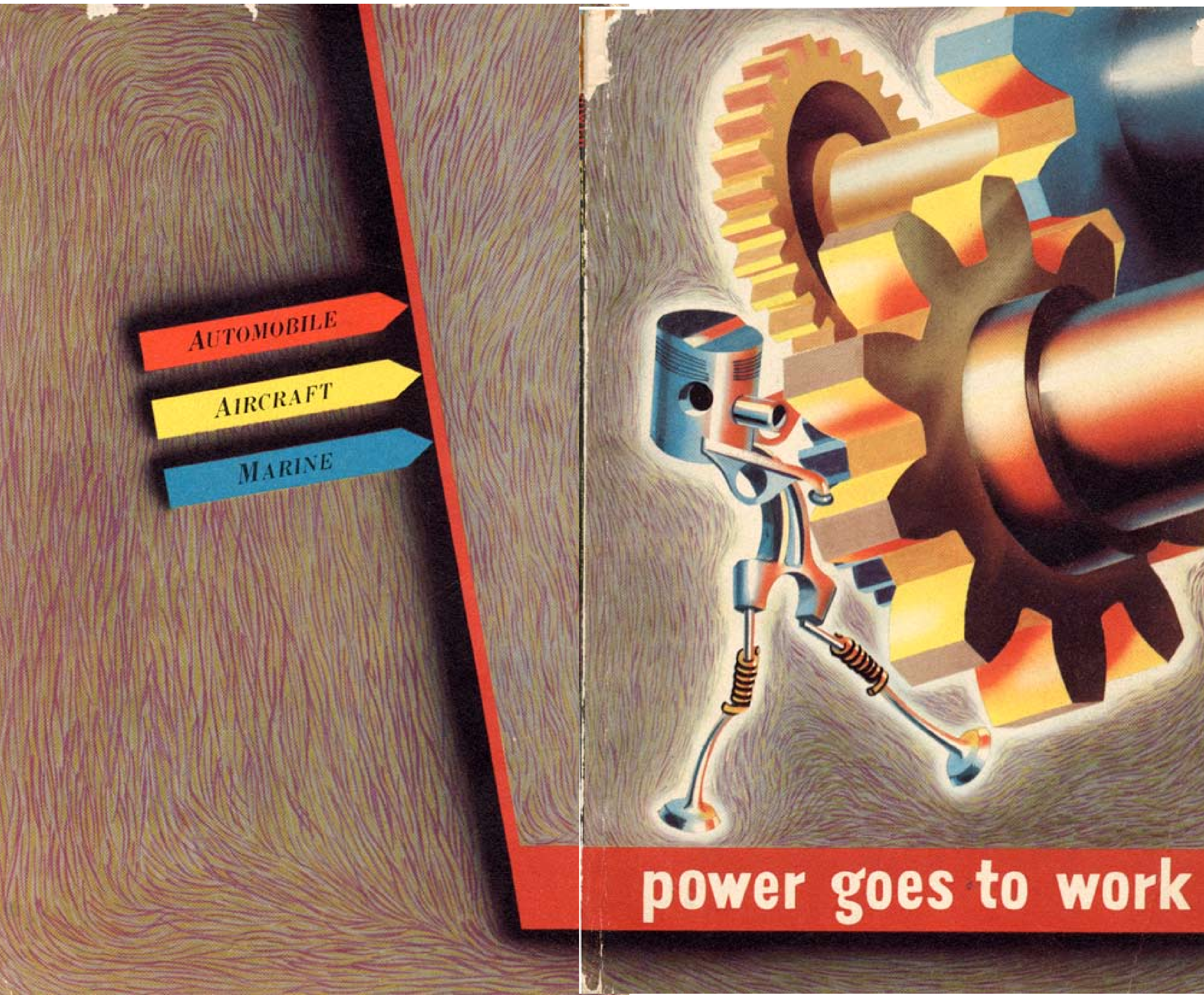

AUTOMOBILE
AIRCRAFT
MARINE
power goes to work

This booklet is an introduction to

POWER TRANSMISSION . . .

. . . the transmission of power from internal combustion engines.

It is an attempt to explain, in simple, non-technical words and many pictures, something about how power is used to drive an automobile, an airplane, and a boat. In a way it might be considered a sequel to "A Power Primer," which did the same thing for the engines used in such vehicles.

This is not an engineering textbook, and we have not attempted to cover the subject in detail. It is too big for that. We know there are omissions, but we have tried to include those things which would be of the most interest to someone who is curious as to what makes a vehicle go or who wants to know what happens to the power after it leaves the engine. For it is only after it leaves the engine that . . .

. . . POWER *goes to work*

POWER
goes to work

An Introduction to the Transmission of Power

GENERAL MOTORS CORPORATION

DETROIT, MICHIGAN

... POWER *goes to work*

WHAT MAKES IT GO?

"What makes an automobile go?"

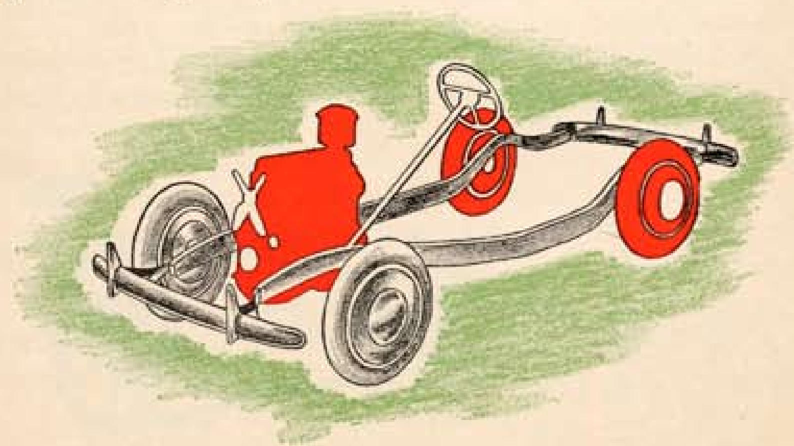
"Why, the engine, of course," is the reply.

"No," someone objects. "The wheels turning around make it go."

What makes an airplane go? The engine—or the propeller?

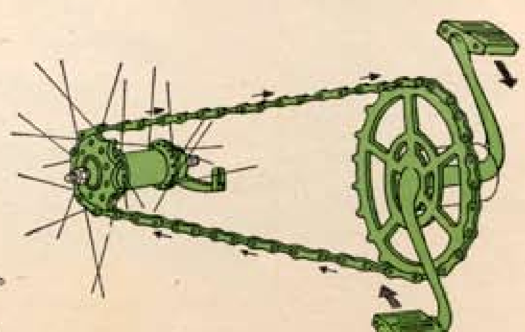
Such an argument quickly becomes ridiculous. It is easy to see that we need both. We must have a source of power, an engine, and we must have something which actually furnishes the push or pull that moves the vehicle.

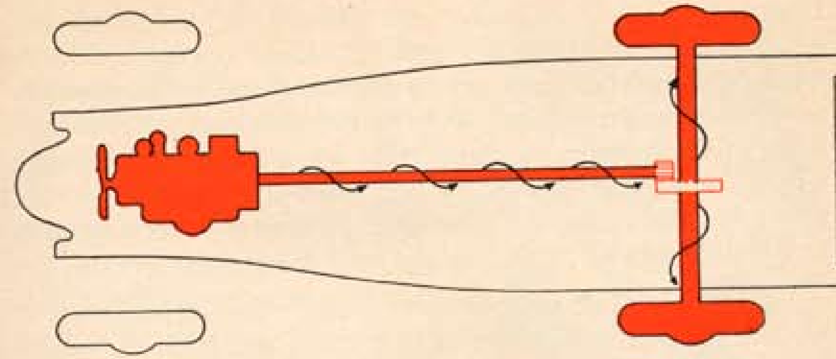
But a lot of people forget about the second part of this chain of power. Everybody talks of gasoline engines or Diesel engines, and they take it for granted that if the engine runs there is nothing else to think about. And the curious person who does try to find out what happens beyond the engine immediately runs into long equations, complicated formulae, talk of "involute curves," "compound gears," and so forth. And he decides that here is a place for engineers, not for him.



In this book we are going to try to explain what happens to the power after it leaves the engine—particularly the power from *internal combustion* engines as used in such things as automobiles, airplanes, and boats. The engine furnishes us with a shaft turning around at a certain speed and with a certain force. What happens from there on? An automobile rolls itself along the ground. An airplane depends on the air to hold it up and make it move. A boat pushes on the water in order to go. They are all different but they all have much in common. They all start with power in one place and use it in another place. But a lot of things happen between the two places, and these are the things we are concerned with here.

Up until quite recently, about the only method of transmitting power to a vehicle was a shaft or straps to fasten it behind an animal. The wheels were only to make it easier to pull—they did not make it move. Not the earliest, but probably the simplest example of a vehicle carrying its own engine which turns a wheel to make it go is the bicycle. The engine of course is the rider. He makes the front sprocket, or gear, go around, which drives the chain, which makes the rear sprocket go around. This is fastened solidly to the wheel, so the wheel goes around, rolls along the ground, and moves the bicycle and rider with it. Here we have a familiar mechanism which is





a definite example of generating power in one place and using it in another place.

But when the internal combustion engine, which has changed our lives in so many ways, came along, it brought some new problems with it. The internal combustion engine has certain fundamental characteristics which make it necessary to have rather complicated gearing in order to make an automobile do the things we want it to do. Power can be transmitted in various ways. But as it comes from the crankshaft of an engine, it is in the form of twist. The engine acts like a powerful giant turning a crank handle which exerts this twisting force on the shafts and gears which connect the engine to the wheels or propeller.

Let us see how this would work in a very simplified form of an automobile power transmission system. This system would not be very satisfactory for starting the car, or turning corners, or climbing hills, but for just driving along on a straight, level road it would be all right. There is a long shaft with one end fastened to the rear of the engine crankshaft, and on its other end, between the rear wheels, is a gear. Running from the center of one rear wheel to the other—fastened solidly to each—is the axle shaft. And at the center of this axle is fastened a circular gear with gear teeth on one side. The two gears fit together, so that as the propeller shaft turns, or twists, the axle turns also and causes the wheels to go around. As the wheels are resting solidly on the ground, we might say that they try to push the ground backward when they begin to turn. But the ground does not move—it is definitely going to stand still—so in order to turn, the wheels must roll forward. They necessarily move the car forward with them, and that is what we have been trying to do all the time.

As we said, this is a very much simplified arrangement. In fact about all we are doing is to make our path of power turn a corner. Or to be more accurate, perhaps we should say that our path splits and each half goes off at a right angle. Our only object is to get that twisting force of the crankshaft back to the rear of the vehicle and facing in a direction where it can twist the wheels. All we have been trying to do is get power from one place to another.

But that is only a part of most power transmission systems. And in many cases the least important part. We often use gears—or wheels, pulleys, etc.—for other purposes.

First, there is the question of speed. Suppose there is an engine running at one speed, but we have a machine we want to drive at half that speed. We can do this with gears. If we want the machine to run twice as fast as the engine, we can also do that—with different gears. We will see how a little later.

Second, there is **torque.** Webster says torque is "that which produces or tends to produce rotation or torsion." In everyday words, it is a force which tries to make something turn around. It is a twist. We can usually put the word "twist" in the place of "torque" and the meaning will be exactly the same. But the engineers prefer "torque".

We use gears to increase or reduce torque. We might have an engine connected directly to a machine by a solid shaft, and the engine could not produce enough torque, or twist, to turn that shaft and run the machine. By putting the right kind of gears between the engine and machine, we could increase the twisting force enough to run the machine.

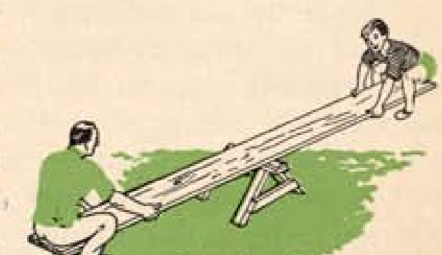
Torque is twist.

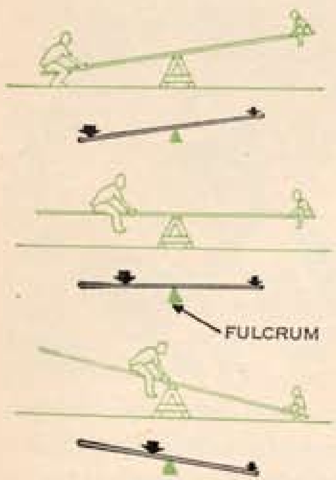
Speed changes and torque changes are all mixed up together. Gear systems which change one will almost always change the other also. But before we get into the why's and wherefore's of that, we are going to go back briefly to some of the fundamentals which form the basis for the whole thing. It may be old and familiar, but it will help explain a lot that follows.

