moving, the electrons set up a current in the electronic valve. Current pulses give birth to voltage pulses, the voltage acts upon the grid of the other half of the trigger, thus "turning the balance".

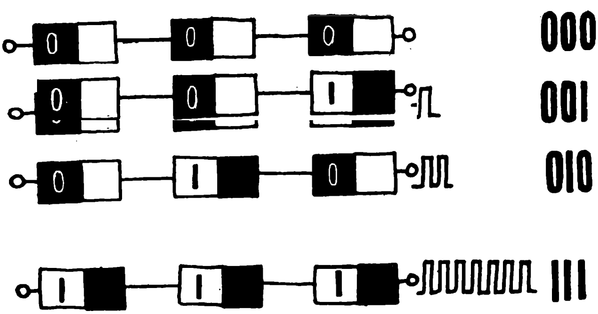
V.9

Let us connect three triggers in a row and make each of them, after the "balance" has once swung there and back, push the next "balance". Such a circuit can be used for counting incoming pulses. The first pulse will change the state of the trigger at the beginning of the row. The second pulse will make the "balance" swing back, and at the same time a pulse from the first trigger will push the second "balance".

With the arrival of the next pair of pulses the trigger at the beginning of the row will again swing there and back and transmit another pulse to trigger *2*.

The first trigger will swing from each pulse, the second, from each pair of pulses, and the third one, from four pulses. For the last trigger to swing "there and back", it is necessary to apply eight pulses, i.e. 2^3.

A circuit of four triggers will change its state after the arrival of 16 pulses (i.e. 2^4), that of five triggers, after 32 pulses (2^5), and the one of n triggers, after 2^n pulses.



And should it be necessary to count millions and milliards of pulses, will not the number of triggers be excessive?

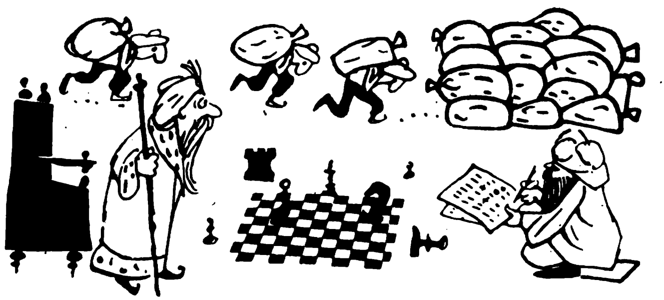
V:10

There is an Indian legend about how King Sheram decided to reward the sage Seta for the game of chess that he had invented.

Seta's request seemed very modest to the King: the sage wished to be rewarded with wheat, with the number of grains placed on each square being twice as large as that on the preceding square.

The board consists of 64 squares. If two grains are placed on the first square, then on the last one there should be 2^{64} grains.

The King was unable to deliver the promised reward. When the number of grains on the last square was calculated, it was found that the amount was 18 quintillion, 446 quadrillion, 744 trillion, 73 billion, 709 million, 551 thousand, 616 grains! It would take two barns stretching from the Earth to the Sun to store all this grain.



Now it is plain that for counting enormous figures the number of triggers required is not very great: 64 triggers can count as many as 2^{64} pulses, which is indeed a fantastic figure.

Cybernetics And Electronics

Who hasn't heard about "wise" machines or computers? Such people, probably, do not exist anymore. Everybody knows that there are computers that translate foreign texts, control complex processes and at times, by way of "cultural leisure", play chess, compose music, write verse.

Who has taught them all this? The creator of all machines, both "unwise" and "wise" ones, is man. But now the machines themselves, and we mean the higher automatons, learn in the process of work, taking into account their own mistakes, and, gathering experience, become ever "wiser" and "wiser". It looks as though the machines might become so "wise" that they will be able to teach those who have created them! Wondrous machines. Their raw material is all kinds of information that comes from without. And the ready product is the solution which has been arrived at in the electronic circuits.

We admire them. But even greater admiration is due to the genius of man, that was able to create them. Engels called human reason the highest blossom of nature. And the highest blossom of electronics is the birth of "thinking" electronic machines.

However, it would be unjust to give all the credit to electronics. It is no accident that all the "wise" machines and automatons pertain to the class of *cybernetic* electronic apparatus. Here most of the credit is due to cybernetics, because all the "wise" machines are designed on the basis of its methods and ideas.

It would seem that in this case the role of electronics is much more modest: it has only served as the basis for realizing the ideas born of cybernetics. And yet one should not hurry in removing electronics to the background: if there were no basis, there would be no ideas as well. And whereas electronics has existed before cybernetics, cybernetics without electronics is unthinkable. Cybernetics has suggested new ingenious circuits. But no matter what circuits it might have developed, still without the swift electron the machine would never be able to perform hundreds and thousands of operations with numbers.

Incidentally, is there any need in drawing a line between the two of the latest trends in modern science and technology? No differences or arguments have cropped up between them, there is only a creative partnership that has given the world marvellous fruit.

However, the next statement will, probably, seem highly strange: electronics did not exert the slightest effort in the development of the first electronic machines. It had everything at its disposal ahead of time: short pulses used in radar circuits, magnetic tapes for "memorizing" calculation data and controlled valves — keys — known since the time of the first triodes. And it should be noted that all these are very simple devices compared to what electronics has by now been able to develop.

What inconvenience can it experience from key circuits, if it has already developed magnetrons, klystrons, innumerous high-frequency devices, pulse oscillators and all kinds of circuits! And strange as it may seem, electronics has laboured much more severely in giving birth to radar and television than in the case of the first electronic computers and devices which have marked a new stage in electronics, the birth of its "high society".

Everything has proven very simple for it: cybernetics has taken the existing circuits and electronic valves and begun connecting them in its own way. Thus cybernetic circuits have come into being. They differ radically from the former electronic circuits: they can "reason", calculate, generalize, draw conclusions. They "think", as it were, independently, whereas the former circuits can function only at the expense of other minds. Theirs is a special "thinking" process: any complex calculation or logical reasoning they break up into two simple elements: "yes" or "no"; "1" or "0". No intricate valves are required for this purpose. This is the way an ordinary triode operates. If it is cut off, there is no current in its anode circuit, and the triode yields the reply "no" or the number "0". If it is rendered conductive by a pulse applied to its grid, the triode yields the reply "yes" or the number "1". And these replies are enough to compile any program, make the most complex of calculations and even express any thought.

Do you remember the children's game, when one of the participants seeks a hidden object, and all the rest tell him whether it is getting "hotter" or "colder"? In principle, "hotter" and "colder" are the same signals "1" or "0", "yes" or "no". On the basis of these signals the seeker finds the cleverly hidden object, having received the coded instructions: "The object you are seeking is in that corner of the room, in the wardrobe opposite the couch, in the third drawer from the bottom in the left-hand row".

Similar instructions in the form of a series of pulses can be given to an electronic circuit.

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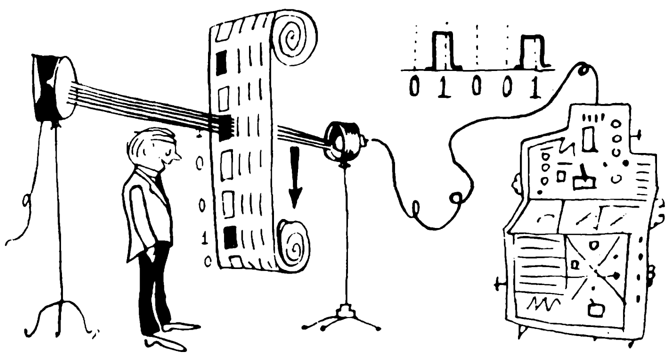
V.11

Every stage in the processing of information in a cybernetic electronic computer invariably involves the use of some electronic devices and circuits. The very first step is the introduction into the computer of the data that are to be processed.

Usually, before being introduced into the computer all the data are recorded on a punched card. This card is a piece

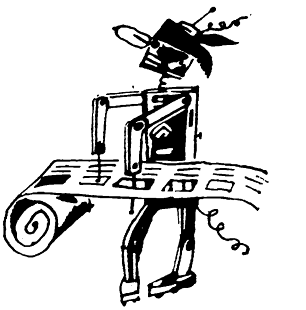


of cardboard on which at definite intervals binary code symbols are marked, with a hole corresponding to "1" and the absence of a hole, to "0".

To introduce these symbols into the computer, the card is uniformly pulled past a source of light by means of a simple mechanism. The light passing through a hole falls on a photocell and, as a result of the photoeffect, a current develops in it. (The photoeffect phenomena are dealt with in the Chapter "Electrons, Waves, Fields", Section "Where Can You Get a Hundred Suns?".) The current begins flowing at the moment when any hole of the card passes between the source of light and the photocell. Consequently, a pulse develops when there is the symbol "1" and the absence of such a pulse corresponds to the symbol "0".

V.12

For many computers a punched card is the only bridge which links it with the outer world. It is their eyes, ears, organs of touch, smell and taste. Because such a computer cannot perceive anything except the symbols recorded on the card in the form of holes and blanks. And this is sometimes inconvenient: for the computer to operate someone else must feel, see and hear and inform the computer of his observations with the aid of punched cards.



But is it not possible to develop such a computer which would be able to make observations independently?

To make man be aware of the surrounding world, nature has endowed him with five senses. And what is to be done about an electronic computer? One can hardly suppose electrons capable of seeing, hearing and feeling.

V.13

Truly, a single electron possesses no sight or hearing, But a collective of them can be endowed not only with hearing and sight, but also with an ability to feel temperature

and pressure, and in time they will, evidently, become able to discern smells and tastes.

The microphone is the ears of a computer: it converts sounds into an electric current. The electron-beam tube can serve as the computer's eyes: it converts an image into a corresponding signal. By processing this signal in special circuits, the computer can tell a dog from a cat, or read texts written in different hands.

By providing the computer with hearing and sight, it can be made to type the speech of an orator or an article from a magazine in several languages simultaneously.

To make the computer work "by ear", it is necessary to develop special circuits capable of selecting for every sound, regardless of who has pronounced it, the corresponding combination of letters. And it is possible to do the opposite: to produce sound signals on the basis of a combination of letters. And then the computer will acquire the power of speech, because it will be able to pronounce out loud what is written in the text.

V.14

And now let us consider the organs of "touch". They are called *transducers*. Transducers help the computer sense ("feel") heat, pressure, the concentration of various solutions, the action of electrical signals, in other words, all what a living human being can feel. They convert all these stimuli into electric signals.

By the way, the computer can respond to variations in external factors (concentration, temperature, pressure) much more keenly than man. To increase the sensitivity, the signal at the output of the transducers is amplified with the aid of electronic devices.

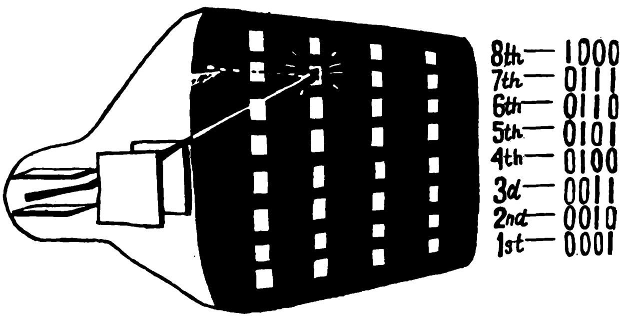
The transducers themselves are usually of a very simple design. To "feel" the temperature of any body, it is sufficient to bring a *thermistor* in contact with it. The thermistor resistance depends on temperature. With an increase in the temperature the resistance changes and so does the current in the thermistor circuit. This is how a temperature transducer operates.

A pressure transducer may be a capacitor, one plate of which is made in the form of a membrane. With an increase in the pressure the membrane is pressed inwards, the gap between the plates decreases, the capacitance increases and the current in the circuit changes.

The microphone and electron-beam tube can also be regarded as transducers. The microphone is a sound transducer and the tube, an image transducer.

V.15

With the aid of transducers the computer makes observations. But this is not enough. It still has to process the results of the observations, compare them with one another and, on

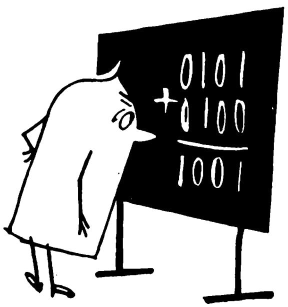


taking a decision, either give man prescriptions and recommendations, or independently exert influence upon the process which has been entrusted to its watch. In other words, on receiving signals from many transducers, the computer must make calculations.