Machines

There are a number of ways a man can increase the force he can apply with his own muscles. Some get to be rather complicated, but they are all made up of one or more simple machines. There are six of these machines. They are the lever, pulley, wheel and axle, inclined plane, wedge, and screw. Let us look at them briefly, with particular attention to one or two which we are going to hear more about later.

We are all familiar with the **lever.** A teeter-totter furnishes an easy way to explain the principle of it. If a child is on one end and his father on the other, the child will go up and the heavier person down. But if his father



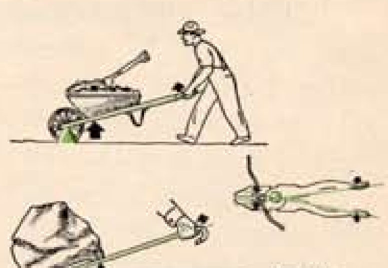


moves closer to the center of the board, nearer and nearer the pivot point, there will come a time when the small weight of the child will raise the heavier person on the other side. If the father weighs twice as much as the child, they will just balance when the father is half as far from the pivot as the child is. That is **leverage**, or **mechanical advantage** — a weight in one place lifts a heavier weight in another place, or a force applied at one point of the lever produces a greater force at another point.

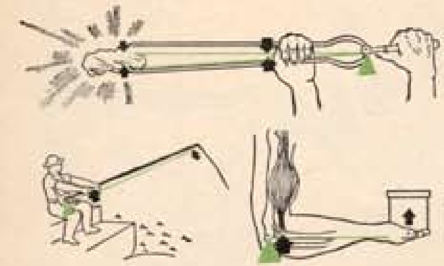
The point of support, or the pivot point, is called the **fulcrum**. This may be between the two forces, as here, or at one end. And the forces or weights may be arranged in different ways.

We have examples of levers all around us. A pair of pliers pinches down on something with much more force than we apply with our fingers. With a crowbar we can lift more than we can lift direct. A nut cracker and a wheelbarrow are other levers in common use.

There are also examples of levers in which the force is decreased. We simply turn things the other way around. Fire tongs do not hold the chunk of coal as tightly as we are squeezing the handles. The fish end of a fish pole does not have the same force that we are supplying near the other end. Our own forearm is a good example of this type of lever. The muscle



Levers.



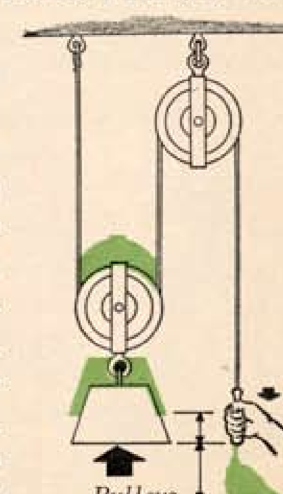
More levers.

pulls at a point very close to the fulcrum, and the weight we are lifting is way out at the end.

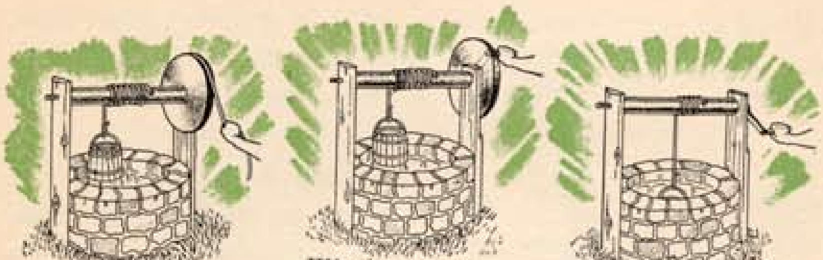
One thing we should notice in all of these cases. When the force is increased, it does not move as far. We may move the handles of a pair of pliers an inch to get a movement of an eighth of an inch at the jaws. The long end of the crowbar moves several feet to move the weight a few inches. Looking at the other side of it, we can jerk a fish out of ten feet of water by moving our hands less than a foot. Whatever we gain in force, we sacrifice in distance, and vice versa.

There are many arrangements of **pulleys**. With the simple one shown here we can hold 100 pounds with a force of 50 pounds. Each rope supports 50 pounds. By arrangements of more pulleys and thus more supporting ropes, we can get a greater mechanical advantage than the 2 to 1 shown. However, we have the same condition we mentioned with the lever. If our 50 pound force moves 1 foot, it will raise the 100 pound weight only ½ foot.

The **wheel and axle** is usually just a wheel fastened to a rod, like the steering wheel of an automobile. A force applied to the outside of the big wheel produces a greater twisting force on the small rod than if we twisted the rod itself. Sometimes we use a handle instead of a wheel, a **crank**, but this does not change the principle. Take a crank and a rod with a rope around it and we have a windlass. The hand will move several



Pulleys.



Wheel and axle.

feet in turning the crank around once. This will turn the rod around once which will wind the rope up only a few inches. But it will lift a much greater weight than we could lift by pulling directly on the rope.

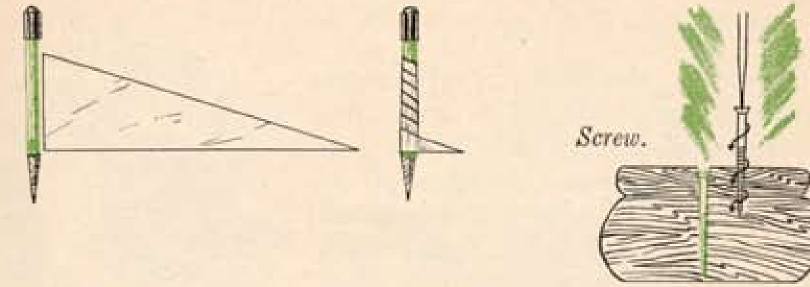
If a truck driver wants to get a barrel onto his truck, he lays a plank from the ground to the edge of the truck platform and rolls the barrel up. This plank is an **inclined plane.** He has to move the barrel a greater distance than he would by lifting it straight up, but it is a lot easier. He can get a barrel on the truck this way that he could not possibly lift.

Inclined plane.

The **wedge** is just a form of inclined plane. We push it under or between the objects to be moved instead of moving the object up the incline.

Wedge.

The **screw** is also a member of the same family. It is an inclined plane wrapped around a rod. As we follow the thread around the outside of the rod, we are continually going up hill. One complete turn of the screw moves the nut only the short distance between two threads. This distance is called the **pitch** of the screw. With a wood screw the action is just the same. Each turn of the screw moves it into the wood a distance equal to the pitch. The metal nut must have threads on the inside



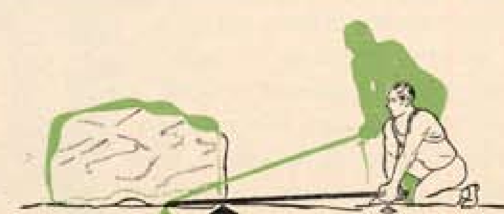
Screw.

which will fit exactly the threads on the outside of the screw, but the wood screw cuts its own threads in the wood as it moves inward. We will hear more about the screw later.

These few devices we have named are often combined in more complicated mechanisms, and some times it is difficult to recognize them as these same simple things. But if we take them apart and look them over carefully, we will find the familiar characteristics of the lever, the screw, or one of the others.

We will find also that these all really work on the same principle. That principle is that if we increase a force by means of one of these machines, that force cannot move as far as the original smaller force moves. As we have pointed out in each case, when we increase the force, we sacrifice distance. In text books, the formula says that *work equals force times distance.* And we cannot increase *work* by means of a lever. If we could, we would have perpetual motion. So the work remains the same, and if force increases, distance decreases, and vice versa.

The action of gears—the principle on which they work—is exactly the same as this. But before we get into that, let us see what a gear is, and what different kinds there are.



Smaller force moves greater distance.

What is a Gear?

A gear is a wheel with bumps or projections on it called **teeth.** These teeth may be on the edge, on the side, or halfway between. Incidentally we no longer talk about **cog wheels** and **cogs**—they are **gears** and **gear teeth.** A gear is usually fastened to a shaft. Sometimes it turns and applies a twisting force to the shaft, and sometimes the shaft is turning and turns the gear with it.

The simplest type of gear is the **spur** gear. This has its teeth cut straight across the edge. For years it was almost universal, but recently other types have become more common in the transportation field. We are going to use it a lot in this book, however, even in places where it is not ordinarily used. It is easier to see and understand its motions, and the principle is exactly the same.

Spur gears.

Another type is the **helical** gear. This is the same as the spur gear, but its teeth are cut at an angle. The teeth of the gear it meshes with must of course be cut at the same angle. It is usually quieter than the ordinary spur gear, and for that reason is preferred for many uses. For the same reason we sometimes use **herringbone** gears. This is like two helical gears fastened together tightly side by side.

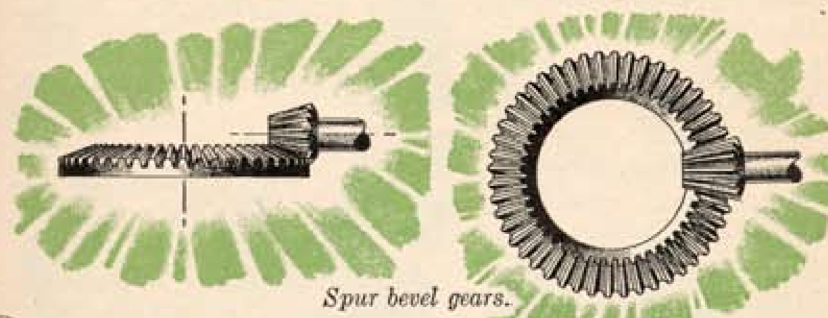
When our power must turn a corner, we ordinarily use a **bevel** gear. The teeth of this gear are not cut on the edge. They are cut, we might say, across the corner. Sometimes it is a spur bevel gear, with straight teeth, but it is more likely to be a

Helical gears.

spiral bevel gear. This is somewhat like a helical gear, except that the teeth, in addition to being set at an angle, are also curved.

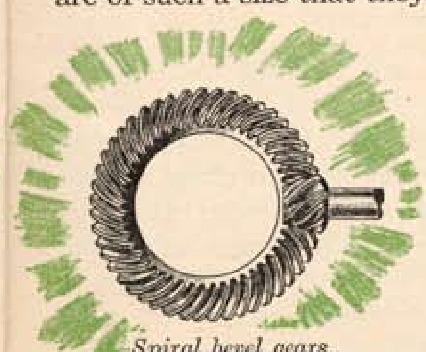
Herringbone gears.

We are going to leave out all the technical terms we can, but there is one we had better explain. **Pitch diameter** is the diameter of the **pitch circle.** The pitch circle is a purely imaginary line running through the gear teeth at a point usually a little outside the half way point of the tooth. The easiest way to define it is to suppose we have two smooth

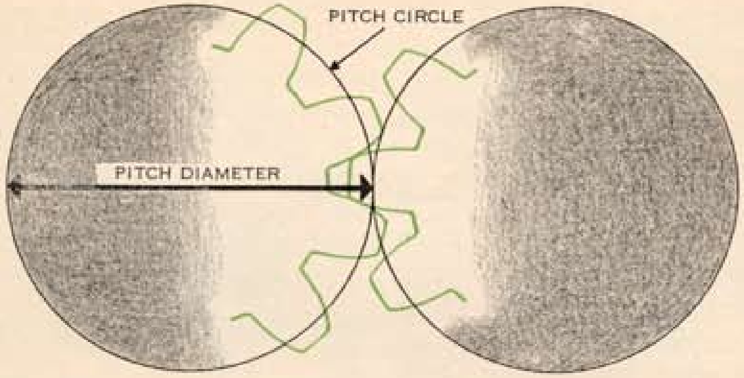


Spur bevel gears.

rollers running together instead of toothed gears. They are of such a size that they run at exactly the same speeds as the gears. In such a case the pitch diameter of a gear would be the same as the diameter of the corresponding roller. From now on in this book, when we speak of the size of a gear we will mean the pitch diameter, as that is what really determines its speed and other characteristics.



Spiral bevel gears.

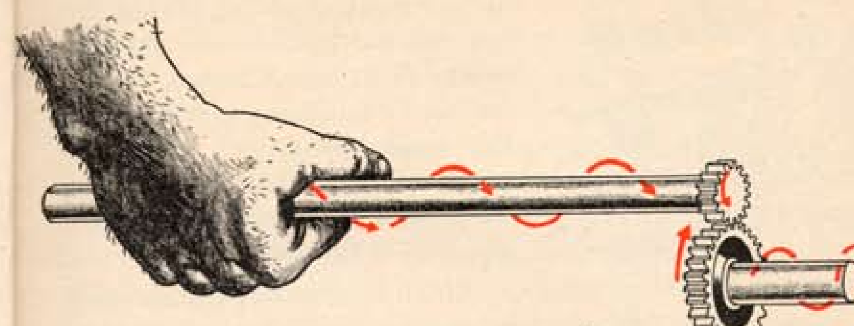


There is still another way of classifying gears. They can be external or internal. To the ordinary person the word "gear" will always bring to mind a picture of an external gear, and he will be right ninety-nine times out of a hundred. But internal gears do play an important part in some mechanisms, as we will see later. An internal gear is simply a ring with teeth cut on the inside instead of the outside. To mesh with it we must have an external gear of smaller size.

Internal gear.

What Does a Gear Do?

A gear is a spinning lever. It can increase or decrease torque in exactly the same way that a lever increases or decreases force. If you are interested in the explanation of this, more details are given on page 24. But these details are not necessary in order to understand what gears do and why we use them. The main thing to remember is that if we have a small gear fastened on one shaft driving a bigger gear on another shaft, the torque of the second shaft will be increased. The second shaft will have more twisting

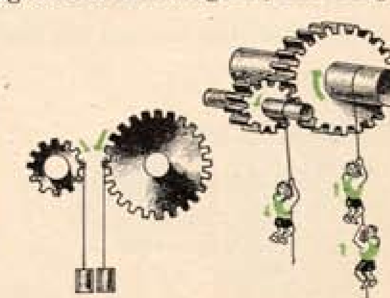


The torque will be increased.

force than the first shaft. If we have an engine driving the small gear, our system now will be able to turn something—say a machine of some sort—that the engine could not turn when they were connected directly together.

The amount the torque is increased depends on the relative size of the gears. If the diameter—pitch diameter—of the second gear is twice the diameter of the first gear, the torque will be doubled. If the second gear is three times

as big the torque will be three times as much, etc. But if the *driving* gear is twice as big as the *driven* gear, the output torque will be cut down to ½ the input torque.



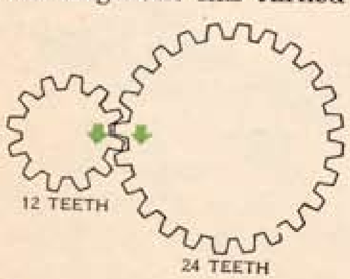
We can also think of a gear as another class of simple machine—the wheel and axle. A force applied at the outside edge of a gear, that is, where the teeth are, will exert a twist

...*Perpetual motion?*

on the shaft. And the bigger the gear is, the greater will be this twist. With equal forces on the teeth of two gears, the shaft of the larger gear will have the greater torque. This is what we have when two gears are in mesh and one is driving the other.

In all this we have to remember one thing. We are not getting this increased torque for nothing. We are not discoverers of perpetual motion and claiming that we get more power out of the engine because we have added some gears to the system. We are still dealing with levers and they still follow the same rules. With levers we said that *whatever we gain in force we lose in distance.* When talking about gears and shafts we say, *whatever we gain in torque we lose in speed.* The two statements are not exactly the same, but we can think of them that way for the moment.

The best way to show this is to count the number of teeth on two gears. The teeth must all be the same size in order to fit together properly. Therefore if the diameter of one gear is twice the diameter of the other, the big one must have twice as many teeth as the small one. Let us say 24 and 12 teeth respectively. As the small one, the driving gear, goes all the way around once, its 12 teeth have meshed with 12 teeth of the larger gear. That means the large one has turned around only halfway. The small

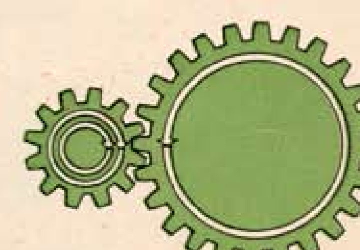


one has to go around again before the large one completes one revolution. So, for every two revolutions of the small driving gear the large driven gear revolves once. And for every 1000 revolutions of the small one the large one has made 500 revolutions. So, if an engine driving the small gear is running at a speed of 1000 revolutions per minute (R.P.M.) the machine driven by the large gear is turning over only 500 R.P.M. We have doubled the torque furnished by the engine. We have increased the twist on the second shaft so now it can turn the machine when perhaps it could not before. But the machine turns only half as fast as it would if it were connected to the engine direct.

Counting the number of teeth on gears is usually easier than measuring the pitch diameter. And as we have just shown it will give us the same information concerning the gear ratio—that is, the amount of change in torque and speed. If the driving gear has 10 teeth and the driven gear 30 teeth, it will take 3 revolutions of the first to get the second all the way around through one revolution. Thus the speed of the driven gear will be ⅓ the speed of the driving gear, and we know from this that the torque will be multiplied by 3. We would say that the gear ratio was 30/10 or 3 to 1. This applies equally as well if we have an odd combination of numbers, such as 39 and 19, only it is not so easy to do the mathematics in our head. The gear ratio would be 39/19, or a little over 2 to 1.

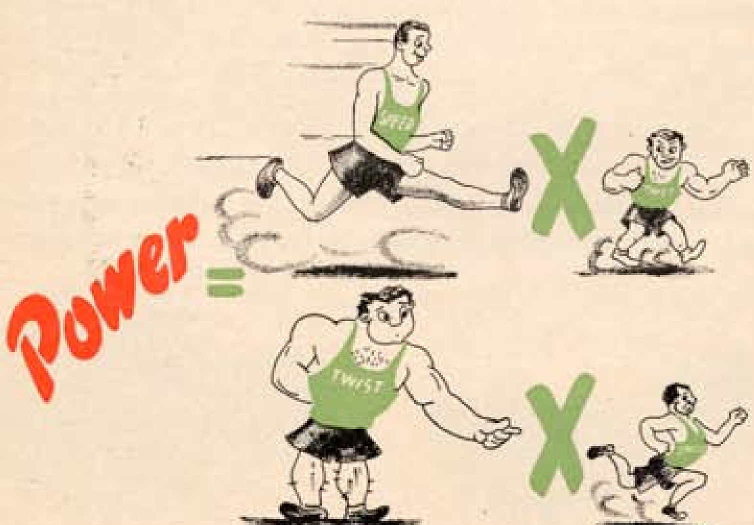
The gear with the greater number of teeth will always run more slowly and will produce the greater torque.

Sometimes we are glad to have this reduction in speed along with the torque increase. In fact the main purpose of



the gears in some mechanisms is to act as speed reducers. In other cases we need both more torque and less speed, so we gain both ways. On the other hand, sometimes we may wish to increase the speed. Maybe we have a machine that has to run at 2000 R.P.M. and an engine running at 1000 R.P.M. In that case we use a gear ratio of 2 to 1 again, but we have to put the large gear on the engine shaft and the small one on the machine shaft. The torque will be cut in half, but if the engine has enough power to drive the machine under those conditions, the machine will run at the required speed of 2000 R.P.M. But we cannot eat our cake and have it too. If we need both more torque and more speed, there is nothing we can do about it—except get more power from the engine.

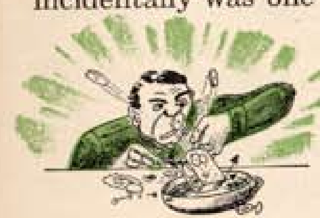
What we have been saying is really the same thing as is expressed by the formula found in text books—that *power equals torque times speed*. The gears cannot change the power; that stays the same. Therefore if the torque increases, the speed must decrease; if the speed goes up, the torque must go down.



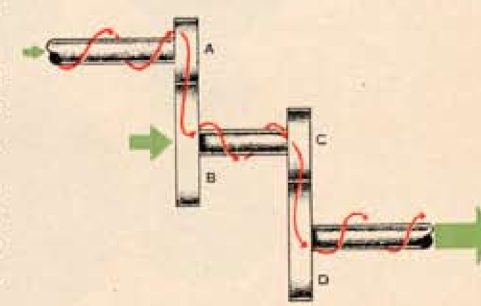
WARNING

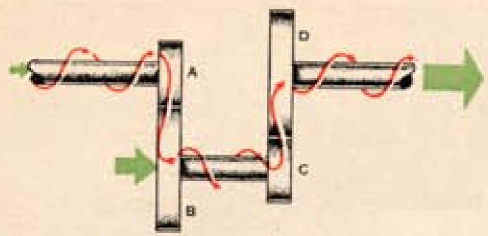
Everything said thus far has to do with gear mechanisms all by themselves, or we might say, with gear mechanisms driven by an engine which is running at *constant speed and constant power*. The statements are not necessarily true when applied to the over-all mechanism as in an automobile where the speed and torque of the engine can change at any time. But even there, if we consider it at any one moment, the same rules apply.

In some mechanisms we have more than two gears between the input and output. A clock or watch—which incidentally was one of the very early users of gears—is a good example of multiple gears in series. Even the cheapest alarm clock sometimes astounds us by the number of gears inside it.



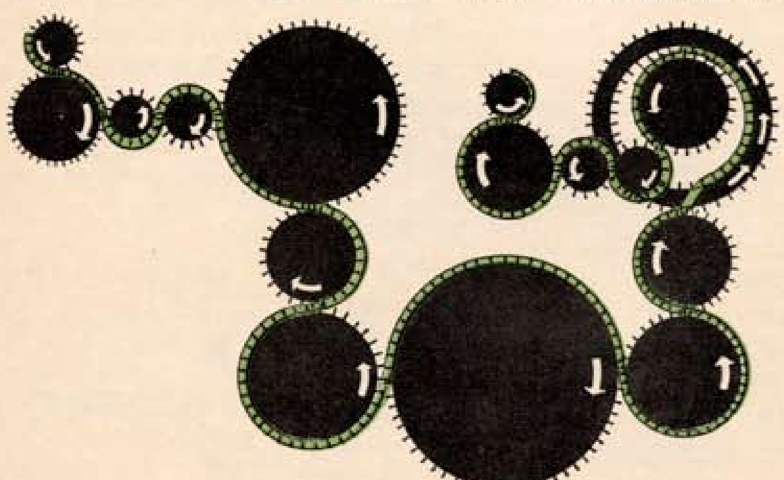
But suppose we look at something simpler to begin with. We will go back to our same two gears with 12 and 24 teeth and add another pair of gears to the system. These are just like the first two—12 and 24 teeth respectively—and the small gear C is fastened on the same shaft as large gear B. Now let us follow the path of the power flowing through this gear train. The engine is connected to the top shaft and is still running at 1000 R.P.M. We already know what happens with the first two gears. The speed is cut in half and the torque doubled. So our second shaft is turning only 500 R.P.M., which means that gear C is turning at that same speed. Now we can forget about





the first two gears and consider only C and D. We know what happens there too, because they are just the same gears with a ratio of 2 to 1. Our speed will be halved again and the torque doubled once more. So our last shaft, which is driving the machine, is turning at only 250 R.P.M., but it is applying to the machine a torque or twist 4 times as much as that delivered by the engine. The over-all ratio of the whole system is 4 to 1.

In any simple case such as this we can get the same effect by using only two gears of the proper ratio. Sometimes, however, there is too great a difference to be efficient, and sometimes it is a matter of convenience or space saving. In actual practice we ordinarily would not arrange the gears as we have here. We would save room by moving the third shaft up above the second. The result would be exactly the same, and we would have the added advantage that the first and third shafts would be directly in line. What we really have here now is a simplified arrangement of a conventional automobile transmission. The third shaft



would extend back to the rear axle to drive the wheels. But we will get into that a little later.

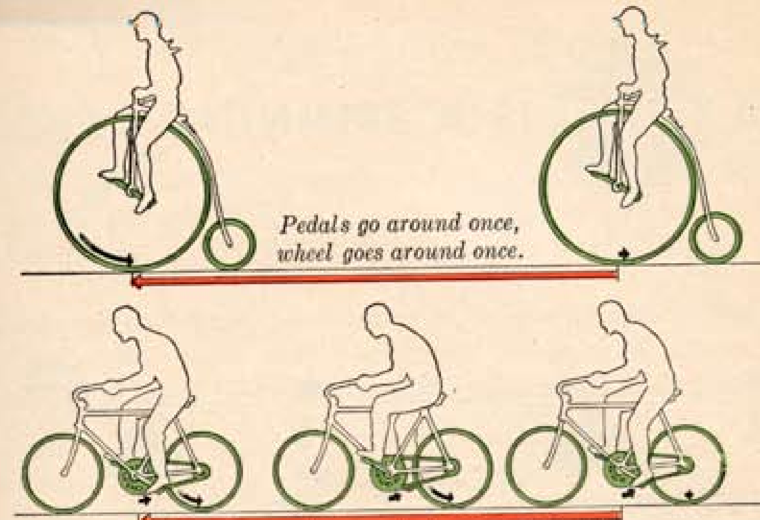
There is another feature in using four gears here instead of two which is sometimes an advantage. And this brings up a characteristic of gears which has probably been self-evident but which we have not mentioned. It has to do with direction of rotation. Looking at a pair of gears it is easy to see that if one shaft rotates in one direction, the other must rotate in the opposite direction. If one runs clockwise, the other must go counter-clockwise. This may be a nuisance in some installations, and in some others it may be just what we want. Sometimes gears are used in order to reverse the direction of rotation and for no other reason. But if we want the output shaft to run the same way as the input shaft, we must use at least three gears. Or, we can use a combination of more gears such as we have just been discussing. To find out which way the final shaft runs in any complicated system of gearing, the best procedure is to go through the whole system and figure out which way each gear turns. And do not forget the exception to the above—when an ordinary external gear is driving an internal gear, both shafts will rotate in the same direction.