The calculations are usually made in the binary system. This means that all the data coming from the transducers in the form of continuously varying voltages must be converted into the binary code. This, seemingly, is a new problem, however the solution has been found with the aid of the electron-beam tube which has come in handy here also.

The screen of the tube is fitted with a lattice and each of its lines or "steps" (levels) is numbered in the binary system: a hole stands for "1" and a blank, for "0". When the voltage from a transducer is applied to the vertical deflection plates, the beam rises. Then it is made to run along a line and a photocell produces a sequence of pulses. For example, the beam runs along the seventh "step" and produces the binary number seven (0111). If the voltage of the transducer increases, the number of the "step" also increases (the beam will run along a higher line).

V.16



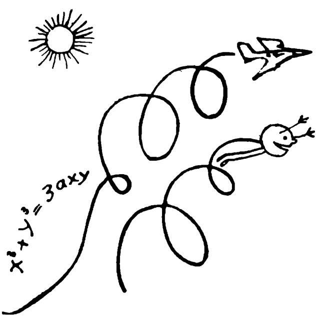
By using the binary system it is possible to reduce all numbers and all operations with numbers to combinations of units (bits) and zeros. Triodes—keys—can add, multiply and divide binary numbers according to programs which are also in the form of a sequence of bits and zeros.

Such is the operating principle of digital computers. Their action is *discrete* (intermittent) because all the magnitudes must be divided into "steps", as shown in Fig. V.15.

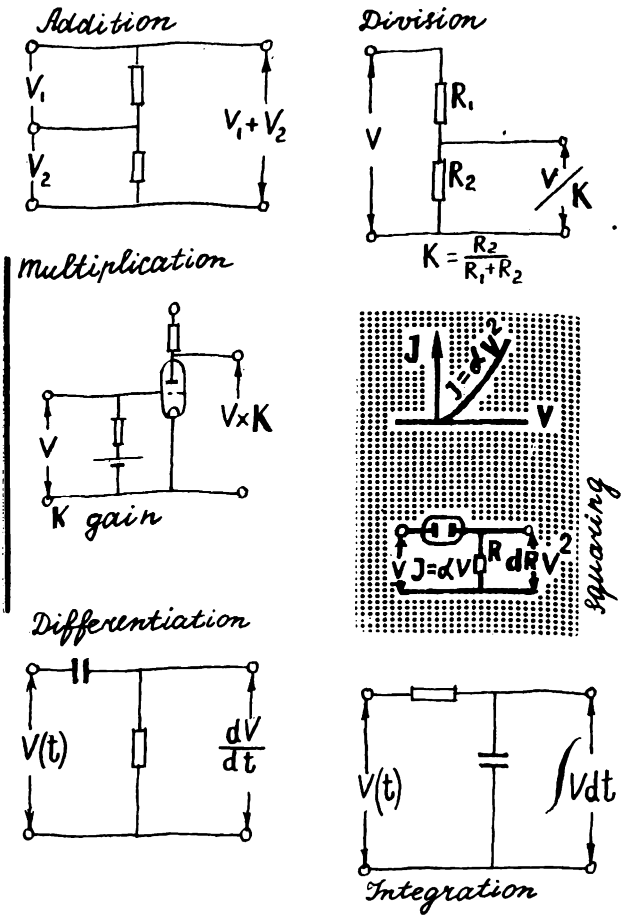
V.17

But there are also computers whose action is continuous. They process the signals coming from transducers without converting them into the binary code.

Diodes, triodes, capacitors and resistors connected in a definite sequence allow electric voltages to be added, multiplied and divided. Even such complex mathematical operations as differentiation and integration are carried out by simple *RC* networks.



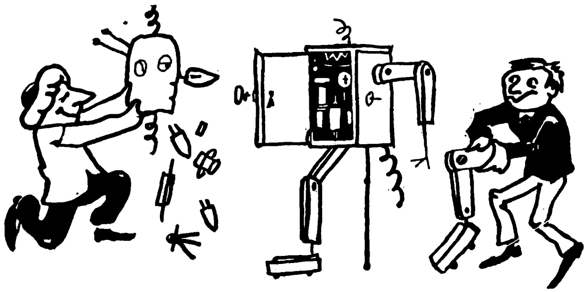
The computer operates according to equations, and an equation reflects a certain process. For example, the equation of current in an oscillatory circuit coincides with that of the motion of a pendulum or a string. Consequently, the motion of electrons in the circuit simulates a mechanical oscillatory process (see III.4).



The motion of electrons can simulate more complex processes: the flight of an aircraft or rocket, the motion of a liquid or gas, a chemical reaction, etc.

Such continuous action computers belong to the class of the so-called *analog computers.*

Once more we become convinced that electronics has been well prepared for the development of "wise" machines: many problems can now be solved with the aid of means long since elaborated by it. The computer (machine) can be remarkably "wise": it can translate a text from one language into another, write poetry, play chess, calculate complex trajectories,



control production, learn and gather experience and even recognise your face. But take any computer to pieces and you will see that there is nothing unusual among its components: the same diodes, triodes, electron-beam tubes, magnets, contacts, relays. And only through the joint action of these simple components results are obtained which some 20-30 years ago not even the most ardent visionary could dream of.

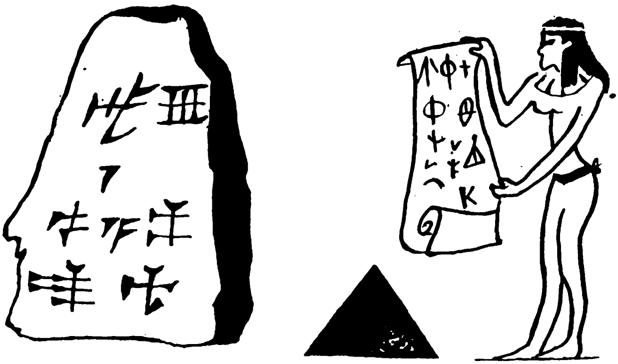
The Flood And The Electronic Ark

There was a time when all the knowledge acquired by man could find room on several slabs of granite. Then the cuneiform inscriptions on stone gave way to scrolls of papyrus with hand-written characters.

This was paralleled by the development of the methods of keeping count: knots on strings, notches on sticks, stones or beads moving along rods or grooves.

In ancient Russia use was made of devices for "stone counting"—a prototype of the abacus. In these devices stones were moved along taut strings. "But it is still better", we find in one of the first instructions, "to use copper or iron wires instead of strings". The ingenuity of these devices, as you can see, was not very great.

But then the flow of information caused the first breakthrough—the emergence of the printing press. The rivulets of information converged into mighty streams. The developing science for the first time set the task of processing data automatically.



Back in the XVII century the outstanding philosopher and mathematician Leibnitz tried to solve the problem with the mechanical means that were available to him. The resultant machine was bulky and intricate. But it was not destined to make a revolution in computing techniques, just as the machine which had been previously developed by Pascal and those developed later by the Russian Academician Pafnuty Chebyshev and the Englishman Charles Babbage. And all this for the very same reason.

The process of calculation by itself is sufficiently complicated. In order to save time an automatic machine making calculations must possess the rapidity of modern electronic computers. And this can be achieved only by means of electronic devices, in which the main moving component is the tiny, agile, mobile electron having imperceptible mass and inertia.

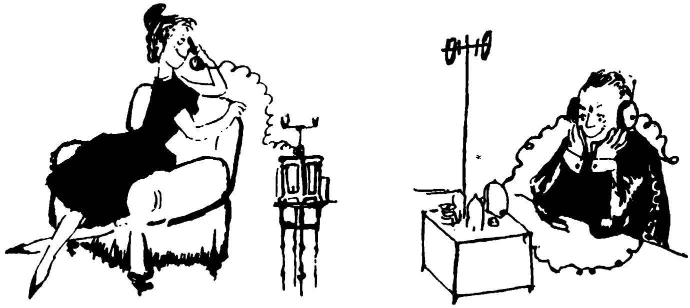
Every second an electronic computer can perform tens and hundreds of thousands of operations with multidigit numbers, and in one second it makes calculations on which a group of 100 calculators would spend several days.

Can such results be achieved by mechanics with its rubbing gears and unwieldy levers, each manipulation whereof requires at least several fractions of a second!

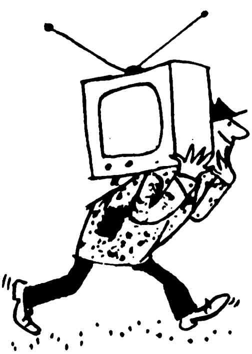
The time has come when further progress of science and technology has become unthinkable without automatic computing and high-speed calculations.

The press, telephone and radio carry reports of the developments of the century from all parts of the world. On a gigantic scale is being carried on research work. Thousands of institutes in all countries are solving one and the same problems. The results are summarized monthly on the pages of 50 000 scientific journals published in 100 languages. An achievement of one man very quickly becomes an achievement of humanity. All scientific data are checked in hundreds of laboratories and increase thousands of times.

Technological installations present an intricate complex of mechanics, power engineering, chemistry and electronics.



No engineer is capable of keeping up with all the engineering novelties necessary for the development of perfect and modern machines. Calculations are becoming more and more complex. Hundreds and thousands of equations must be solved to forecast weather, calculate space trajectories or investigate proteins. Computation time is becoming fantastically enormous. To solve a system of 100 equations would take one mathematician 4 years of work, and a system of 1000 equations would take 60 generations of mathematicians to do the job in 4000 years.



And how many equations must mankind solve in general?

Our usual measures are far too inadequate to even picture the great amount of information that must be processed in solving modern scientific problems. Take, for instance, the study of polymers and proteins. Their molecules consist of long chains of atoms, and any permutation of the links of this chain gives an entirely new substance. If we were to take one sample of all the types of protein chains existing in the world and twist them into a rope, then light radiated

at the beginning of this rope would take 75 years to reach its end! And light travels at a speed of 300 000 kilometres per second!

The ocean of knowledge is infinite. All the obtained information must be processed, compared, generalized, classified—otherwise no further progress is thinkable. Is it not the time to stop?

No, reason born of nature will never give man any peace, he will continue to acquire new knowledge, learn new secrets of the universe, study the structure of the Metagalaxy and the structure of pi-mesons, probing ever deeper and broader.

More and more streams are flowing into the ocean of human knowledge. The ocean of information is becoming wider and wider, mankind is threatened by a Great Flood.

That is why man is developing machines that can process all the knowledge obtained; machines that can obtain information themselves, compare it, generalize, classify and communicate the results.

The power of reason is limitless. Man bravely plies the ocean he has created himself, having built, like the legendary Noah, a life-saving electronic ark.

THIS LIES AT THE BASIS

V.19

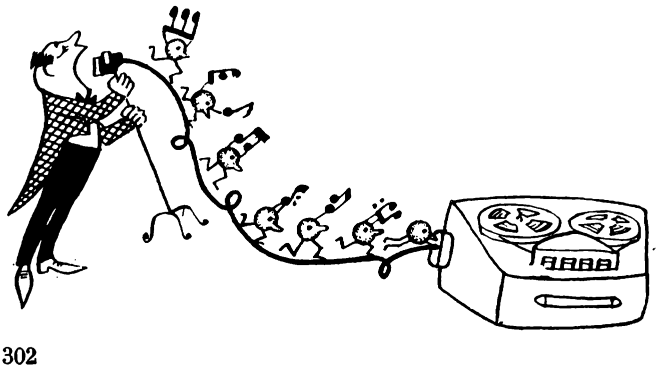
Everyone knows that the ability to remember is characteristic of people and, to some extent, of animals. But with the advent of cybernetics it was found that inanimate objects can also be endowed with something like memory. Slabs of granite still "remember" the events someone had recorded in cuneiform. In exactly the same way events are "remembered" by books; a stick with notches remembers the number of horses or sheep. All these are sys ems of *long-time memory.*

Abacuses remember numbers for a short time—only while the calculation lasts. Our own memory also has different "shelves". Some of them store remote events, while others, only what will be required today or tomorrow: the time a show starts, the number of a house, railway coach or compartment. Sometimes, when we have little faith in our memories, we seek aid in the "memory" of inanimate objects, for example, a knot in a handkerchief.

Electronic computers also have two kinds of memory. For intermediate calculations there is a short-time *finite memory.* Final results are stored in the system of long-time memory.

Just what is the "memory" of a computer?