We should point out one more thing before we leave this subject. If we consider the gear system of any wheeled vehicle, we must consider the wheels themselves. The size of the wheels has just as much to do with the over-all drive ratio as do the gears. It is the backward force the wheel exerts on the ground which makes the vehicle go, and if we have a certain torque or twist on the wheel shaft, this force at the ground depends on the size of the wheel. The larger the wheel, the less the force.

As an example, let us look at the bicycle. And let us look first at the bicycle as it was back in the early Nineties. That great high front wheel with the rider perched on top of it. The size of the front wheel was a matter of much pride and argument in those days. A 56 inch wheel was fairly good. But a long-legged person who could straddle a 60 inch wheel really had something to brag about.

Why was the wheel made so big? It is very simple. They used a big wheel instead of using gears. The pedals were connected directly to the hub of the wheel, so every time the rider's feet went around once the wheel went around once. With a wheel of the size used today that would mean that the bicycle would move forward about 7 feet. But one revolution of that big wheel would roll it forward about 15 feet. This meant that pedalling at the same speed would make the high-wheeler go twice as fast. It might be harder to get started and tough-going on hills, but speed was what counted.

Eventually the "safety" became popular and is now the only kind of bicycle we know. It was objected to at first as being too complicated, but it was really very simple. The driving wheel was reduced to about half its former size and gears were used to give the rider the same effect he had before. Let us say we have 20 teeth on the front gear and 10 teeth on the back gear. We can disregard the chain because all that is for is to allow us to separate the gears. As far as the ratio is concerned we can think of the gears as meshing together directly. So we have a ratio of 1 to 2. The back gear will revolve twice as fast as the front gear, and thus the wheel will go around twice each time the pedals go around once. This gives us exactly the same result



Pedals go around once, wheel goes around once.

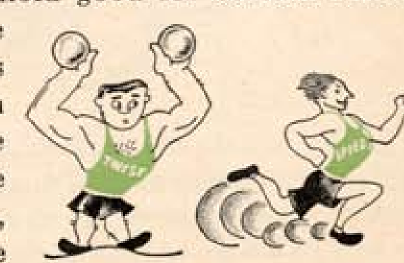
Pedals go around once, wheel goes around twice.

as if the wheel were twice as big and the pedals connected directly to it. The gears have cut the torque in half, but the driving wheel is only half the size of the big wheel, so the force between the wheel and the ground is the same in both cases.

Why a Transmission?

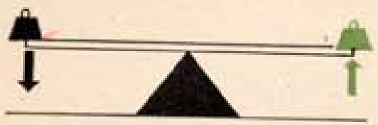
The question might be raised, "Why use a transmission anyway? If any gain in torque is at the expense of speed, and vice versa, why not just put in an engine of the proper size and use only the gears necessary to get the power to where we need it?"

This argument might hold good for certain conditions. But in the cases we are going to consider in this book, where we have an internal combustion engine driving a vehicle, there are two things against it. One, the power necessary to make

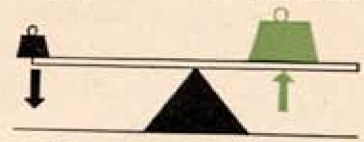


A GEAR IS A SPINNING LEVER

Take an ordinary lever, 20 inches long, pivoted on a fulcrum.



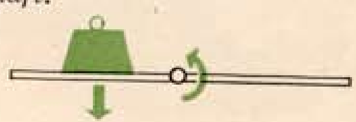
A 100 pound force down at A exerts a 100 pound force up at B.
100 x 10 = 100 x 10



A 100 pound force down at A exerts a 200 pound force up at C.
100 x 10 = 200 x 5

Let us change our fulcrum into a shaft, fastened solidly to the lever. If a force pushes down on one end of the lever, this applies a twist, or torque, to the shaft.

A force of 100 pounds at A causes a torque of 1000 pound-inches on the shaft.
100 x 10 = 1000



A force of 200 pounds at B also causes a torque of 1000 pound-inches on the shaft.
200 x 5 = 1000

Now suppose we turn things around the other way, and have the shaft try to turn the lever. If the shaft is exerting a torque of 1000 pound-inches, it will create a force of 100 pounds at A, or 200 pounds at B.

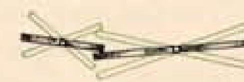
* * * * *

Now let us take two of these levers, one 10 inches long and the other 20 inches long. Arrange them so one end of the short one is resting on one end of the long one. A torque of 500 pound-inches is applied to the shaft of the shorter one.

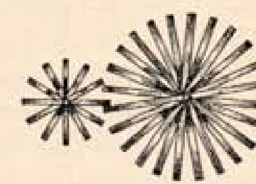
There will be a force of 100 pounds down at A, the end of the short lever. 100 x 5 = 500.

This will exert the same force, 100 pounds, down at B, the end of the long lever. This force will create a torque on the second shaft of 1000 pound-inches. 100 x 10 = 1000.

Our input torque was 500 pound-inches, and our output torque is now 1000 pound-inches, because the lever is longer.



But these two levers would not move the shaft very far. So we add another pair of levers, and then another.

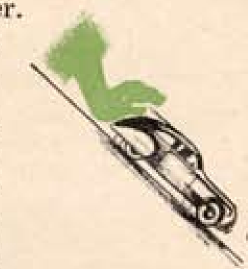


When we have added enough of these to fill the circle, we have a set of gears.

The driving gear is 10 inches in diameter; the driven gear 20 inches. The input torque is 500 pound-inches; the output torque 1000 pound-inches. Thus the torque is multiplied in the same ratio as the size of the gears.

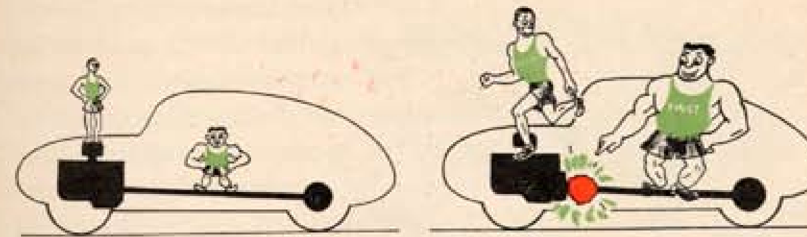
the vehicle go is very changeable. And two, the power delivered by the engine is also very changeable, depending on conditions.

Whether we are considering an automobile, an airplane, or a boat, quite a lot of force is used to get it started, to get it moving. Less force is needed to keep it moving at a moderate speed. A lot of force is needed again to drive it at very high speeds, force to overcome the resistance of the air and water. And of course with automobiles we have hills, with airplanes we have steep climbs and dives and changing air density. So it is easy to see that we never know from one moment to the next just what force is going to be necessary at the wheels or propeller.



And if we consider the characteristics of the engine, it is easy to see that we do not always get the power from it when we want it. We just said we needed a lot of force to get started, when the vehicle is standing still or moving very slowly. And that is just the time that the engine does not furnish very much power. One of the fundamentals of internal combustion engines is that they must run fairly fast before they can produce much power. They do not twist that shaft very hard when they are turning over slowly.

But if we put the right kind of gears in there we can kill two birds with one stone. The gears in an automobile let the engine run at high speed while the wheels are turning slowly, and at the same time they themselves increase the torque which is being delivered by the engine. Thus the transmission is responsible for more twist on the propeller shaft due to letting the engine run faster and deliver more power, and then it increases that twist still more by its multiplication of torque. So for starting, this arrangement is fine. But it is not so good for higher speeds, and that is why automobiles have some means for changing the gear ratio,



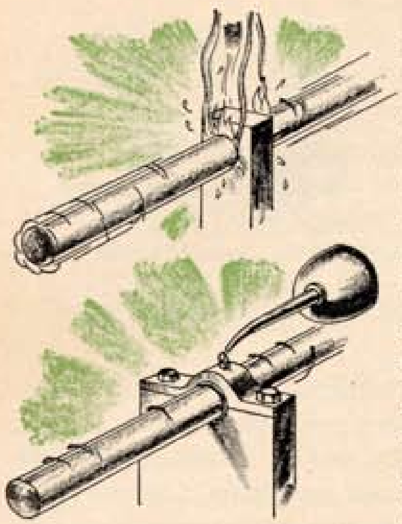
We gain in two ways.

depending on the load and speed of the car and the judgment of the driver.

It is possible to drive a car without ever shifting gears if we are careful to stay on hard level roads and if we do not object to other cars going by us and leaving us behind at traffic signals. And in airplanes and boats it is common to have a direct drive from the engine to the propeller. But even in these last two cases we often have gearing between the engine and the propeller, and we have propellers which in themselves act somewhat the same as a variable speed transmission. It is much the same story as in the automobile—we do not get the torque from the engine at the right speed. The propeller wants to go one speed, the engine wants to go another. But we will get into more details of that later.

Friction

There is one factor which always enters into the transmission of power which we have neglected thus far. That is friction. Friction has its good points and its bad points. We would have difficulty doing a great many things if there were no friction in the world. Try walking without it, for example. The only reason an automobile moves is because of the friction between the tires and the road. An automobile clutch depends entirely on friction.



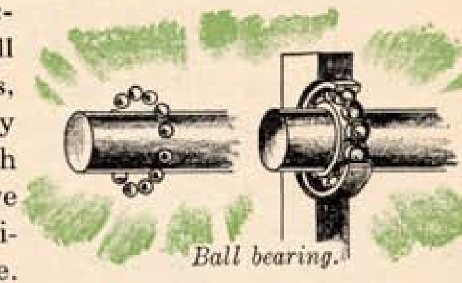
But in transmitting power, most of the effects of friction that we think about and talk about are the troublesome ones. That is probably because they are the ones we have to do something about. Whenever two gears are running together, there is some friction. This means that some of the power is used up—wasted—in overcoming that friction. A shaft running in a bearing creates friction, which means more wasted power. And if there is too much of this friction in any one place, it means that the part will get very hot. And this may result in swelling up and sticking and all sorts of damage.

So we have to do the same things that are done in almost every moving mechanism. We have to use bearings to cut down the friction of all rotating shafts, and we have to furnish lubrication to these bearings and to the gears.

A little oil makes all the difference in the world in the amount of friction. A thin film of oil—no matter how thin—permits two metal surfaces of the right kind to rub against each other for very long periods with little wear and no damage. There are various ways used to get this lubricant to the right place. Sometimes a pump forces oil under pressure to the points needing it; it circulates all the time the mechanism is running. Many parts are oiled by the mist and spray splashed up by gears churning up the oil in the bottom of the case. Other points are packed permanently with grease, or have means to force grease into them every so often.

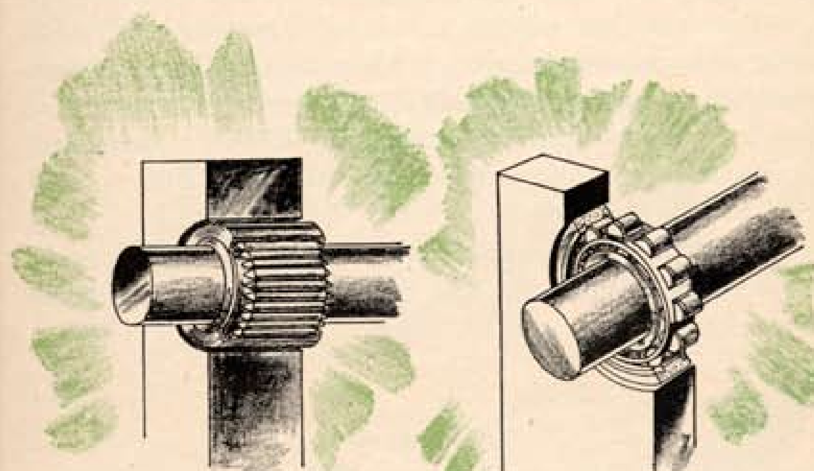
Plain bearings are used in many places—that is, bearings in which a metal shaft runs inside a metal ring of special bearing material. But in transmission systems we

use a number of anti-friction bearings. These are ball bearings, roller bearings, and needle bearings. They have let us do things which without them would have been difficult and complicated, if not impossible. They have had a lot to do with the high speeds at which shafts and gears now run.



Ball bearing.

In all our discussion and figures so far in this book we have not taken friction into account at all. All our mechanisms were perfect machines, with no losses due to friction. And we are going to continue to do that to a large extent in the rest of the book. Friction is a variable factor and hard to pin down. Bearings and lubrication are a very important subject, but too large a subject to cover here. So in most of the examples we show, we will just assume that the mechanism has proper bearings and is well lubricated in some way or other.



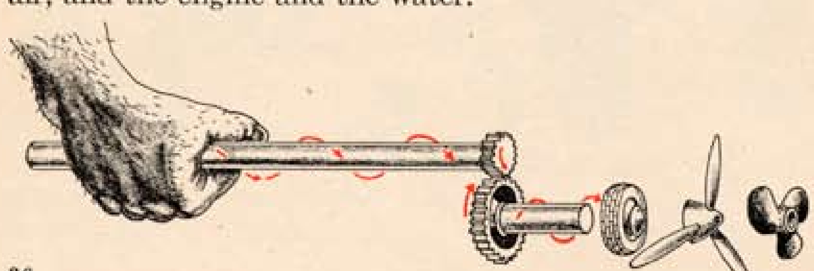
Needle bearing. *Roller bearing.*

So far we have given just a general picture of the field of power transmission in vehicles using internal combustion engines, and have tried to point out the why's and where-fore's of some of the arrangements. Essentially the problem is that we need a force to move the vehicle and we have an engine which must furnish that force. But the complication comes in because these are not always equal. The engine does not always furnish the right amount of torque at the right speed. So we must put something in between which can take the torque and speed of the engine and change them so they will come as close as possible to what the wheels or propeller need at that moment.

We compromise very often. Usually we don't try to make it too exact under all conditions because the mechanism becomes too complicated and expensive. And luckily the internal combustion engine is flexible enough to cover a wide range of conditions.

From now on we are going to show some of these power transmission systems in more detail. They are classified as **automobile, aircraft,** and **marine.** It will not be complete because there are too many different types and because changes come quickly in this field. But we will try to hit the high spots.

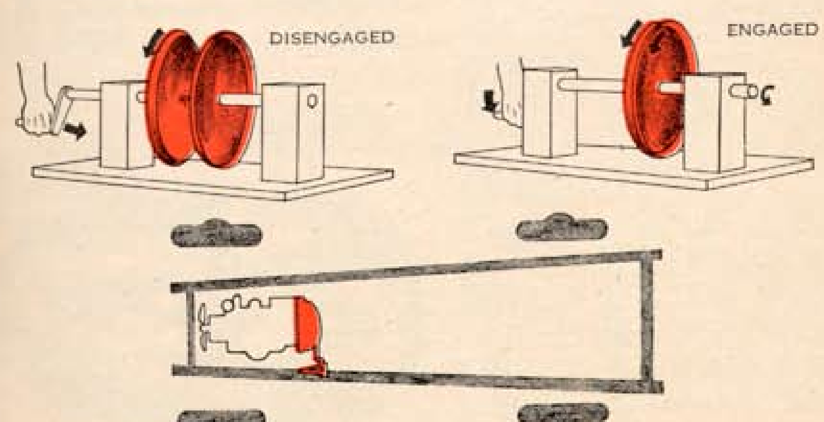
We will try to show the main points of what goes on between the engine and the ground, the engine and the air, and the engine and the water.

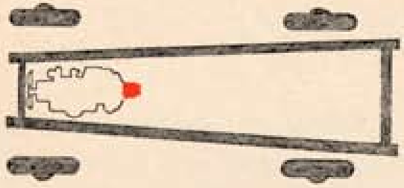


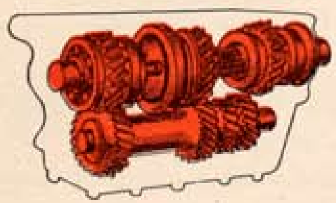
AUTOMOBILE

In an automobile there are a lot of things between the engine and the rear wheels. Some kinds of cars have more, others have less. Some have one thing, others have something else. They all have more than the simplified system we showed in the early part of this book. As we said, that might be all right for driving straight ahead on a level road, but there would be a lot of places where it would not be all right. So we will start out here with a complete power transmission system of a typical automobile. We will explain briefly what each part does, without much attention to how it does it, and we may take liberties with what it looks like. Later on we will take up the more important parts individually and go into greater detail.

Starting from the engine, the first thing we come to is the **clutch.** Its job is to disconnect the engine from the power transmission system when the driver so desires. When it is disengaged, the driving and driven plates are separated, and what the engine does has no effect on the rest of the drive system and what the wheels are doing has no effect on the engine. There are several reasons we want to be able to do that at certain times and under certain conditions.

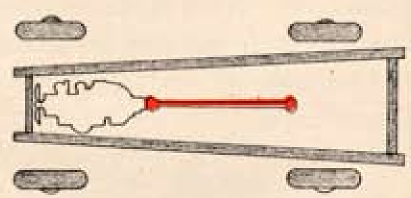




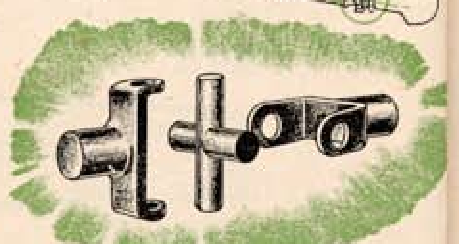


Next is the **transmission.** The reason for calling it this is not too clear. "Torque converter" or the English expression "gear set" gives us a better idea of what it is and what it does. But everyone still calls it "transmission." Its purpose is to let us change the ratio between the engine and the rear wheels. When the car is starting we can run the engine fast and drive the wheels slowly, increasing the torque or driving force at the same time. When we are going faster we can change the ratio, so that the wheels are turning at more nearly the same speed as the engine. Finally, in direct drive, the shaft behind the transmission is connected directly to the shaft from the clutch, and it is just as if the transmission were not there at all. There is also a reverse gear in the transmission, so that we can make the car go backward, and a neutral position, in which no movement or power is transmitted.

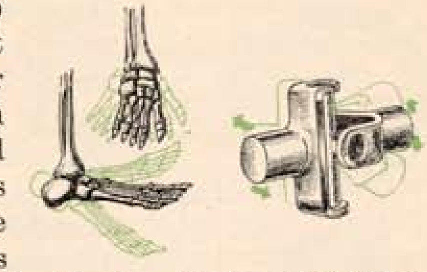
A large part of the rest of this book will be about the transmission and the various forms it takes. So we will save the rest for later.



From the transmission, the **propeller shaft** runs back to the rear of the car. This is a hollow or solid steel shaft, sometimes enclosed in an outer tube, sometimes left open. At the front end is a **universal joint**, and in many cars there is another universal joint at the rear end of the shaft.

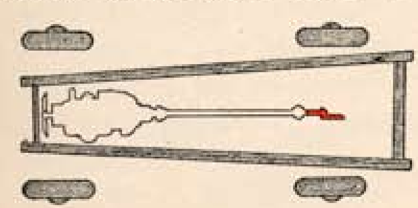


These are usually made up of two U-shaped pieces at right angles to each other and fastened together by a cross having arms of equal length. The U-shaped yokes can pivot on the arms of the cross, and inasmuch as there are two of these pivots, the two shafts can be at an angle to one another and can still turn around and transmit power. They do not have to be in a straight line. This is very important, because even if we could design the car to have them in a straight line to begin with, every time we went over a bump they would get out of line. The rear axle moves with the wheels, up and down with every bump, while the transmission does not move so much, being fastened to the frame. So the universal joint lets the propeller shaft keep on turning even though its two ends are moving around relative to each other.

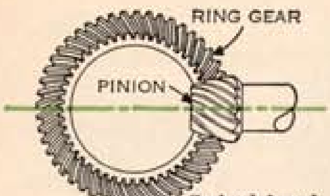


At the rear end of the propeller shaft is fastened a short shaft carrying a gear on the end. This is a bevel gear and is called the **pinion.** It meshes with the **ring gear** which is mounted on the rear axle. Thus as the propeller shaft turns, the pinion drives the ring gear around which turns the rear axle and the wheels. This pinion and ring gear combination is often called the **final drive.**

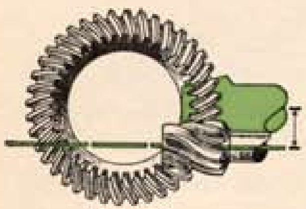
For many years these rear axle gears were of the spiral bevel type. But now most cars use what are called **hypoid** gears. They are about the same as spiral bevel gears, except that the pinion does not meet the ring gear at its center line. It meets it at a lower point, which means that the shape of the teeth must be different. This allows us to lower the whole propeller shaft, which in turn lets us make the whole car lower.



It is easy to see that the pinion is much smaller than the ring gear so we know



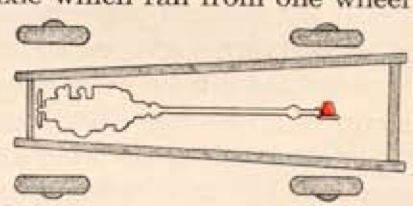
Spiral bevel.



Hypoid.

immediately that there is a speed reduction here, and an increase in torque. In most passenger cars, this ratio is somewhere around 4 to 1. The axles and wheels are turning only about a quarter as fast as the propeller shaft. It should be noted that this speed reduction and torque increase are always there and always stay the same. Even when we say we are in direct drive we are referring only to the transmission, and this rear axle ratio is still effective. And if the transmission is in low gear, say a ratio of 3 to 1, the overall ratio between the engine and rear wheels will be 3 x 4, or 12 to 1.

In the simplified automobile drive system which we showed in the first part of this book, the ring gear was fastened directly to a solid axle which ran from one wheel to the other. This would be all right for going straight. But when the car turns a corner, we have a problem. The wheel on the outside of the turn must travel farther than the inside wheel.

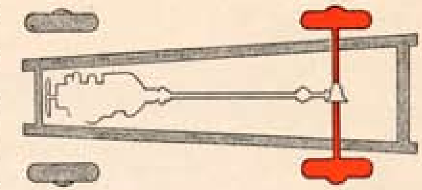


It is like a horse race. The jockeys all try to get the inside position on the curves because the inside horse does not have to run as far as those on the outside. In an automobile we use a **differential** to take care of this. It allows one wheel to travel faster than the other, even though they are both driving.

The inside is shorter.

Instead of fastening the ring gear to the axle, it is bolted to the differential case. There is a separate axle shaft for each wheel, which runs from the wheel

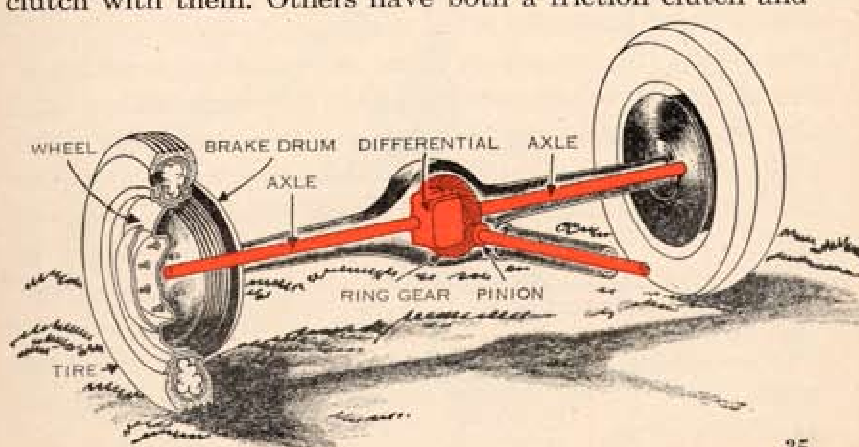
into the differential. Thus as the ring gear turns, the differential case turns around with it and the differential gears inside drive the two axles. If the car is going straight ahead the two axles revolve at the same speed; if the car turns, the differential adjusts the speeds accordingly. Just how it does it, we will see later.

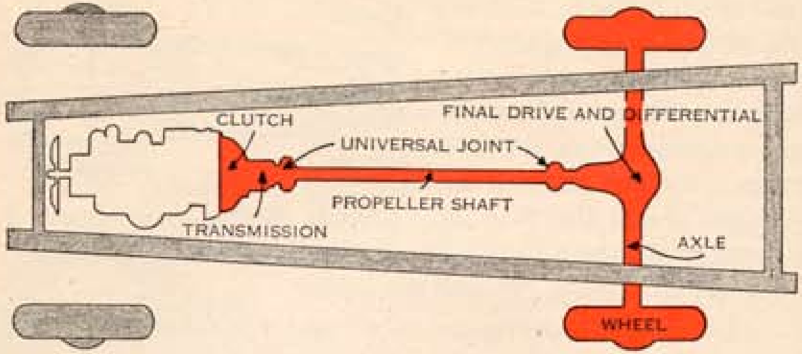


The axles are comparatively slender steel shafts. They have a flange at the outer end to which the wheel and brake drum are bolted. Around the axle is the axle housing. This holds the parts of the brake which do not turn with the wheel, and also supports the bearing in which the outer end of the axle shaft runs.