V.20



It turns out that "memory" was also developed by electronics long before the advent of electronic computers. Say, equipment for recording signals on a magnetic tape. If we wish to keep a recording of a favourite aria, we use a tape recorder. It "remembers" the melody, the voice of the singer and the accompaniment much better than we could ourselves. What is more, there is a certainty that the tape will not soon forget the recorded aria.

V.21

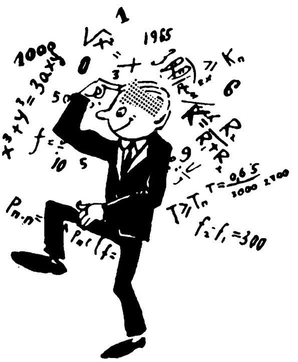
An electrone-beam tube also has a memory: a pulse trace left by the beam on the screen is retained for a certain time and then disappears. When the beam travels across the screen again, the trace is renewed. (See Chapter I, Sections "Traces of Things Invisible" and "About the Saw, the Beam and the

Key".) The property of the tube to retain an image is known as the *afterglow.* Afterglow lasts for a second or for several fractions of a second. Since the beam moves much faster than the tape of a tape recorder, the tube can memorize a large number of the binary code symbols much faster than the tape recorder can. This is the short-time (finite) memory: a lot of data can be quickly introduced into it, but only for a short time.

Instead of a simple screen, memory tubes have a lattice made up of capacitive cells, reminiscent of a honeycomb. Passing along each line of the lattice, the beam marks down some number. Each cell stores one symbol of the binary code —"1" or "0". The speed of the beam is selected so that it approaches the next cell exactly at the moment when the next symbol pulse is applied to the modulating electrode of the tube.

V.22

Familiarizing ourselves with binary counting circuits, we have come across another type of memory—a chain of triggers (see V.9).



Indeed, after several pulses have flipped the triggers, the chain remembers their number. But it is disadvantageous to store this number in the memory of the counting trigger chain: too many triggers would be required. Therefore the numbers obtained during the operation of triggers are then transferred to electron-beam tubes, to that short-time memory which is required only for intermediate results, such as "put down two, carry three".

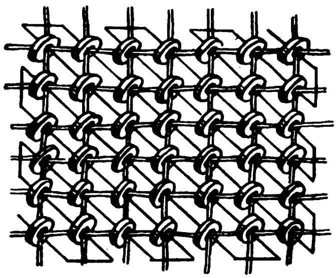
V.23

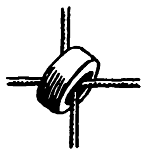
Numbers cannot be stored for long in the cells of memory tubes. If the calculation is completed, the result has to be transferred to the long-time memory. Scanning the cells, the beam will convert their charges into a pulsating current, the current will act upon the head of a magnetic recording

unit, the magnetic field of the head will leave a trace on a tape: it will record the information. When this information is required, the magnetic recording can be converted back into current pulses by means of a second head.

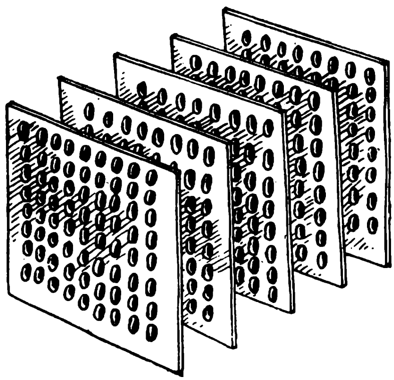
However, such a memory has one inconvenience: if the required number is recorded at the end of the tape, then to extract it from the memory the whole tape has to be rewound onto another reel. Such searching for data in a long-time memory system takes a lot of time, that is why the magnetic-tape recording is somewhat like a library: it stores what is not required very often, but serves for a long time.

V.24





The use of ferrite memory units has become widespread. Unlike tubes and magnetic tape, these memory units were developed specially for electronic computers.



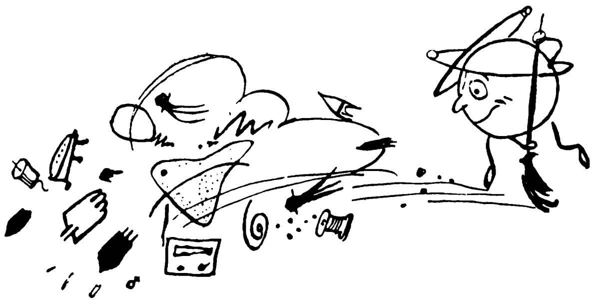
Ferrite is a mixture of iron oxide with oxides of other metals. This material possesses very good magnetic properties.

Ferrite rings are assembled in a special lattice. If a vertical and a horizontal wire of the lattice simultaneously receive a signal, then the ring which is located at their intersection will change its magnetic state—the symbol "0" will be replaced by the symbol "1".

To read out the numbers there is a third wire that runs diagonally across the lattice.

Lately the set of rings has been replaced by ferrite plates with holes. The distance between the holes is selected so that the magnetic field around each of the holes does not affect the others. This design has helped reduce the size of the storage unit several times.

V.25



Aspiring to make the memory as compact as possible, the experts are trying to "teach" atoms of various substances the binary system. An excited atom corresponds to the symbol "1" and a normal one, to the symbol "0".

What Is Required Of Electronics?

While we have been acquainting with the elements of "wise" machines, we have repeatedly come to the conclusion that electronics has everything necessary for the development of such machines. More than that, it has had all this beforehand, because radar has long made use of tubes and pulses, and diodes and triodes and triggers.

But the reader may get a false impression that having reached its "prime", electronics may rest on its laurels.

Electronics has placed all its elements at the disposal of cybernetics, so now let cybernetics worry about how to make the best of them, which programs to elaborate, and how to connect the elements to carry out these programs.

Actually, that is not how matters stand. The advent of electronic computers has given such a mighty impetus to the development of electronics that all its preceding stages now seem no more than the period of early childhood.

Well, then, just what is required of electronics, if all the necessary elements have been in its possession for a long time?

Yes, it has them, but there are elements and elements. It is possible to make a computer by employing ordinary valves, yet in all of the modern computing equipment use is made not of vacuum valves, but of semiconductors. Valves have proven too bulky. They consume a lot of power and often fail. While electronics developed household and special radio receivers, transmitters and measuring instruments where the number of valves numbered anything from one to dozens, the shortcomings of vacuum valves could be put up with. But when machines using hundreds of thousands of diodes and triodes were developed, the shortcomings of vacuum valves became a hindrance to the development of electronic computers.

If each of the several thousands of valves in a computer is capable of operating for hundreds of hours, then the whole computer will get out of order several times a day due to the failure of one of the valves. As a result, it will spend the greater part of its life being repaired and will not be able to accomplish any complex calculation. True, reliability can be improved by providing a stand-by for every unit, just as in major theatres where there is an understudy to act a part if the main performer has fallen ill. But this is not the way out either: if a valve computer occupies several rooms, then how much space will be required, if a stand-by is provided for each of its valves?

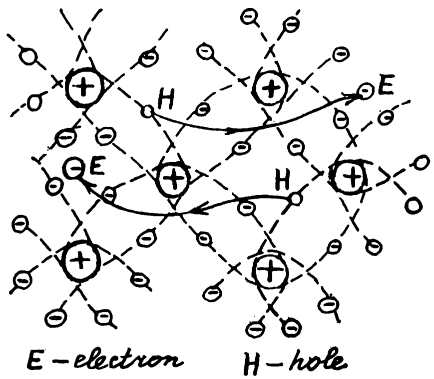
And what about the problem of power consumption? Such a computer alone would require a power plant big enough to supply a whole town!

There is only one alternative: electronic computers must employ semiconductors.

THIS LIES AT THE BASIS

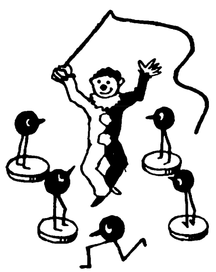
V.26

Many times we have already mentioned that inside metals there are free electrons. But in insulators and semiconductor crystals at low temperatures there are no such electrons.



Here they are all bound to atoms. For example, in germanium crystals the outer shell of each atom is formed by 4 bound electrons. At the same time each of the electrons is subjected to the action of neighbouring atoms. Four neighbouring atoms "fetter" each of the electrons from four different sides.

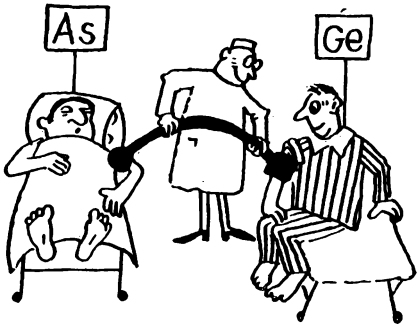
V.27



But then an extraneous atom, whose outer shell has 5 and not 4 electrons, has penetrated into this structure. This atom has settled in a node of the crystal lattice, with four of its electrons immediately finding place in the structure shown in Fig. V.27. Now the fifth electron here is at a loose end. Impurities, whose atoms have such "extra" electrons are known as *donor* impurities. For germanium or silicon a suitable donor impurity can be arsenic and antimony.

V.28

The "transfusion of blood" obtained from many donor atoms supply germanium or silicon crystals with free electrons.



When an external voltage is applied the "blood" begins circulating through the crystal—an electric current begins to flow through it.

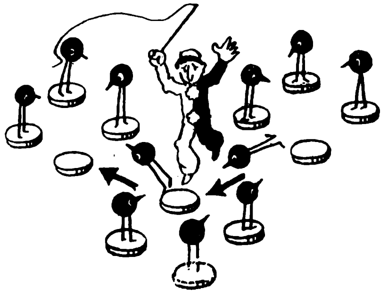
V.29

Another impurity that can be used is indium, whose outer shell has 3 and not 5 electrons.

All the three electrons of the indium atom will find place in the crystal structure, but one electron will be missing.

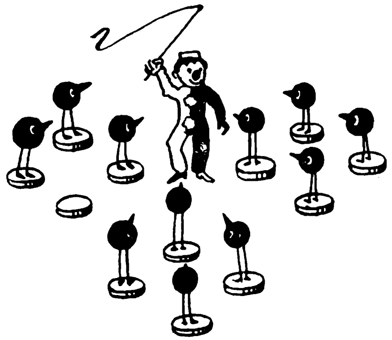
The experts call this "empty space" a *hole*.

An impurity which produces holes in the crystal structure is called an *acceptor* impurity.



V.30

At the spot where a hole has developed the charge of the atomic nucleus will not be balanced and such an atom will be found to have an extra portion of positive charge. The

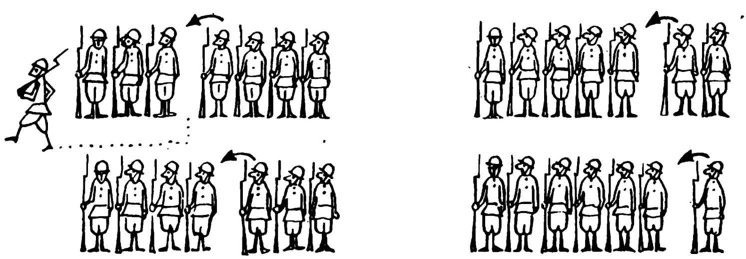


positively charged atom will attract electrons from all directions. The closest one will occupy the vacant place. In this atom the hole will disappear. But then a hole will be formed in the atom from which the electron has just escaped.

The new hole will experience the same as the former one: the place vacated by the electron will soon be occupied by another one. Now the hole will move to a third atom, and from a neighbouring fourth atom a new electron will arrive. The electrons by turns will occupy the vacant place and this place itself will move in the opposite direction.

V.31

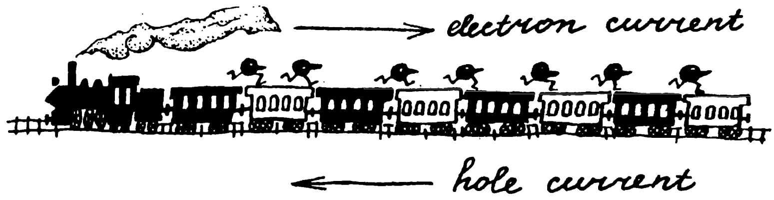
The same thing occurs when one of the soldiers leaves the rank, and the rest are ordered to close ranks. Each soldier



in turn moves one step to the right, while the empty space moves to the left. This is exactly how the holes move in a crystal.