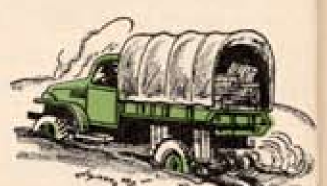
The **wheel** itself is probably familiar to everyone, as it is in plain sight on the outside of the car. It is essentially a metal disc with a rim around the outside which the tire fits into. A rubber tube inside the tire holds air under pressure. It is the outside surface of this tire which pushes on the ground and really makes the car move. But the engine furnishes this force, and all the other things we have just mentioned have a certain part of the job to do in getting that force from one place to the other.

We said this was for a typical automobile. But they are not all like this. Some transmissions do not need a friction clutch with them. Others have both a friction clutch and

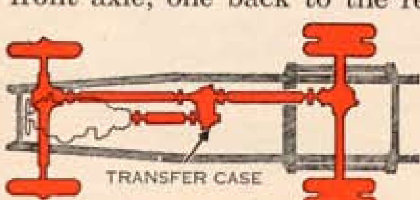




hydraulic coupling or "fluid flywheel." In some trucks and busses we find quite a variety of additional features. We cannot try to show them all, but we will mention two arrangements used on special purpose trucks. These are for use in rough going where more than the usual traction is needed, where two wheels might get in a mud hole and not be able to pull out of it. So instead of having the engine drive just two wheels, it drives four wheels or six wheels. A four wheel vehicle driving on all four wheels is known as a 4x4, and one with six wheels, all driving, is a 6x6. A 4x6 is a six wheel truck with four driving wheels.

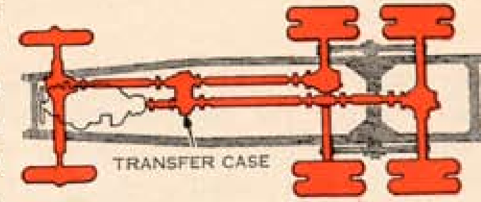


To get such a drive we use a transfer case. In back of the regular transmission is another set of gears. Essentially this consists of three gears meshing together in series, extending out to one side of the transmission. The first and third gears are the same size. From each side of the third gear a propeller shaft extends, one forward to the front axle, one back to the rear axle. Each axle is driven just as we have shown in the two wheel drive, except that in the front axle we must have some universal joints in order to steer.



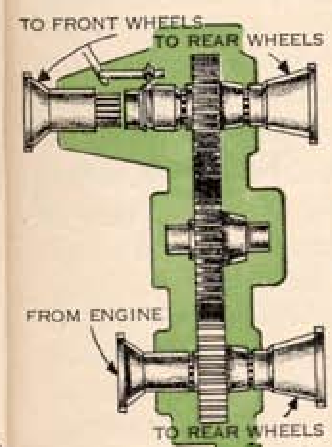
Four-wheel drive—(4 x 4).

For a six-wheel drive a third propeller shaft extends straight back from the first gear in the transfer case; that is, in line with the regular transmission. Thus we have one input shaft into the transfer case and three output shafts.



Six-wheel drive—(6 x 6).

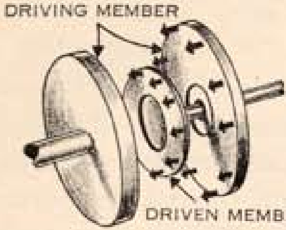
With the first and third gears the same size we have no change of speed or torque in the transfer case. Usually, however, there is another pair of gears in it which can be shifted to give us a different ratio. A two speed transfer case doubles the number of gear ratios available in the regular transmission.



That covers the high points of an automotive power transmission system. Now we will start over again with the clutch and go into a little more detail about some of these units.

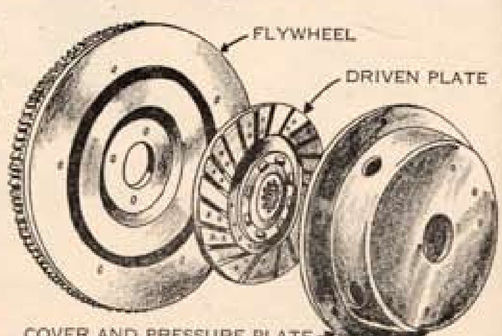
Clutch

It is sometimes said that a good clutch *must slip* while being engaged and *must not slip* when it is engaged. This is almost a definition of a clutch. It is easy to see why when we consider what a clutch is for and what we want it to do.

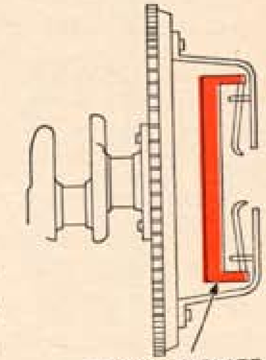


First, we need something to disconnect the engine from the wheels, so that the engine can run while the car is standing still. Otherwise we would have to stop the engine every time we came to a traffic light. And it would be a problem to start the engine while it was connected to the drive system. Also, with most transmissions, we have to disconnect it from the engine in order to shift gears easily.

There are various ways in which we could take care of these things, but we need something else. We need something which will take hold *gradually*, which will not jump abruptly from no connection at all to a direct, solid connection. When we want to start a car, we have to speed the engine up in order to get enough power to move it. At the same time the wheels are standing still. We cannot, in one moment, bring the speed of the wheels up to the speed of the engine; there would be a terrible jerk. And when we shift gears after the car is moving, we have almost the same situation—the wheels and propeller shaft are not turning at the same speed as the engine. So we want something which will slip a little, which will take hold gently at first and gradually grab harder and harder. Thus the rear wheels can start to move slowly and gradually pick up speed, until finally everything is turning at

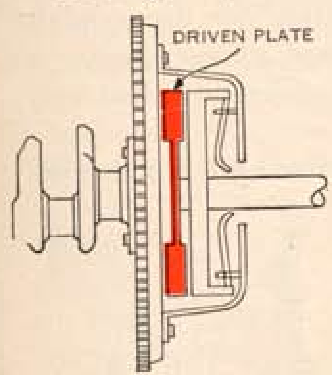


the same rate and the clutch is solidly engaged. From then on, of course, we do not want any slipping, because that is just wasting power and heating things up.

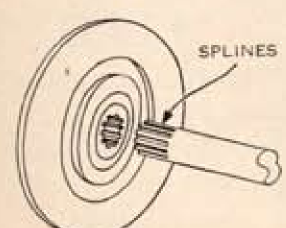


The kind of clutch we are talking about depends on friction for transmitting power. In fact, its full name is "friction clutch," as there are other types of devices commonly called clutches. In most automobile use it consists of one plate squeezed tightly between two other plates. The one in the middle is the **driven member**; it is connected to the shaft leading back into the transmission. The other two are the **driving members**; they are connected directly to the engine. A strong spring, or springs, forces the two driving members together. This tightens their grip on the middle plate until they are all turning together as one unit.

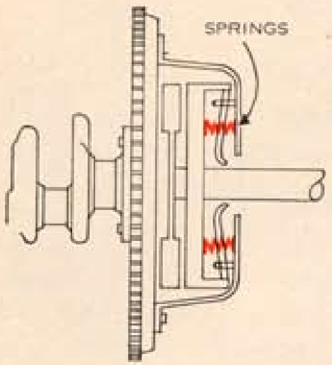
The engine flywheel is used for the first driving member. Its surface is made very smooth where the driven plate pushes up against it.



The other driving member is called the **pressure plate.** It is a fairly heavy ring of cast iron, smooth on one side. It is fastened to the cover, which is bolted to the flywheel, so they all turn together. It is fastened in such a way that it can slide back and forth.



The **driven plate** is a flat disc of steel with friction facing fastened on each side. The plate is fastened by **splines** to a shaft going to the transmission. This means it fits

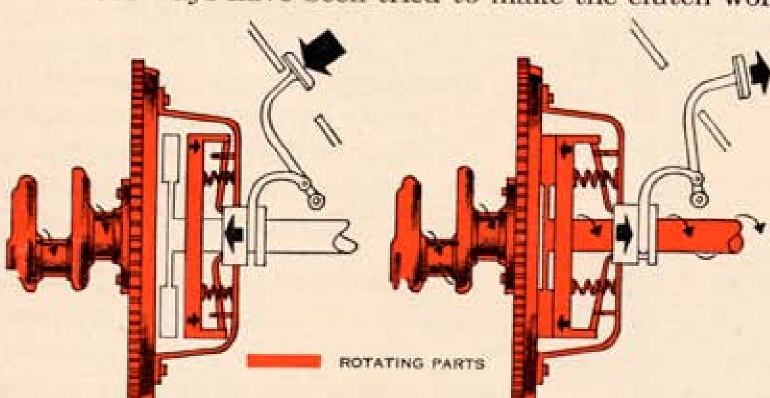


into grooves on the shaft so that they must turn together but the plate can slide forward and backward on the shaft.

A series of coil springs, or sometimes one large flat spring, act between the clutch cover and the pressure plate. They push the pressure plate toward the flywheel, squeezing the driven plate between the two. The springs are always trying to engage the clutch, and they are strong enough to keep it from slipping under any ordinary conditions. To disengage the clutch, the driver pushes on the pedal. This works through levers to pull back the pressure plate against the force of the springs. This lets the driven plate loose and disconnects the transmission shaft from the engine crankshaft.

There have been many different designs of clutches in the past, and the present ones do not all look just like what we have shown. Sometimes more than one driven plate is used, with a corresponding increase in the number of driving plates. And there are other differences. But they all work on the same principle.

Various ways have been tried to make the clutch work

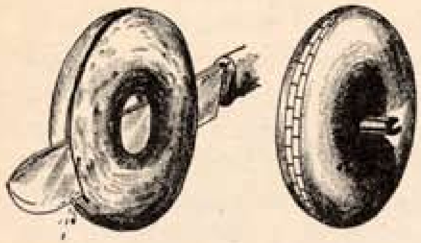


Pedal down, clutch disengaged *Pedal up, clutch engaged.*

automatically, that is to engage and disengage without effort on the part of the driver. Sometimes vacuum power is used to operate the linkage of a standard clutch. Sometimes the clutch itself is changed to operate centrifugally. We won't go into the details of it. The principle remains the same, but centrifugal weights are arranged to engage the clutch when the engine gets up to a certain speed and disengage it when it drops below a certain speed.

There is another more common type of clutch which is really a centrifugal clutch. This is the **hydraulic coupling**, or as it is more often called, the **fluid flywheel**. Sometimes this replaces the friction clutch entirely, taking its place between the engine and transmission. In other arrangements we have both—first the fluid flywheel behind the engine, then the friction clutch, then the transmission. The fluid flywheel does not do everything the friction clutch can do, and it does some things the friction clutch cannot do. But it is a centrifugal clutch in this way—if we run the engine slowly, it will not start the rear wheels turning; when we speed up the engine, it gradually takes hold until finally the engine is driving the rear wheels with practically no slip.

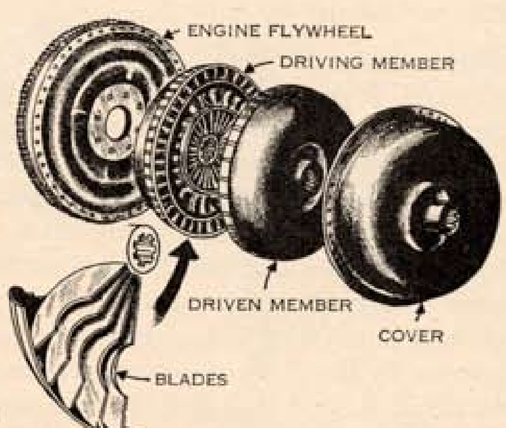
How does it work? Suppose we start with a simple example. If we shoot steel balls at the blades of this paddle wheel, each ball will give the wheel a little push, will try to turn it around. If we can shoot them fast enough and hard enough, the wheel will keep spinning. Now if we think of water or oil as being made up of a lot of small liquid balls, we can shoot these at the wheel and get the same results. You have probably seen water wheels which worked much like this, driven by the water falling over a dam or by the flow of a swift stream. That is about what we do in a fluid flywheel. But in an automobile we have

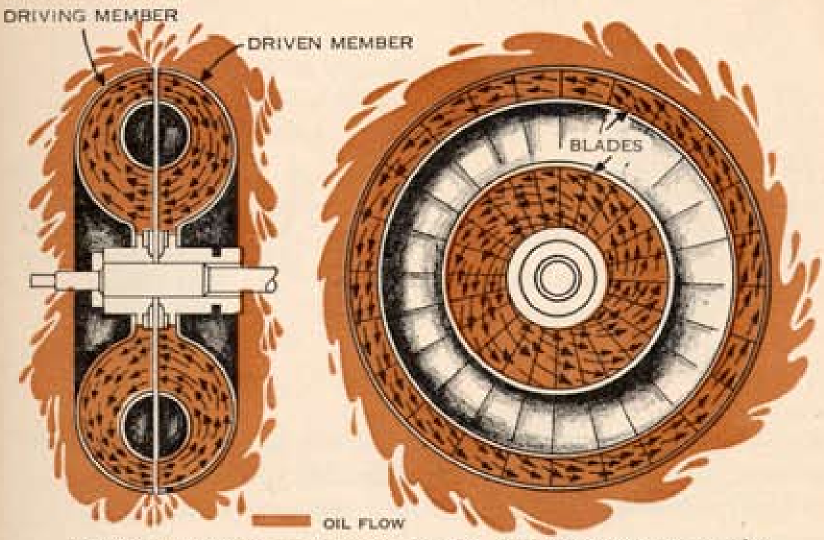


to make an artificial stream. What it amounts to is a pump forcing oil against a turbine or hydraulic motor. Many years ago it was found that the most efficient way to do this was to get the pump and motor close together, to more or less combine them. The result was a hydraulic coupling essentially the same as the fluid flywheel we use today.