V.32

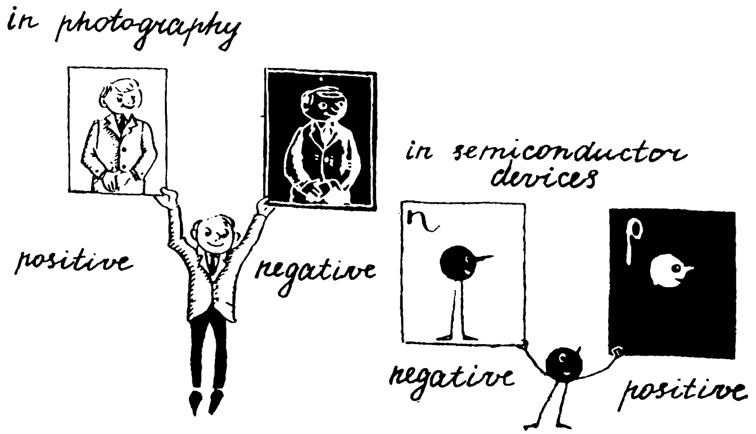
The hole itself carries no charge. But at the spot where it is formed the charge of the atom is unbalanced, because one electron is missing. So where there is a hole, there is a portion of positive charge. If the holes move, then, like a shadow, positive charges move together with them. Thus a peculiar *hole current* arises.



A field produced in a crystal under the effect of voltage applied to it controls this movement: the electrons flow towards the positive electrode, filling the holes in their way. The holes will move towards the negative electrode.

V.33

It is said that a crystal supplied with extra electrons by a donor impurity possesses *n-type conductivity*; the letter *n*



in this case means that conduction is due to negative charges (*n* stands for negative).

If there are holes, we have *p-type conductivity* (*p* stands for positive).

Neither Fish, Flesh, Nor Fowl

Needs one mention here that in many electronic devices semiconductors are now used instead of valves? This will hardly surprize anyone. One can hear of this everywhere. In trains, parks and streets you can meet young people with portable radio sets with fancy straps carelessly slung over their shoulders. Commonly such a receiver is called a transistor, although, actually, the transistor is not the receiver itself, but a device in it which has replaced the radio valve.

Evidently, you know this. But why and in virtue of what qualities have semiconductors found such a wide application? and why "semi"?

Ever since engineering has begun dealing with electricity it is using two categories of materials: insulators and conductors. Conductors are required to transmit current; for this purpose use is made of electric wires of materials offering low resistance to the flow of electric current (copper, aluminium, silver). And for the wires not to become short-circuited, and for the current to flow in the required direction, each wire is surrounded with a material which does not conduct current. That is why insulators are also employed ever since people have begun using electric current.

Wires are made of metal. In addition to metals, gases and solutions of salts are also conductors (see I.12, I.13).

Insulators are materials, such as porcelain, ceramics, glass, rubber. Air is also an insulator, that is why air has to be exhausted from the envelopes of radio valves for electric current to flow (see I.14).

But materials have also been known whose properties do not match either category. They have been called semiconductors, although they just as well might have been called semi-insulators. These substances conduct current somewhat better than insulators and, at the same time, considerably worse than conductors do; in short, they are poor insulators and poor conductors. Such properties are possessed by some pure elements: silicon, selenium, germanium, tellurium. And there are chemical compounds which have similar properties, for example, oxides of certain metals, compounds including

sulphur (sulphides) or selenium (selenides). Some metal alloys also behave like semiconductors.

Like in insulators, in semiconductors all the electrons are firmly bound to the atoms (see V.26). When semiconductor crystals are heated, some electrons manage to escape the influence of the atoms. Since there are few such electrons, the current flowing through heated semiconductor crystals is very small.

All the above has been known long ago. The properties of germanium had been predicted by Mendeleev, who, incidentally, discovered it. He called it ekasilicon to stress its affinity with silicon.

The German scientist Winkler made a thorough study of the properties of germanium and in honour of his homeland he gave it the name that it still bears today.

Of course, the chemists had to study both germanium and silicon. But neither electrical engineering nor electronics paid any attention to them for a long time. And it was only natural, for what was the use of a material which could serve neither as a reliable insulator nor a good conductor? Something in between, "half-and-half", in short, good for nothing.

The Secret Of The Magic Point

Electronics took an interest in silicon and germanium much later. But at first application found certain oxides, in particular, two crystals—zincite and chalcopyrite. It was found that these crystals possess a wonderful property: they can serve as a valve, i.e. rectify electric current (those who have forgotten about the rectifying properties of diodes should refer to I.16). In that case they can be used for detecting: to single out the audio-frequency current from the carrier signals.

That is just what was done. Strange as it may seem, it is not the diodes we have spoken about all the time, that were used in the very first radio receivers (crystal sets) for the purpose of detecting, but real semiconductors. But what trouble it was to handle them!

With a thin whisker having a point of several tenths of a micron, it was necessary to grope for a magic point on the crystal. Move the whisker a little aside, and the sound disappears. And much time had to be spent to find the necessary point on the crystal again. Where such a point should be and what is the secret of its magic power, at that time no one knew. And God forbid, that in searching for the magic point you inadvertently picked it off with the point of the whisker—there might not be another such point on the crystal. The whisker was then mounted on a spring, so that it pressed the crystal as "gently" as possible.

Not many were capable of mastering this trick. At that time army "listeners" who were clever in finding the magic point were worth their weight in gold at headquarters. Everyone gave a big sigh of relief, when electronics offerred valve diodes instead of the crystals.

Then triodes came into being and these made it possible to amplify greatly weakened signals that had travelled over great distances. Valves were soon being used everywhere, and no one remembered the crystals at all.

It had remained a mystery why only certain points of the crystal could single out audio signals and why the crystals could detect signals in general.

One Turn Of The Spiral

Dialectics asserts that development proceeds upward along the turns of a spiral. There comes a moment when the ideas of former days begin to sound differently because by that time science has overcome one more "turn". This is exactly what happened to crystals.

For a very long time valve diodes met the requirements of all fields of engineering. But as radar kept going higher and higher up the frequency scale, the ordinary diode was becoming less and less satisfactory. Between the cathode and anode of the diode there is a parasitic capacitance that we are familiar with. And like in the case of the triode, the higher the frequency, the more noticeable the effect of the capacitance, and in the centimetre range such a diode could not operate at all. Here crystals were recalled.

By the way, there was yet another event when crystals gained popularity. In 1924 a scientific worker at the laboratory headed by Bonch-Bruyevich in Nizhni Novgorod Oleg Losev for the first time in the history of electronics achieved amplification without the use of valves. The basis of the device, which Losev called a crystodyne, was a semiconductor crystal. This event caused a sensation. The American magazine Radio News reported about it in an article entitled "Sensational Invention". Other magazines called the crystodyne "an epoch-making invention" and predicted that in time crystals would replace vacuum valves.

But this did not happen at that time. The valve satisfied all demands, the flourishing of vacuum techniques was just beginning, and each year brought to light ever new merits and unexpected possibilities of vacuum valves.

As for semiconductor crystals, science at that time only began studying their structure, while technology was unable to produce pure crystals free of impurities for the needs of electronics. All in all, by that time the development of semiconductor techniques, which had begun with the very first crystal sets, did not yet complete its first "turn".

Two decades later radar posed the problem in a new way: on the basis of a crystal a new detector must be developed for super-high frequencies. By that time science had gathered important data concerning crystals. The physicists already knew that current in crystals may be of different nature: either a flow of negative electrons, or that of positive charges, caused by the movement of holes (see V.27—V.32).

Only then it became known wherein lies the power of the magic point, which wireless "listeners" had sought with such a difficulty.

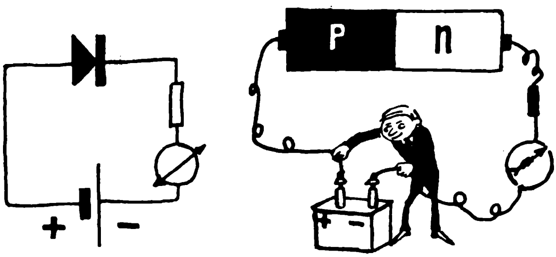
P-N JUNCTIONS ARE REQUIRED

THIS LIES AT THE BASIS

V.34

To make a semiconductor diode two crystals should be coupled. One of them should possess *n*-type and the other, *p*-type conductivity (see V.33).

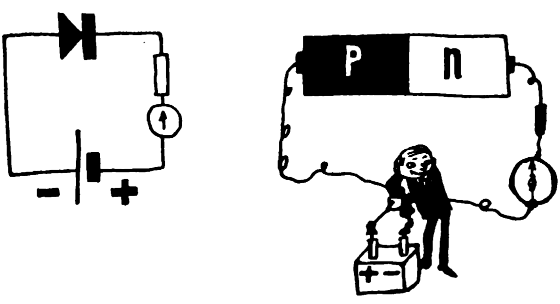
Such a device can serve as a rectifier no worse than a valve diode (see I.16). If the positive terminal of a voltage source



is connected to the crystal with *p*-type conductivity and the negative one, to the other crystal of the pair, then a current will flow through contact surface between the two crystals.

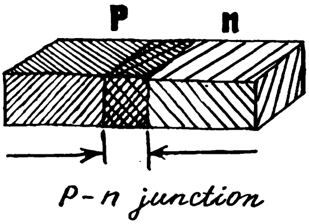
V.35

If the connection of the terminals is reversed, the rectifier will be cut off, the diode will break the circuit. Why?



V.36

At the contact surface between the crystals having *n*- and *p*-type conductivity a special zone known as the *p-n junction* is formed. The thickness of the *p-n* junction is only



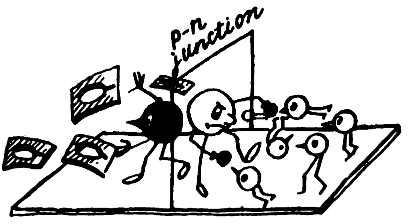
several tenths of a micron, nevertheless, it is this thin layer that plays the most important part in semiconductor techniques.

V.37

Each of the donor atoms, on giving up one of its five electrons, ceases to be neutral and becomes a positive ion.

With acceptors everything is quite the reverse. They have a tendency to add a fourth electron to their own three ones and become negative ions.

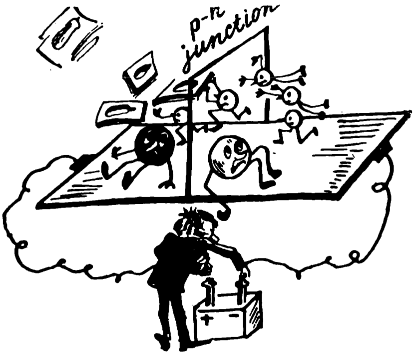
It is these ions that crowd in the zone of the *p-n* junction.



The negative ions on their side "push back" free electrons, while the positive ions hinder the movement of holes. Thus, the zone of the *p-n* junction forms, as it were, a sort of barrier for electrons and holes.

V.38

In the case of direct connection of the crystal diode the positive terminal of the source is connected on the side of *p*-type conductivity and the negative one, on the side of *n*-type conductivity. The positive pole of the source "pushes" the positive charges towards the *p-n* junction zone and helps them overcome this barrier. In the same way the negative pole of the source helps the electrons to move.

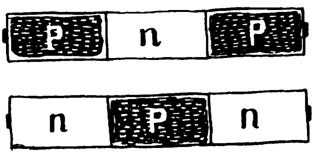


The two streams of charges move towards each other, and an electric current flows through the diode (see V.34).

If the connection is reversed, the poles of the voltage source "pull" the electrons and holes away from the junction, the barrier becomes insurmountable and no current flows through the diode (see V.35 and V.37).

V.39

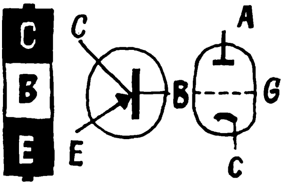
A semiconductor triode (transistor) has two *p-n* junctions. The sections with *n*- and *p*-type conductivity may be arranged



in different ways, that is why two different types of transistors are recognized: *p-n-p* transistors and *n-p-n* transistors.

V.40

In a transistor the *emitter E* serves as the cathode. It is the source of all charges, whose movement gives rise to current. The *collector C* is similar to the anode, and the *base B* acts like the grid.