The working parts of a fluid flywheel look very much like a doughnut. But the doughnut is sliced down the middle, so there is no connection between the two halves. One half is fastened to the engine crankshaft; the other to the clutch, or transmission, or some part eventually leading to the rear wheels. The doughnut is hollow, but each half has a number of straight radial blades leading from the hub to the outside edge. Very often a section of each blade is cut away, and in that space is put a metal plate or guide ring shaped like half of another, smaller doughnut. The two halves of the fluid flywheel are just alike, and when we put them together we have what looks like a skinny doughnut inside a fat one, with thin blades connecting the two.

To make this complete we put a cover around it all, the cover often being fastened solidly to one of the rotating members. Then we fill it almost full of oil. Now if the engine is running, the first half of the fluid flywheel, the **driving member,** is turning with it. If it is turning fairly fast, the oil is being thrown toward the outside of the doughnut by centrifugal force, just



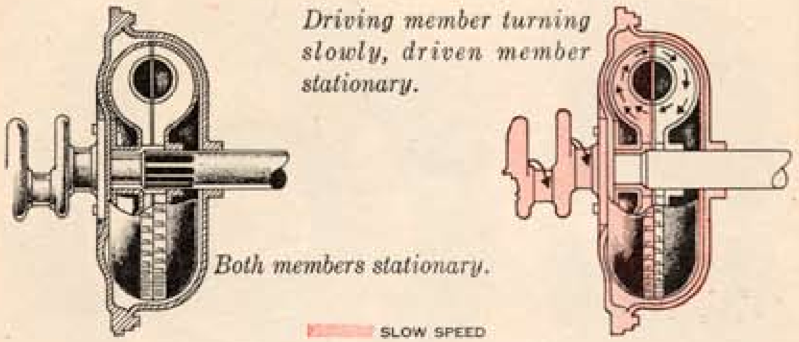


Oil flows outward in driving member, inward in driven member, and is also forced in other direction by blades of driving member.

like marbles on a phonograph turn-table. When it gets to the outside it wants to keep on going, and the only place it can go is across into the other half of the doughnut, the **driven member.**

All this time that the oil is being forced outward, it is also being whirled around in the other direction by the blades of the driving member. Consequently, when it crosses over into the driven member, it hits against those blades just as in the water wheel we mentioned and pushes them around. This tends to slow up the drops of oil, and they travel toward the hub, or center, of the driven member, then across to the driving member and repeat the whole process. Thus we have the oil continually circulating, outward in the driving member, inward in the driven member. And at the same time it is traveling in a direction at right angles to this, being pushed by the blades of the driving member and pushing on the blades of the driven member.

The driven member can never go quite



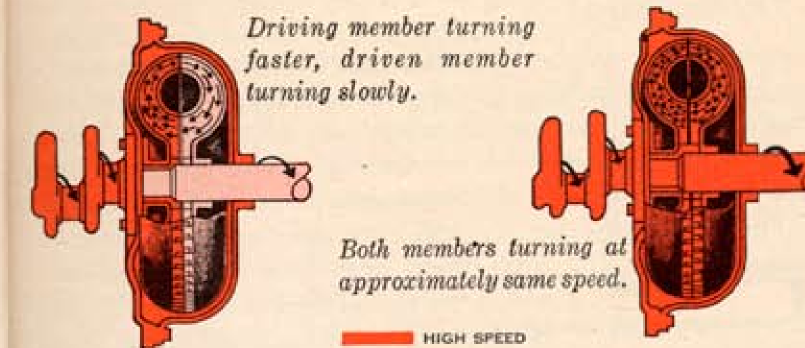
Both members stationary.

Driving member turning slowly, driven member stationary.

as fast as the driving member. There is always a certain amount of slip no matter how fast they are turning. But at ordinary driving speeds this may amount to less than one percent so it is not serious. When we get below a certain speed, however, this slip begins to get greater. Finally it gets down to the point where the driven member does not turn at all. There is still some torque being applied to it, but it is not enough to make the rear wheels turn and move the car. This means that we can stand at a traffic signal with the transmission in gear and the car will stand still just as if a friction clutch were disengaged. Then as we speed up the engine, the driven member begins to turn, gradually picks up speed and finally is running at approximately the same speed as the engine.

We mentioned that the driving member and driven member were just alike. There may be slight differences in them, but they are enough alike that a fluid flywheel can drive in one direction as well as the other. The oil just circulates in the opposite direction, from what was the driven member to the driving member. Thus if the car is coasting or being pushed, the wheels drive the engine just about the same as if there were a solid connection there.

The use of a fluid flywheel gives smoother pick-up and makes it impossible to stall the engine when starting or climbing a hill. It also smooths out jerks, especially at low speeds, and in some ways acts as a centrifugal clutch. As we will see later, those characteristics let us use certain types of transmissions and shift gears in certain ways

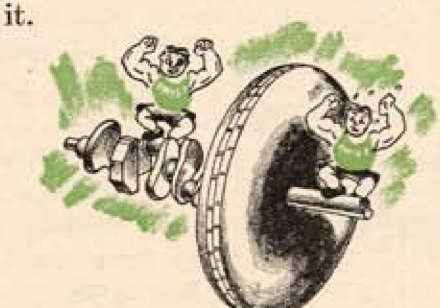


Driving member turning faster, driven member turning slowly.

Both members turning at approximately same speed.

which would not be satisfactory without a fluid flywheel. But we must remember that this is just a clutch. It is not a transmission. It cannot replace the transmission because it does not increase the torque—it only transmits the torque which the engine delivers to it. We will see later on in this book some mechanisms which look very much like it and which do multiply torque. But they are different. We will point out just how they are different when we get there.

We have described the first items in back of the engine in the power train. The next major unit is the transmission, but we are going to skip that for the time being. The subject of transmissions includes several different varieties which we must consider separately to a certain extent, so we will leave them for the last. Now we will go back to the rear axle and try to show what a differential does and how it does it.

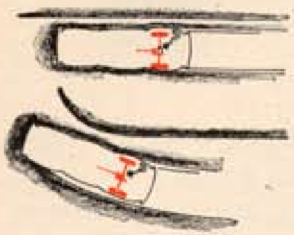


A fluid flywheel does not increase the torque.

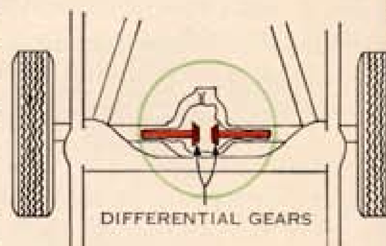
Differential

When we look at the rear axle drive system of an automobile, the pinion and ring gear and various parts of the differential seem to be all mixed up together, just one mechanism. But when we consider what they do, we find there are two entirely different jobs being taken care of.

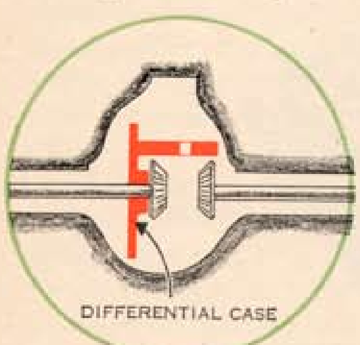
The job of the pinion and ring gear combination, or final drive, is to take the torque provided by the propeller shaft, increase it about four times, and turn it at right angles so it can twist the wheels and drive the car.



The differential is meant for just one thing. That is to let the wheels run at different speeds while still driving the car. It transmits equal torque to both wheels even when one is going faster than the other. If it was not necessary to have this difference in speed, we would throw away the differential and have a much simpler rear axle and drive system. Some cars have been built without one, but it is very hard on the tires; they have to slip or skid on the road whenever a corner is turned.

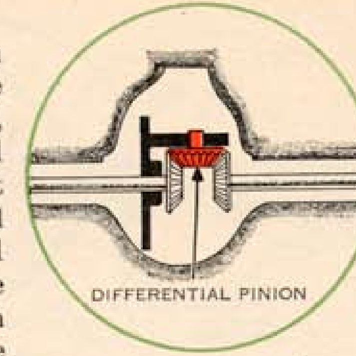


A differential is one of those mechanisms whose action is easy to see when it is working right in front of you, but it is not so easy to describe. We will build it up piece by piece, however, and try to show how simple it really is.

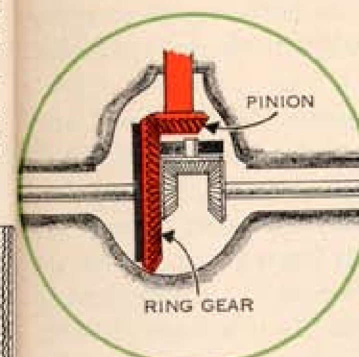


First we have the two axles, each with a wheel on one end and a gear on the other end. These are small spur bevel gears, and are called **differential gears** or **side gears**. Then we add what is called the **differential case**, but

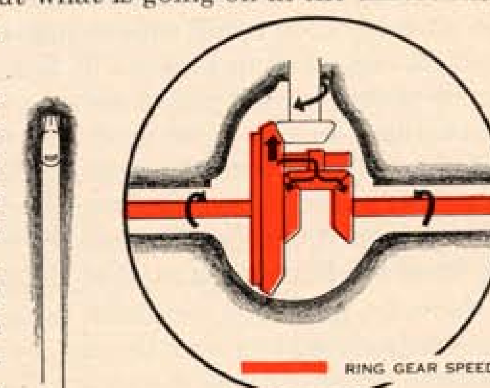
which we will show as just a crooked bar fastened around one of the axles. It is loose on the axle, however, so it can turn around on it. In this case we mount another gear, the **differential pinion.** This is a small bevel gear which fits in between the two side gears and meshes with both of them. There we have all the necessary parts for a differential—just three gears and a case.



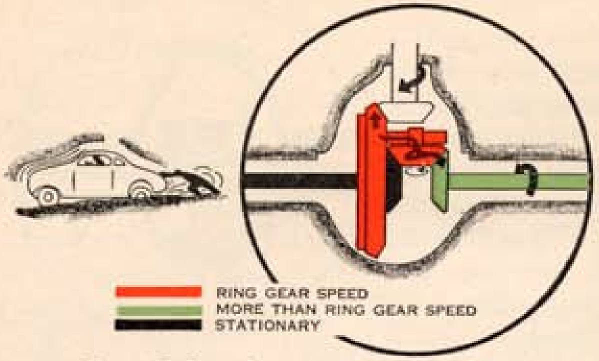
We will add one more part, however, just to make it easier to tell the story. That is the ring gear. It is fastened solidly to the differential case. Thus the case is going around all the time, at the same speed as the ring gear. This should be noted carefully, as we are likely to think of a "case" as something stationary, just an enclosure for the working parts. But here what it is is the driving member of the differential. As long as the ring gear is revolving it goes around too, at the same speed. It carries the differential pinion around with it, but otherwise it knows nothing about what is going on in the differential. It just keeps going around.



Now suppose we are going straight ahead on a smooth road. The wheels should be turning at the same speed. Engine power is driving the ring gear, so the differential case is going around, carrying



Straight ahead—everything turns together.



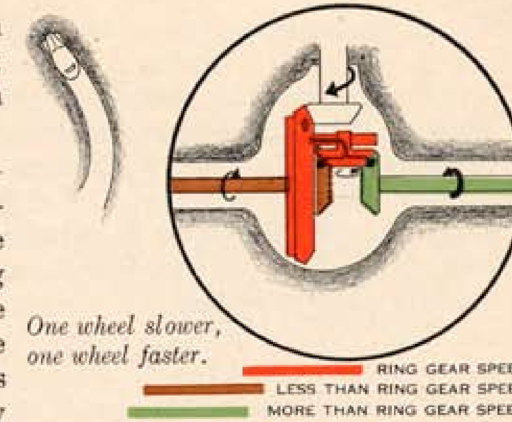
One wheel stationary—other turns faster.

the pinion with it. This turns the two side gears, and the whole mechanism revolves as one solid unit. The gears are not turning on one another. The pinion is simply connecting the two side gears together; they could just as well be bolted together solidly. They are turning at the same speed as the differential case. It is the same as if we had no differential at all, because our wheels are traveling together and we do not need one.