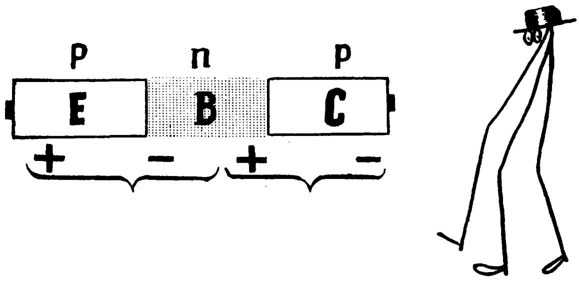


In amplification, the input signal is applied to the section $E—B$ (between the emitter and the base). Having connected a load (resistor) to the section $B—C$ (base—collector), the signal amplified by the transistor can be taken off across this load.

How does amplification take place?

V.41

The section $E—B$ behaves like an open valve: an external battery helps the electrons and holes to overcome the barrier (just as in Fig. V.34).

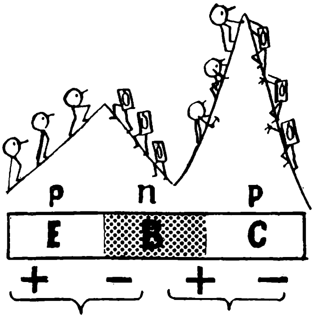


The section $B—C$ is like a cut-off valve: the battery prevents the passage of carriers over the barrier (just as in Fig. V.35).

As a result, the resistance of section $E—B$ will be insignificant, while that of section $B—C$ will be very high.

V.42

The current passing over both barriers remains practically unchanged. To be more precise, it decreases somewhat due to the fact that some of the electrons merge with holes, fil-



ling the "empty spaces". This phenomenon is known as *recombination.*

As a rule, not more than three per cent of the charges recombine. This means that the current through junction $B—C$ will come to 97 per cent of the current through junction $E—B$. At the same time the resistance of junction $B—C$ (cut-off valve) is tens of times higher than that of junction $E—B$ (open valve).

So, the current is nearly the same, while the resistance of the output is tens of times higher than that of the input. Consequently, according to Ohm's law, the voltage of the signal at the output will exceed that of the input signal also several tens of times.

Hence the amplification.

What Were The Wireless "Listeners" Seeking For?

At the time when the "listeners" were mastering the art of seeking for the magic point, it was believed that current rectification takes place at the border between the crystal and the metal, i.e. at the place where the point of the whisker touches the crystal. But it has turned out that rectification and detection occur in a totally different way. Under the action of oxygen and moisture contained in the air the surface of the crystal becomes covered with an oxide film. In some crystals this film, by sheer luck, also has semiconductor properties. What is more, to achieve rectification, the type of its conductivity must differ from that of the crystal proper: if free electrons predominate in the crystal (n-type conductivity), then the conductivity of the oxide film must be of the p-type. In this case the crystal together with the oxide film forms a rectifier, like that shown in Fig. V.34.

The oxide film is formed due to chance effects, but no one knew of its significance, and no one examined how even and strong was the layer covering the crystal. Naturally, under such conditions it was a matter of pure chance to find a point where the film was thin and strong enough and formed together with the crystal proper a *p-n* junction. It was sufficient to scratch the thin film with the whisker for the junction to disappear and the crystal to stop rectifying. Hence the use of the spring and the long searches for the magic point with a light touch of the whisker.

An attempt was made at that time to make junction diodes by placing in contact two different crystals—zincite and chalcopyrite. And again, because of the poor surface of the oxides which provided for the *p*- and *n*-type conductivity, rectification took place not over the entire contact surface, but only at individual points.

All this became known much later, when the primitive crystal sets had been long ago replaced by valve superheterodynes, and the "wireless listeners" became first class radio operators and could maintain reliable communication with any corner of the globe. Then it became necessary to solve a new problem: to develop a crystal detector for waves of the centimetre range.

By that time solid-state physicists had already studied well the nature of crystals and the electrical phenomena which take place in semiconductors. An important contribution to these investigations was made by the Soviet scientist, Academician Abram Ioffe, the Japanese scientists Torikata and Yokoyama, the German Karl Braun and the Englishman Ickles.

And technology had mastered the production of pure silicon and germanium crystals with additions of impurities required to obtain the *n*- or *p*-type conductivity.

To appreciate what was the cost of this victory it suffices to quote the following figures: in the crystals used for making semiconductor devices it is permissible to have but one atom of any deleterious impurity per one milliard atoms of germanium or one atom of the impurity per 1000 milliard atoms of silicon! It is such super-pure crystals with *n*- and *p*-type conductivity that are used to make devices replacing vacuum valves—the semiconductor diodes (see V.34) and triodes or transistors (see V.40). The first transistor was developed by the American physicists Bardin and Brettain in 1948. Two point contacts with the *p*-type conductivity were fused into a germanium crystal possessing the *n*-type conductivity. Subsequently such transistors have become to be known as *point* transistors, to differentiate them from *junction* transistors (see V.36).

The prototype of the junction transistor was developed by the American physicist Shokly in 1951.

The world appreciated the significance of these discoveries. A Nobel Prise awarded to the three inventors of the first transistors marked the importance of this event.

The advent of transistors has made all designers of electronic equipment more and more forget vacuum valves and, wherever possible, give preference to semiconductors. For semiconductors, in addition to their small size, have a number of other advantages. They consume much less power and have a service life ten times that of vacuum valves.

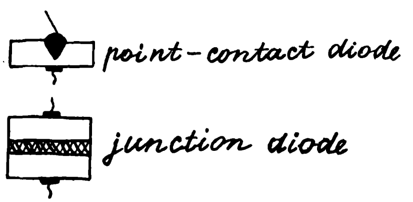
A semiconductor diode or a transistor does not require any heater, or filament, without which no vacuum valve can operate. This seemingly minor feature brings with it important consequences. Nearly half the power consumed by vacuum valves is used for supplying their heaters or filaments.

When a valve is switched on and off, the heater warms up and then cools. Such "shocks" cause it to fail much sooner than other elements of the valve. "A chain is no stronger than its weakest link"—so the saying goes. In a vacuum valve the weakest link is the filament. And the failure of any vacuum valve is a highly unpleasant thing—the whole unit fails, and it is not always simple to find out which of the many scores of valves (and in electronic computers, out of many thousands!) has failed at a given moment. For the specialist the absence of the filament alone is a good reason to give preference, wherever possible, to semiconductor devices. And if you take into account their high reliability, small size and weight, it becomes then obvious why the advent of semiconductor devices was tantamount to a re-birth of electronics; this marked a new and very fruitful stage in its development.

V.43

The point contacts employed in semiconductor diodes have replaced the whiskers that gave so much trouble to early wireless men.

Diodes with point contacts are good for detection at superhigh frequencies, because the capacitance of the point contact is extremely small. But it also has a shortcoming: this contact cannot carry a heavy current.

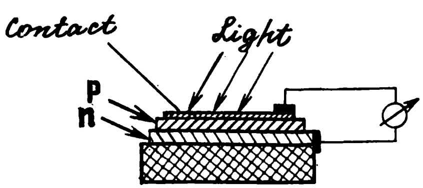


For the detection of powerful signals and the rectification of large currents *junction diodes* have been developed. The capacitance of such diodes is considerably greater, but they can carry currents of up to 2000 amperes.

V.44

The semiconductor diode has found application in many fields.

Wide use is made of the so-called *photodiodes*, which convert light energy into electric current.



"Eyes" containing photodiodes ensure the safety of the worker in many factory shops: should he absentmindedly reach with his hand into a dangerous zone, the beam is interrupted and a signal from the photodiode immediately stops the machine.

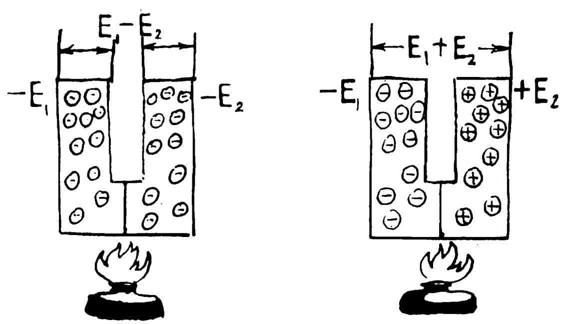
Photodiodes together with electric pulse counters can be used for counting any products at a factory, such as pieces of soap, cigarettes, matches, needles, car wheels, or the

number of passangers in the underground. The "eye" can clear a conveyor belt of rejects: if the part does not have the necessary holes, the "eye" sends a signal to an automatic device which removes the part from the belt.

V.45

Thanks to semiconductors, electric power now can be obtained directly from heat.

Metal thermocouples had already been known before the emergence of semiconductor converters.



When metal rods are heated, electrons escape from the atomic shells and become free (see I.8). With an increase in the temperature, the electrons move more and more intensively, it becomes too cramped for them and they stream towards the cold ends. In a thermocouple the rods are made of different metals, therefore the charges at the ends will be of the same sign ("minus"), but of different magnitude (at one end the magnitude of the charge will greatly exceed that at the other end). As a result, a potential difference develops across the ends ($E_1 - E_2$).

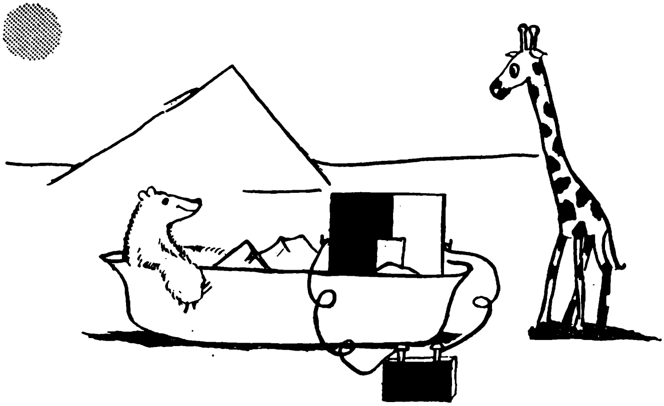
If instead of metals we take semiconductor rods with *p*- and *n*-type conductivity, electrons will then accumulate at one end and holes, at the other. The difference in potential between these ends will be much greater than in the case of the metal thermocouple, because at one end there will be a positive charge and at the other, a negative one.

Therefore the efficiency of semiconductor thermocouples is about fifty times higher than that of metal thermocouples.

V.46

There are many reversible phenomena in nature.

Electronics also makes use of reversibility. In some devices electric current produces a magnetic field, and in others, an alternating magnetic field causes current to flow.



Reversibility is also inherent in thermocouples

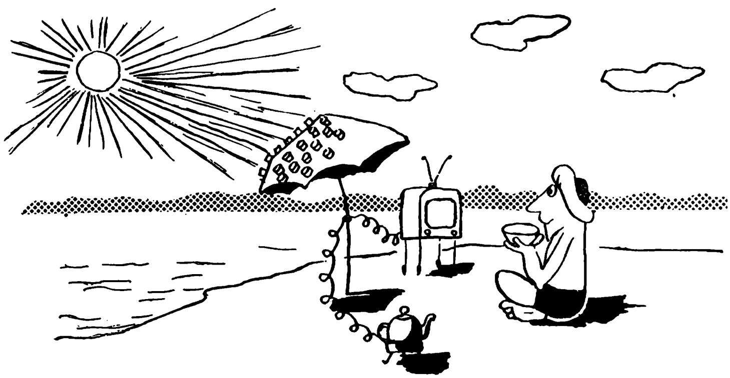
The difference between the temperatures at the ends of semiconductor or metal rods produces a difference in potential between these ends (see V.45). If you do the opposite and produce a potential difference across the ends of a thermocouple by means of an external voltage source, then a temperature difference will develop at the junction of the semiconductor or metal rods.

Such experiments were conducted earlier by Academician Lentz: in front of the astonished public (he then read lectures in St. Petersburg) Lentz turned a drop of water into a piece of ice with the aid of a metal thermocouple.

However, metal thermocouples can provide for a temperature difference of only a few degrees. But with a semiconductor thermocouple it is possible to obtain a temperature difference of sixty degrees. This is quite an appreciable amount.

V.47

Semiconductors have made it possible to convert into electricity various kinds of radiant energy—radioactive, thermal, light and, particularly, that of sunbeams.



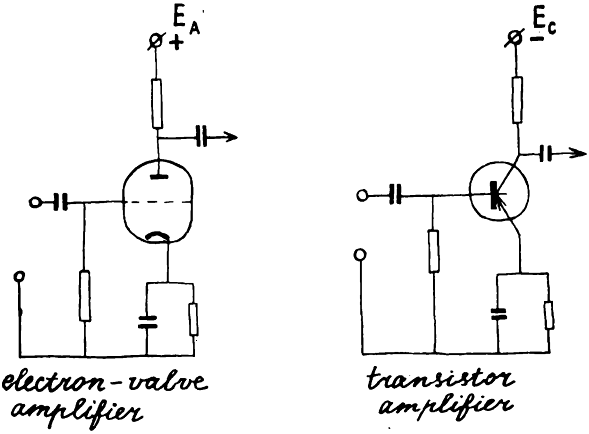
Solar batteries are very convenient for satellites: it is never cloudy in space—all the clouds remain below.

If a semiconductor diode is placed close to a radioactive material, an *atomic battery* is formed, which is capable of supplying electric power for many years.

V.48

Transistors have made a real revolution in engineering. This is hardly to be wondered at: remember all the possibilities that once were opened up before electronics by valve triodes? It is the triode that has made it possible to develop oscillators and amplifiers, mixers and modulators of radio signals—the great variety of receivers, transmitters and measuring circuits now in existence.

The transistor can amplify a signal no worse than a valve triode. And since its characteristic curve also contains curvilinear sections, it can perform all the various operations



with signals, that we have dealt with when familiarizing ourselves with the broad field which we have called "The Kingdom of Crooked Mirrors".

The Project Of An Electronic "Brain"

There are now so many fields of application for semiconductors that even a simple listing of them would take up many pages. In the preceding section we have described only a few examples, which allow one to judge of the various applications and properties of semiconductors. But here the reader has a right to ask: why are we dealing with semiconductor devices in the Chapter "Elements of Wise Machines"?

On the whole, the question is understandable. Semiconductors are required not only for electronic computers. They have attracted the attention of specialists in many fields, beginning from surgeons and ending with metallurgists. And not only of specialists. Everyone needs semiconductors. Even he who has a valve radio set at home would still like to have a portable transistor radio of the size of a cigarette case.

No one is going to deny the convenience of such a receiver. But when it comes to electronic computers and automatic machines, the size and weight are then no longer a question of convenience, but a question of the vitality of the machine. At times it is precisely the dimensions that determine whether a future machine is to be or not to be.

For example, computers for piloting aircraft are very necessary: the flight speeds have become so high that at times the pilot simply doesn't have enough time to make the decisions without which it is impossible to pilot the aircraft. A computer "thinks" much faster. But the trouble is that it can "consider" only within the framework of the program that has been introduced into it. But there may arise so many various flight conditions that no program can foresee them all ahead of time. Here the computer is inferior to the pilot. In order to extend the capabilities of the machine and to bring it closer to the craftsmanship of man—pilot—very complex circuits are required, an enormous computer memory, and the ability to gain experience, so as to become ever more qualified and "wiser". If all these requirements were to be embodied in an actual design, the computer would prove so bulky that no aircraft could take off with it.

Here two requirements come into conflict: on the one hand the computer must be as compact as possible and, on the other, as "wise" as possible.

To bring this conflict into a bolder relief, let us suppose that some designer has set himself the task of making a computer in no way inferior to the human brain. He will be faced with a fathomless sea of questions. What kind of cells should be taken as the basis? What circuits should be assembled with them? How should it be programmed?

But before delving into these questions, the designer will, evidently, wish to imagine what such a "brain" will look like in general.

According to the latest scientific data, the brain cortex contains 10^{10} cells (neurons). The number of cells is possibly much greater. The figure 10^{10} is an approximation, for no one has ever counted neurons.

Suppose it is only 10^{10}. What will a "brain" look like if instead of 10^{10} cells it had, say, 10^{10} triggers?

If the designer were to use ordinary valves and components as the basis, then even with the best of designing he would not be able to fit more than five components into each cubic decimetre.

Each trigger contains about ten components, in 10^{10} triggers there will be 10^{11} components. This means that the volume of such a unit will be

$$\frac{10^{11}}{5}\ dm^3 = 2 \cdot 10^{10}\ dm^3 = 20 \cdot 10^6 m^3$$

This volume is easy to imagine: a gigantic box 2 kilometres long and 100 metres high and wide. Quite a structure! And now imagine what kind of a power source will be required to supply 10^{10} triggers? But can even such a fantastic circuit operate no worse than a real brain? Nothing of the kind!

Firstly, there is the question of reliability. If we assume that on the average each trigger fails once in 5 years, then in this gigantic system an average of about 60 triggers will fail every second.

Since electronic circuits are designed in such a way that the failure of any component deranges the whole circuit, the "brain" will be permanently out of order: instead of operation there will be continuous repairs.

But suppose, due to some fortunate circumstances, the fantastic "brain" should happen to be in order and operate for 5-10 minutes. Will it prove sufficiently "wise" during these minutes at least? Of course not. The potentialities of a real brain are not determined by the number of cells. The important thing is their interaction. Even were it possible to assemble a system of 10^{10} triggers, no one as yet has any idea as to how they should be connected. And, incidentally, a trigger is no real substitute for a neuron. Their similarity consists in that both the neuron and the trigger have two states designated by "1" and "0" (see V.5—V.8). But whereas the trigger reacts identically to all pulses that arrive, the neuron differentiates them according to their intensity and frequency. The trigger has only one input, while the neuron is connected to many cells, and its "response" depends on the combination of pulses and on their source. In simulating the pattern of a neuron one trigger is not enough: the circuit of an artificial neuron is much more complex.

Any contamporary designer would have hardly dared to undertake the task of developing a whole electronic "brain".

But there has been no lack of those who wanted to "design" the main cell of the brain, the neuron. Over a hundred types of circuits have already been developed which operate similarly to the neuron. The word "similarly" is used on purpose, because the properties of living neurons have not been fully investigated.

Artificial neurons are called neurites, neuristors or artrons. They are all much more complex than a trigger, the number of components in the neuristor circuit being about 10 times that in a single trigger.

Should anyone wish to assemble an artificial brain including 10^{10} neuristors or artrons, then the "box" would be 10 times bigger still. At first glance the problem seems utopic. However, let us not draw hasty conclusions. For we have not yet taken into account the potentialities of the electronics to come. More than that, all of the above discussion covers experience of the days past.

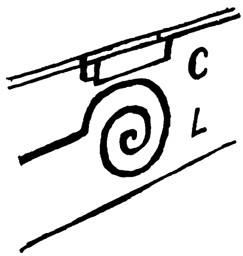
Why make an artificial brain employing valves, when there are semiconductors? And, in addition, it should be borne in mind that the advent of semiconductor devices has made the specialists revise the design of all components and units, first making them *miniature* and then, even *microminiature*, decreasing dimensions several hundreds of thousands of times.

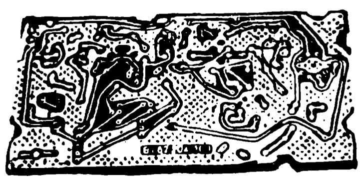
V.49

Compared to a valve, coils, capacitors and resistors always seem tiny. But for semiconductor devices components of the old design are far too bulky.

V.50

Printed circuits have become introduced into the production of electronic equipment simultaneously with semiconductors. On an insulating board (plate) special places are



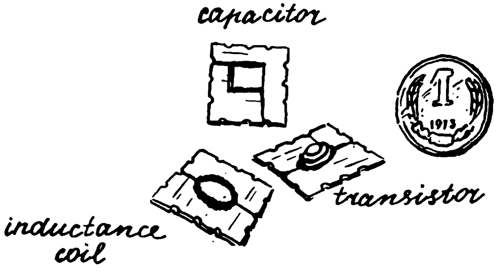


provided for transistors and semiconductor diodes, and then resistors, capacitors, inductors and connecting wires are printed on it.

To make a capacitor it is sufficient to print two plates on each side of the board. A spiral printed on the board replaces a coil. Thin zigzag lines make resistors of the required value.

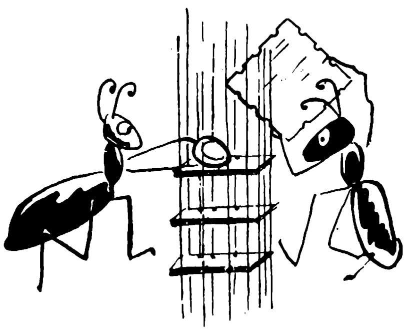
V.51

Striving to decrease the volume of electronic equipment, designers have come to the conclusion that a lot of empty space remain in the equipment because all the components (valves, coils, resistors) are of different "fashion". Then there has occurred an idea of standardizing them. Small square boards of the same size accommodate diodes, triodes, capacitors, resistors—a single component on each board.



V.52

The small boards are arranged one above the other like a set of shelves: the components are on the shelves and current flows along the uprights. When designing such a unit it



is very important not to mix up the shelves and the uprights: for example, the middle upright on the right should connect the capacitor lying on the upper shelf with the collector of the transistor several shelves lower.

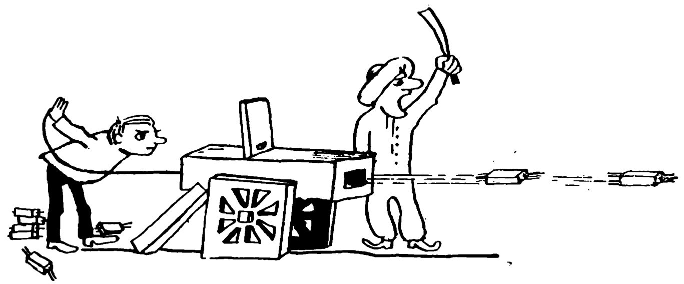
V.53

When the whole circuit is assembled, it is filled with a special compound and the "set of shelves" becomes a miniature and monolithic *micromodule*.

V.54

The volume of electronic equipment made up of micromodules is approximately 2000 times smaller than that of valve equipment.

In addition, equipment made up of micromodules is exceptionally durable. Whereas a valve receiver can fail due to shocks and shaking, micromodule equipment is capable of withstanding even very powerful blows.



In order to check such modules for durability, they are shot out of special cannons. If after such a "shake-up", the module continues to operate, this means that its durability is sufficiently high.

V.55

The development of *thin films* has marked the next step in the miniaturization of electronic equipment.

A film of metals or semiconductors is applied onto a plate made of an insulating material. The thickness of this film is infinitesimal: sometimes it is equal to the size of molecules laid on in a single even layer!

The thin metal film possesses a high resistance. This makes it possible to fit several million ohms within a length of 1 millimetre.

A film capacitor is like a three-layer sandwich: a film of metal, a film of insulator (dielectric) and on top, a metal film again. Thanks to the extremely thin dielectric film it is possible to obtain very high capacitances with a small size of the plates (compare with Fig. III.21).

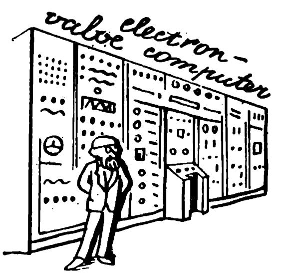
Transistors are also three-layered: a layer with the *p*-type conductivity, then a layer with the *n*-type conductivity and then another one with the *p*-type conductivity.

Such transistors are so small that up to 20 000 of them can be put on a postage stamp!

These are some examples of the achievements of "microscopic electronics" in recent years, for 20 000 vacuum valves would fill a whole railway boxcar!

V.56

The rate of the development and introduction of superminiature electronics is truly fantastic. Electronic computing techniques are only about two decades old. And in this fairly short time there have already emerged four generations of electronic computers!

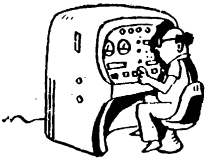


The latest in superminiature electronic equipment are *solid circuits*.

Taking as a basis a piece of ceramics or a semiconductor crystal, the designers of solid circuits subject them to technological processing with the aid of physical and chemical means.

A thin "design" covers the whole surface of the material. In some places it is subjected to chemical etching and oxidation, in others, to diffusion and thin film deposition, in still others, to heat treatment and in some, to the action of electric or magnetic fields.

As a result of such a processing on the surface of the material is formed an intricate network of microcells, each of



which possesses a certain set of electric and magnetic properties. Then the processed surface is covered with a glass film, and the piece of material turns into a solid circuit. The function of each microcell is similar to that of a circuit consisting of many transistors, diodes, resistors, inductors and capacitors.

Solid circuits are noted for their durability and reliability, low power consumption and exceptionally small volume: an electronic unit performing a whole set of computing or logical operations can pass through the eye of a needle!

Truly, the art of the developers of solid circuits approaches the perfection of nature: within a tiny piece of a material there proceed complex, interrelated, purposeful processes, a peculiar "electronic life" takes place.

V.57

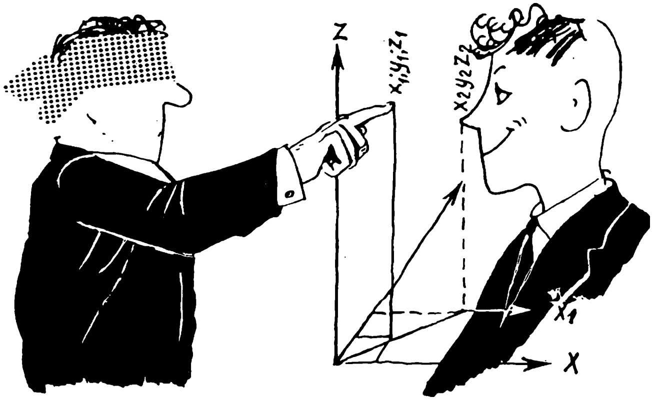
An artificial "brain" made up of micromodules would be 2000 times smaller than that employing valves. Nevertheless, a system of 10^{10} electronic "neurons" would be 10 metres high and 100 metres wide and long and would occupy a whole city block.

A "brain" made up of thin film circuits would occupy a volume 100 times smaller still and would become a cube with an edge 10 metres long.

A "brain" based on solid circuits would be still smaller. Of course this falls short of the perfection of nature, yet certain functions of the brain can now be reproduced much more fully than a few years ago.

Models (Simulators) Of Living Things

In recent years electronics has developed a great variety of models (see V.17). The conditions of smelting metals and the cycles of their machining, the flight of missiles, rockets and aircraft, chemical and physical processes, conveyance



by various means of transportation, financial operations and the course of the fulfilment of production plans—all this has been simulated.

However the most complex has been and remains the simulation of the processes taking place in a living organism. Let us begin with a simple example.

Have you ever tried to find your own nose in the dark? Has it been easy for you to touch it with the tip of your finger? Evidently it has. But try and find the tip of someone elses nose in the dark. Now it will not be so easy—you will have to grope about with your hands for a long time before you happen to find it. And if the owner of the nose begins turning his head? Again you will have to grope. But your own nose does not get lost in the dark, and at any moment you can touch it without missing. Why?

Because the brain receives signals from the face muscles and from the muscles of the hand. The brain compares their positions and finds the error signals, or, as the mathematicians say, the difference in coordinates. At any moment the brain can send a command to the actuating organ (hand) and bring the error signal to zero.

The same tracking can be achieved respective of extraneous objects (including somebody elses nose) on condition that these objects are illuminated. The brain receives signals from your eyes, which fix the position of these objects, and also from your hand. But in the dark there is no tracking. For the tracking requires a feedforward and feedback. The feedforward provides for the transmission of commands from the brain to the muscles, while the feedback serves to determine how close the object is.

The communication links in a living organism are very much like the circuit of any tracking automaton. In both cases the systems have an object to control, an actuating organ, error signals, feedforward and feedback.

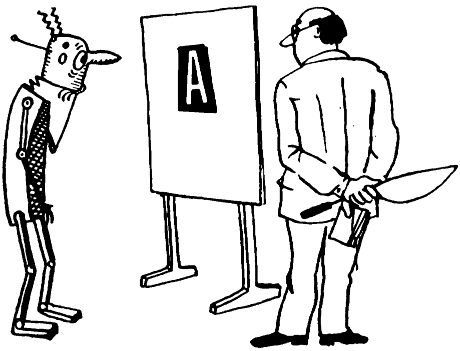
And this formed the starting point of cybernetics: the common principles of control used both by automatic equipment and living organisms were discovered. However, in addition to the similarities, there are also differences, and by no means all of them have as yet been understood.

We have learned to simulate the work of muscles with sufficient precision. It has been even possible to design an automatic hand which, on receiving amplified biosignals from the muscles of the human hand, repeats exactly all its motions.

To make a model of the brain is a much more complex affair. Nevertheless, even here no small achievements have been scored. So far, of course, we can speak only of simulating individual functions. However, even then many difficulties crop up. And no wonder: after all, the brain is the most complex system in the world, and the engineers dispose of no instructions or diagrams. They have no chance to take a peep at the functioning brain and have to be satisfied with but speculations and using electronic simulators for checking them. But even this roundabout way has brought no mean crop of fruit.

One of the most vivid examples, probably, is the computer which can recognize visual images. It is called a perceptron. The model of an eye developed for this computer contains hundreds of photocells. Its artificial brain consists of thousands of electronic "neurons", united in a complex network.

The process of teaching a perceptron is somewhat reminiscent of the training of animals. The computer is shown a letter which it should differentiate from others. If the computer "recognizes" it, an "encouragement" signal is sent to the brain", which strengthens the link formed between the neurons. In such cases an animal trainer gives it a savory tidbit. If the computer confuses the given letter with another, it is sent a "punishment signal" (this replaces a whip). After "seeing" the letter 10-15 times the computer begins to "reco gnize" it. What is more, it can tell the letter even in cases when it is of different size, or has been printed in different type.



One perceptron has been designed in Kiev, another in Cornell University, USA. The American perceptron has been developed to an order placed by the Military Department. It does more than merely recognize printed letters. It has been taught to look at an aerial photograph and "recognize" a hangar or a grounded aircraft.

Nature Has Long Been Aware Of This

There can be no doubt that by simulating certain processes in living organisms electronics scored many successes. But many things are as yet not clear. Much has still to be studied and developed.

And then at the junction of two seemingly absolutely dissimilar sciences—biology and electronics—there comes into being a new domain of knowledge. It has been given the name of *bionics.* It has happened so that biology and electronics have many interests in common and they may in many ways be helpful to each other.

As usual, it all began with minor things. It was noticed long ago that the males of certain insects fly many kilometres away from their mates and then return to them unerringly.

The French entomologist Fabre made a suggestion that there exists a sort of radio communication between the male and the female. To check this hypothesis he placed a female silkworm moth in a breeding case, and soon from all directions there arrived about 60 males. The males were caught, marked and removed in various directions several kilometres away. Forty minutes later the marked males again returned to the female!

Supposing that communication was conducted in the infrared frequency range, the scientists put the female into a jar made of glass which was impervious to any infrared rays. The supposition was confirmed: the "faithful knights" no longer flew in response to her call.

The next supposition was that the antenna receiving the infrared rays were the insects antennae. And indeed, males deprived of their antennae could no longer find their six-legged mates.

At first such discoveries gave rise to many doubts. It was hard to assimilate the thought that radio, one of the greatest achievements of the 20th century, had been "invented" by nature millions of ages ago. Could it be that all the inventions involving radio belong to nature alone?

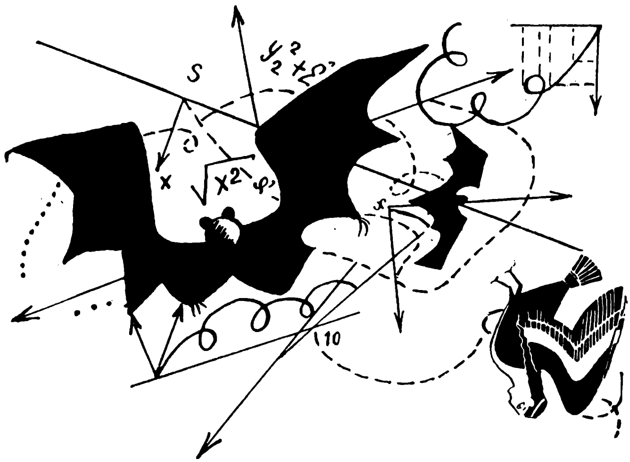
But the facts have accumulated and in the end human beings realized that the degree of perfection achieved in this by nature is so high that even today the quality of the "devices" created by it cannot be surpassed.

Now the characteristics of many such "devices" have been thoroughly studied. For instance, it has become known that nature has supplied the bat with a kind of sonar operating in the supersonic range. The bat radiates a series of pulses having a duration of two thousandths of a second. And the carrier frequency varies during the pulse from 45 to 90 kHz. Consequently, in this case nature makes use of frequency modulation. The pulses follow one another with a frequency of 10-12 Hz, but when the bat approaches an obstacle, the pulse repetition frequency increases to 250 Hz.

And the moths that the bats are feeding on have their ears similar to small microphones. Their "tuning" range encompasses the frequencies of all the signals radiated by the "sonar" of the bat: the scientists have established that the ears of the moth respond to signals from 10 to 100 kHz.

It has been found possible even to connect the microminiature "device" to an amplifier. This has resulted in the development of a fine receiver for detecting the signals of bats.

Such an abundance of figures in a report on bats and moths may seem strange. One might think that the subject is not live organisms, but some equipment developed by man.



But what can you do? The latest developments of bionics more and more convince that to investigate biological problems a purely engineering approach is required.

Those who have seen bats in flight, could not have failed to notice the intricacy of their flight path. The bats fly this way and that, seemingly without any purpose. Actually, each of their movements is remarkably well calculated. Having intercepted and caught an insect, it immediately changes its course to pursue another insect that has come within the field of view of its "sonar". Scientists have estimated that a bat destroys, on the average, one mosquito every 6 seconds.

The perfect "sonar" that nature has endowed the bat with allows it to keep its surroundings under constant surveillance. The "sonar" also ensures effective pursuance of insects and safety in a headlong flight: the bat can detect in good time any obstacles in its way and by-pass them.

In its mode of operations the "sonar" or "radar" of bats is very similar to the radar of airfields designed for observing space during landing of aircraft and getting them on course. But there is a noticeable difference between them: the airfield radar installations weigh tons, while that of the bat weighs only 0.1 gram!

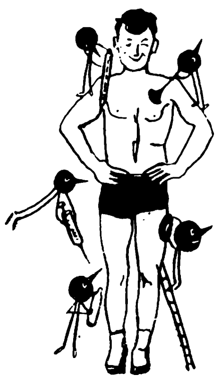
Now this really is miniaturization! And it should be noted that many of the properties of the miniature "radars" created by nature still remain a puzzle.

For example, it is hard to explain how the bat can tell its own reflected signal from the signals of other bats or from special interference signals which have been produced during experiments. When these questions will be answered, then, evidently, it will become possible to substantially improve all the radar techniques now in use.

Incidentally, this is not the only example. The "sonar" of dolphins and guinea pigs significantly excels the means which are now being used by the submarine fleet in precision, range and ability to detect very small obstacles.

THIS LIES AT THE BASIS

V.58



The word "bionics" is a blend of the words "biology" and "electronics". In addition to bionics, there also exists *biological electronics*, which, while being similar to bionics terminologically, yet has its own tasks.

Bionics studies and simulates processes inherent in living organisms. But biological electronics develops devices that help study organisms. These devices are also used in medical practice.

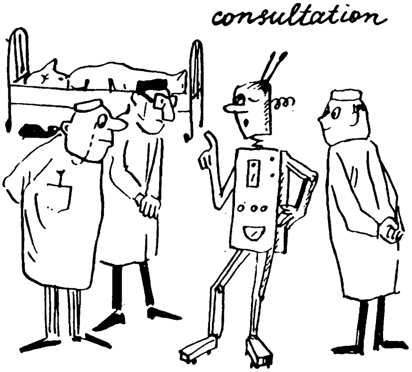
V.59

Modern medicine and electronics are bound together by the closest of ties. Try and imagine a clinic without X-ray equipment that allows the physician to look inside the body, without electrocardiographs that record the rhythms of heartbeats, without methods of treatment with ultra-high frequency current. Deprive medicine of all this, and it can no longer be called modern.

All these means have been put at the disposal of medicine by electronics. X-rays which penetrate to the depths of living tissues are produced with the aid of a concentrated and intense beam of electrons directed at a special mirror. Electronic oscillators generate ultra-high frequency signals for treatment. Electronic valves in an instrument which records electrocardiograms amplify the signals transmitted by the beating heart.

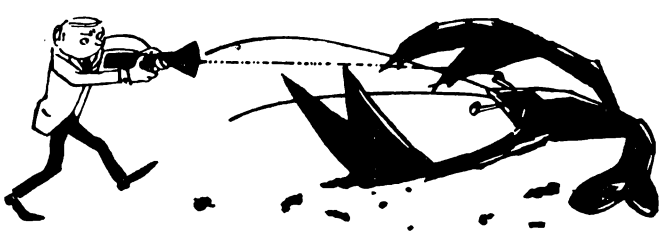
V.60

The best that electronics creates it willingly passes on to medicine for prolonging the life and improving the health of people. No sooner have electronic computers emerged than application has immediately been found for them here too: by comparing a multitude of symptoms, they immediately and precisely make a diagnosis, because the memory of one electronic "brain" can store the experience of many physicians.



V.61

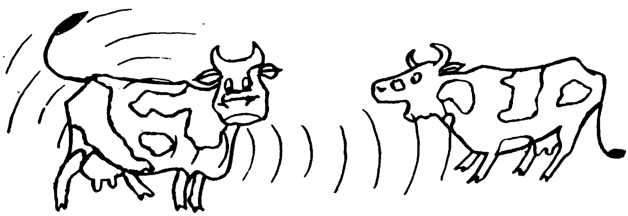
Engineers have as yet not investigated all the potentialities of lasers, but medicine has already begun using them. We have already dealt with their use in surgery. An attempt has been made to use the very same beams for fighting mankind's most fatal foe—to overcome insidious and merciless cancer. A group of Boston surgeons headed by Doctor MacGraff used laser radiations to cure up to 50 per cent of experimental monkeys who had cancer. There is hope that man suffering from cancer will also be helped by these beams.



V.62

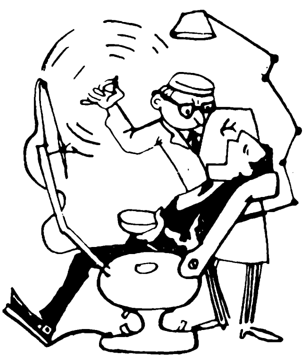
Transistors have proven very valuable for medicine, because in a number of investigations the instrument used should be very small. By using transistors it has become possible to develop a "transmitting pill", as it were. The patient swallows the pill, and on reaching the stomach, it reports of the conditions there. The same devices have proven useful in cattle-raising.

Cows graze on the meadows of Poland, and in the stomach of each of them there is a similar device. Receiving its signals, the Polish scientists keep track of the assimilation of food, so as to find the most effective diet for the cows.



V.63

A strange case occurred recently in America. Two patients went to see doctors with most unusual complaints: both of them were haunted by a voice that kept suggesting they should buy something: sometimes it was soap, sometimes refrigerators. And this continued day after day.

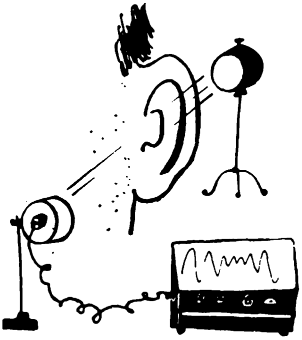


A psychologist found nothing wrong with them. Medicine was stumped. Then unexpectedly a significant detail came to light. It turned out that both of the "patients" recently had crowns fitted on their teeth, and what is more, by the same dentist. The material he used for cementing the crowns in place possessed semiconductor properties. Miniature crystal sets were formed inside the crowns, which by chance happened to be tuned to the wavelength of commercial radio broadcasts. Via the nerves of the teeth the detected signal was transmitted directly to the brain.

Perhaps, in time this type of radio communication may be used intentionally. Many patients would, probably, not be averse to having a receiver in a crown if, in view of the bitter experience of the first two people, a way could be found to switch them off.

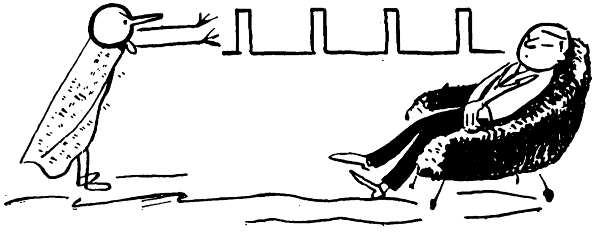
V.64

Most interesting is the design of a device which watches over the patient's breathing during operations. Normal breathing ensures a definite amount of oxygen in the blood. The amount of oxygen affects the transparency of the blood. It is sufficient to direct light at the patient's ear and to place a photodiode (see V.44) on the other side of it and a problem of great importance is solved: the composition of the blood can be controlled throughout the entire course of the operation, in other words, it can be seen how the patient is breathing.

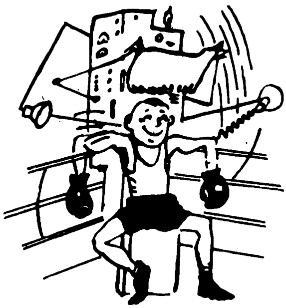


V.65

Peculiar is the effect that may be produced on human beings by current pulses: they cause man to fall asleep. The reasons for such a reaction are as yet not sufficiently clear, but as for the results, they are obvious. A special pulse generator serves as a wonderful means for treating nervous diseases.



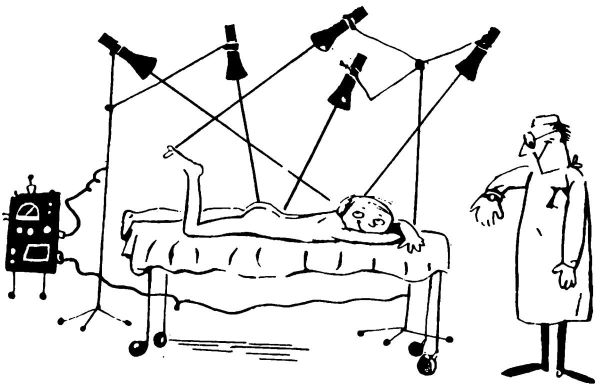
V.66



But with other frequencies and amplitudes, pulses become a source of strength and vigour. They can be used for training damaged muscles, eliminating the after-effects of paralysis. This is done with the aid of electric masseurs in combination with electronic simulators—sources of pulses of a definite frequency.

V.67

The problem of using electric pulses for treatment by the needling method is now being studied. Needling in this case is no more than a figure of speech. Needles as such are not required: an electric pulse penetrates living tissues and excites definite nerve centres no worse than the thinnest of needles.



V.68

Medicine is long familiar with a heart disease that is known as "lateral heart block". The heartbeat rate falls to 10-20 beats per minute, and death stares the patient in the face. To fight this disease, the physicians of the Moscow Second Medical

Institute decided to make use of electronic stimulators and applied for help to a public designing bureau. Electronic heart stimulators were known before, but the pulse generators were always positioned externally, and special electrodes were introduced into the heart. This method was inconvenient and even dangerous: microbes could penetrate into the body through the openings for the electrodes. The cooperation of the physicians and engineers has resulted in the

development of an implanted semiconductor stimulator. It weighs only 125 grams and consumes so little power that a small battery is enough for operating it continuously for two and a half years.

Who Is In Debt To Whom?

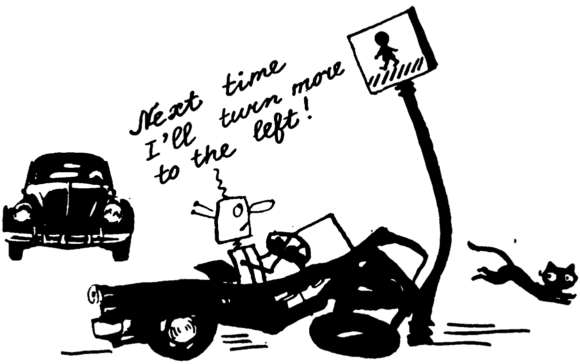
Possibly the time may come when the design of certain "living devices" will have been studied so thoroughly that for the engineer it will only remain to make an exact copy of it for technical needs. But as of now such problems are solved in a different way: bats did not give birth to radar; radar was developed by engineers. But the means and methods that made their appearance in radar techniques, helped study the bat.

Nevertheless, it is now possible to try to reverse the process. Bionics allows us to "learn from nature". Engineers learn from the sunflower how to follow the movement of the sun; from fish and dogs they borrow the ability of detecting barely perceptible smells; whales and dolphins serve as examples of the best proportions for swimming fast, while the stork provides food for thought in respect of what factors will ensure the most economic flight of flying apparatus.

Nature has many such perfect "devices", of which engineers can as yet only dream. It was found that rattle snakes have a receiver tuned to infrared wavelengths. This receiver is so perfect that it responds to temperature differences of several thousandths of a degree! No living object that radiates heat can escape the surveillance of such a receiver.

The eyes of frogs and "horseshoe" crabs are capable of intensifying the outline of one object against the background of all the others. A wonderful quality! An instrument endowed with such a property would be able to make detailed. analyses of roentgenograms or aerial photographs taken at great altitudes.

How do pigeons orient? Why do they always find the way home? Even if they are driven away in a dark basket, still they return unerringly.



There are various suppositions. Some ascert that the pigeon receives solar radiation and orients itself accordingly. Others believe that a pigeon has a special "device" which responds to the rotation of the Earth. Still others advance a hypothesis that the orientation of pigeons is based on the reception of the earth's magnetic field. The problem is being studied. And again, of course, with the help of electronics. A pigeon is equipped with a miniature radio transmitter whose signals make it possible to keep track of its entire flight.

Turtles orient themselves in the sea no worse than pigeons do. They swim thousands of kilometres away and then return to a definite place to lay their eggs.

There is another common quality of living organisms which will, probably, make engineers most envious of all. This is the ability of adaptation to widely differing and at times unexpected circumstances, the ability of orientation in new circumstances, interaction with the environment.

In this sense the most complex of automatic machines is much more primitive than the simplest of organisms. And this is an extremely necessary quality. Without such a quality it is impossible to develop an electronic device that would be able to drive a car along city streets, solve complex production problems, conduct scientific experiments. In all these cases unforeseen complications may arise. A living organism will nearly always find a way out. But computers are still too lop-sided: if even a single factor is not taken into account in their program, the whole control process will be null and void.

Bionics will help solve these problems also. It is first necessary to asceratin how they are solved by a living organism.

Bionics is a young science. It has as yet no integrated universal methods at its disposal. So far no special textbooks have been written about bionics, nor exhaustive fundamental works. But there are interests shared in common by electronics and biology, there are undiscovered principles created by nature, and there is an appeal for physicists, biologists and engineers to pool their efforts in order to learn, understand and apply.

One might even say that bionics does not yet even exist as a science—it has only been proclaimed.

The Fruit Of A Single Century

Now we have reached the home stretch. Now we can summarize everything we have encountered along the way.

We would have liked to deal with many things. But we have had to restrict ourselves to that which is basic. To deal only with the fundamental ideas which have cropped up at different stages in the development of electronics and served as the main landmarks along its glorious path. To show how one and the same idea can be used for widely differing aims. And mainly to convince the reader that without electronics there would be no 20th century, exactly as there would be no culture of ancient Hellenes without their palaces, temples and remarkable sculptures.

Just think: the whole gigantic structure of electronics has been erected by mankind in but a single century. Only about 100 years ago Helmholtz had discovered the "portion of electricity", the carrier of which later proved to be the electron.

On coming to the end of the road, it is always useful to look back for the last time. A panorama will unfold before you and, perhaps, the last impression will prove to be the fullest one.

What does electronics look like, if, giving it a parting glance, we'll try to see all of it at once.

One can imagine a gigantic tree, the roots of which penetrate deep into the soil of science, while the branches reach out to all fields of knowledge.

That is what this mighty tree looks like at the present moment., But what will happen to it tomorrow, in ten and twenty years time? The scientist will not dare answer this question. Nor would the science fiction writer risk it. Who can tell what new branches will grow and what fruit they will bear? After all, at the beginning of our century this tree had only produced its first shoot.

The first radio station developed by Popov connected Kronshtadt with the island of Gogland in 1900. Since then each decade gave birth to a new branch.

The first decade of our century—radio is learning how to talk.

The twenties—long-distance transmission. Communication by ultra-short waves reflected by the ionosphere.

The thirties—mastering of television.

The forties—radar stations, wavelengths of 3 centimetres, remarkable devices: klystron, magnetron, travelling wave tube.

The fifties—computers, the introduction of semiconductor devices.

The sixties—quantum oscillators. Beams of light came to the assistance of radio waves.

The seventies.....

What will the nearest decades bring? This is not so simple to guess. Some twenty years ago no one even thought of an electronic brain, or of the development of "wise" machines.

So far electronics has been developing tempestuously, but in the second half of the century the rate of its development will grow ever faster. One cannot predict all the trends in its development, but can confidently say: whatever fields of engineering may emerge in the near or distant future, electronics will for a long time remain at the fore.

TO THE READER

Mir Publishers welcome your comments on the content, translation, and design of the book.

We would also be pleased to receive any suggestions you care to make about our future publications.

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