Now let us take the other extreme. We will hold one wheel so it cannot turn. What happens in the differential? The case is turned as before, again carrying the pinion with it. But one axle is held, so its side gear cannot go around. Therefore, the pinion must turn. The pinion is being carried around by the case, but at the same time is revolving around its own short shaft. It must in order to stay meshed with the stationary side gear. It is running around the stationary gear.

But what is happening to the other side gear while this is going on? It is meshed with the pinion too, but it is free to turn. It is being turned just the same as it was in the first case, but *in addition* it is being turned more by the revolving of the pinion on its own shaft. The pinion is revolving in the right direction so that its motion is added to the movement of the differential case. So the second side gear is turning faster than before. In fact this axle and wheel are turning exactly twice as fast as when the two wheels were running at the same speed.

Now let us take a situation in between these two extremes. Both wheels are turning, but one is going faster than the other. This is the case we ordinarily have in an automobile turning a corner. The inside wheel travels a



One wheel slower, one wheel faster.

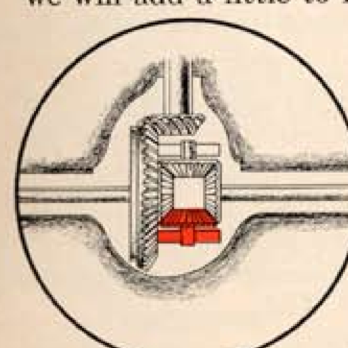
shorter distance than the outside wheel; therefore it must turn around more slowly.

The inside wheel—and thus the differential gear on its axle shaft — is revolving more slowly than the differential case. The differential gear is turning more slowly than the pinion is being carried around. So we have the same general effect as when it was held tight—the pinion must turn on its own shaft. It will not turn as fast as before but it will turn. And it again turns in a direction to add to the speed of the opposite differential gear. It adds to it exactly the amount taken away from the slower gear and wheel.

For example, suppose the differential case is being driven at 500 revolutions per minute. Then if the inside wheel is turning 400 RPM, the outer one must be turning 600 RPM. If one is turning 490 RPM, the other is 510 RPM. And in the extreme case we had, if one is standing still, which is 0 RPM, the other turns 1000 RPM. That is the way a differential must work—what is subtracted from one side must be added to the other. The ring gear speed always splits the difference between the two.

To make our mechanism look more like the real thing, we will add a little to it. This does not change its operation in any way however. We will complete the case, and add another pinion to the bottom. This pinion simply does exactly the same thing as the first one, and helps it do the job we have just described.

The differential is a very necessary thing. It acts as a sort of balance between the rear wheels.



Now our differential is complete.

But it can be a nuisance at times. This is usually when we have a situation giving us the result we mentioned earlier—one wheel standing still, the other going twice as fast as usual. It is easy to do this. All we have to do is stop the car so one rear wheel is on dry pavement or road, and the other is on a slick patch of ice. The differential will drive the wheel which is the easier to turn. So the wheel on the ice will just spin, the other one will stand still, and—which is usually more important—the car will stand still. We get the same effect when one wheel is stuck in deep sand or mud, and the other one is comparatively free to turn. To avoid this trouble, various kinds of differentials have been designed which will permit some difference in speed between the two wheels, but will not let one spin while the other stands still. Most of these are rather complicated and expensive, however.

We have described to some extent all the main parts of the power path except the transmission. Now it is time for that.

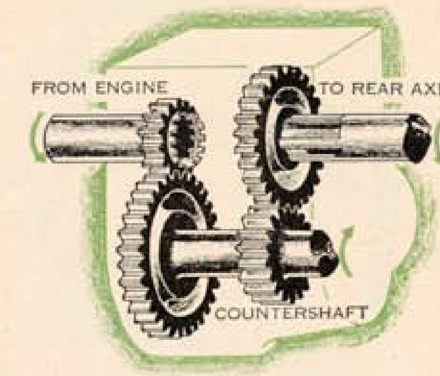
Transmission

The transmission is a box full of gears. It is located behind the clutch, and its case is usually fastened to the clutch housing, so the whole thing looks like an extension of the engine. The purpose of the transmission we have mentioned before—it is to let us vary the speed and torque of the rear axle in relation to the speed and torque of the engine.

For some years most passenger cars in this country have had three ratios or "speeds" in the transmission for forward driving. There have been several with four ratios, and some special transmissions which were different in many respects. We will leave all that until later however; and what we say here applies to the simple, three-speed, conventional transmission.

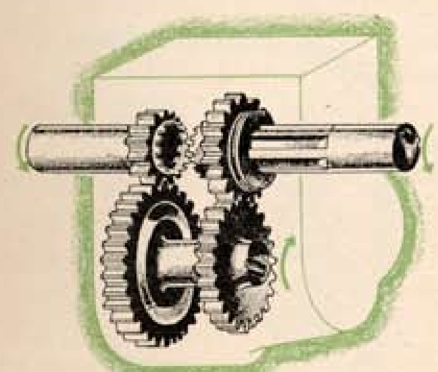
First speed, or low gear, is used for starting and for

steep hills or heavy going in sand or mud. It lets the engine run fast while the car runs slowly. The engine runs 2½ to 3 times as fast as the propeller shaft. The exact figure varies in different cars. This means, of course, that the torque of the propeller shaft is increased just as much as its speed is cut down. Thus we have a lot of twist on the rear wheels to get the car started from a stand-still, or for use any other time we need it.

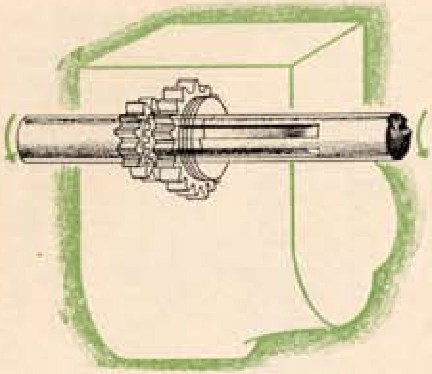


First or low gear.

This is done with four gears and three shafts. A small gear on the shaft from the clutch drives a larger gear fastened to the transmission **countershaft.** Another smaller gear fastened on the counter shaft drives a large gear on the third shaft. This last shaft goes to a universal joint on the front end of the propeller shaft. Thus we have the same arrangement we showed earlier. There is a certain speed reduction in the first two gears, and then some more reduction in the second set of two gears. The countershaft is running at a speed in between the speeds of the other two shafts. And the third shaft is of course running most slowly and with the greatest torque.


Second, or intermediate gear.

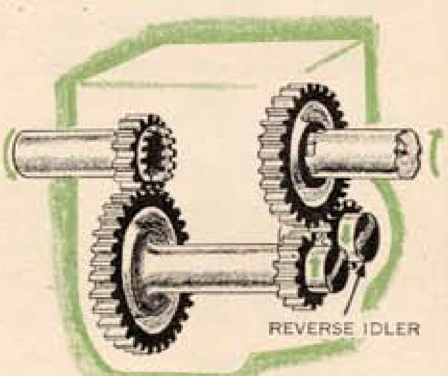
Second, or intermediate gear, works in about the same way. The first two gears are the same as we used in low gear. The next pair are different however. They are almost the same size, and sometimes the countershaft gear may be the larger. Thus the countershaft runs at the same


Third, or high gear.

speed as before, but there is little if any additional reduction from that to the third shaft. So the wheels will run faster for the same engine speed than they did in low gear. The usual ratio in second speed is around $1\frac{2}{3}$ to 1. This means that the propeller shaft will run at 1000 RPM when the engine is running 1670 RPM.

Third, or high speed, is direct drive. The transmission does not do anything. We simply connect the first and third shafts together, and they turn as one. The propeller shaft turns the same speed as the engine, and delivers engine torque. Sticking to figures, we would say the ratio is 1 to 1.

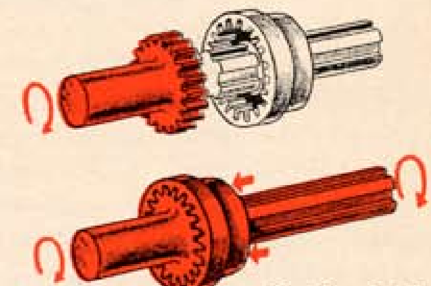
Besides the three forward speeds, there are two other combinations we can get in a transmission. There is **neutral**, in which the transmission shaft is entirely disconnected from the clutch shaft, and the engine cannot drive the propeller shaft or anything beyond the transmission. It has about the same effect as disengaging the clutch. And there is **reverse.** It is a complicated matter to make an internal combustion engine run backwards, so we run it in one direction all the time and use gears to reverse the direction of rotation. We put an extra gear in between the countershaft and the final drive shaft. It is called the **reverse idler.** We drive the countershaft in the same way as before, it drives this reverse idler which in turn



Reverse gear.

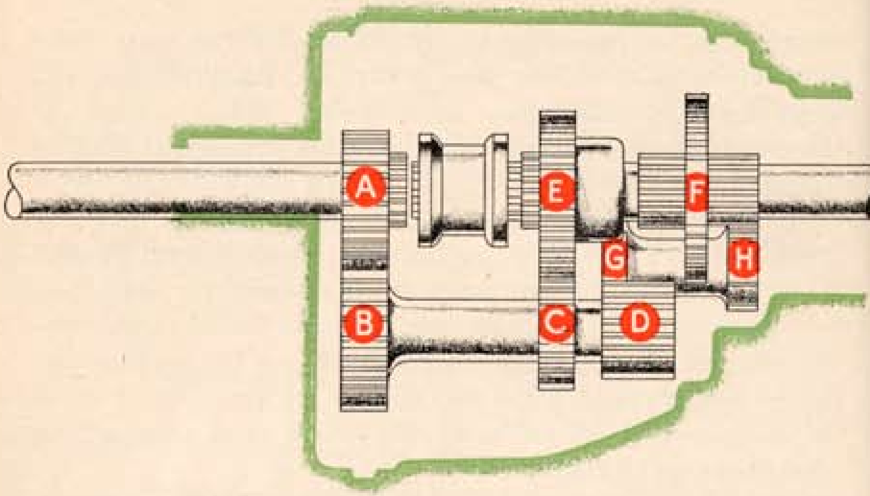
drives the low speed gear on the final drive shaft. The system is just like low gear which we described first except for this extra gear in between. This changes the direction of rotation, and we can see that the final shaft is turning opposite to what it was in all the previous cases. The ratio of reverse is about the same as low gear, or even lower. This is logical, because we may want to pull hard in reverse but we never want to back up very fast.

We have shown all the combinations found in an ordinary, three-speed transmission. These can be put together in various ways to make a complete transmission, but we cannot show them all here. They first used to slide the gears back and forth on the shafts to get them into mesh and out of mesh. This can be done by using a square shaft or a splined, or grooved, shaft. In this way a gear is fastened solidly to its shaft as far as revolving is concerned, but it can slide along it.


Positive clutch.

Now we commonly use the so-called **constant mesh** transmission. Some of the gears still slide, but some are constantly in mesh with each other and rotate all the time. But these gears do not necessarily drive the shaft. They are free to rotate on it until they are connected to it by a clutch. We should explain that this is not a friction clutch. It is a **positive clutch**—more like a gear—having teeth that fit into similar teeth on the gear. It is called a clutch because its only job is to connect or disconnect the gear and the shaft.

Let us look at a complete constant-mesh transmission, and note briefly what gears and shafts there are. There is the clutch shaft with gear A fastened solidly to it. There is the countershaft with all three gears, B, C, and D, fastened solidly to it. A and B are constant-mesh gears, so whenever the engine is running and the clutch engaged,

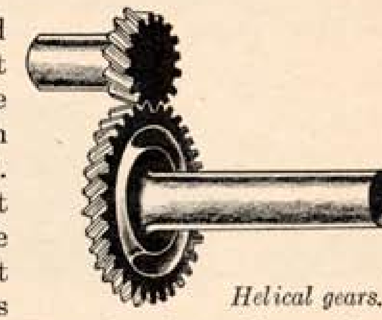


Constant mesh transmission in neutral.

the countershaft and its three gears are turning. Then there is the transmission main shaft, with the two gears E and F. E is in constant-mesh with C, but is free to rotate on its own shaft except when connected to it by a clutch arrangement. F is splined to the main shaft, so it turns with it but can slide back and forth. Finally we have the reverse idler, which is now a short shaft with the *two* gears G and H solidly fastened to it. G is always in mesh with D.

This may look rather complicated, but there is not really a great deal to it. And with this arrangement it is very simple to get any speed or gear we want. We can see that even in neutral the countershaft gears, gear E, and the reverse idler gears are all revolving. But the main shaft is standing still. Now suppose we slide gear F along the shaft. If we slide it in one direction it meshes with D and we have low gear. If we slide it the other way it meshes with H and we have reverse. We are using two gears on the reverse idler now, but as they are both fastened solidly on the same shaft and rotate in the same direction, the principle has not changed from that in our first example.

The path the power takes through the transmission in the various speeds is shown more clearly on page 56.



Helical gears.

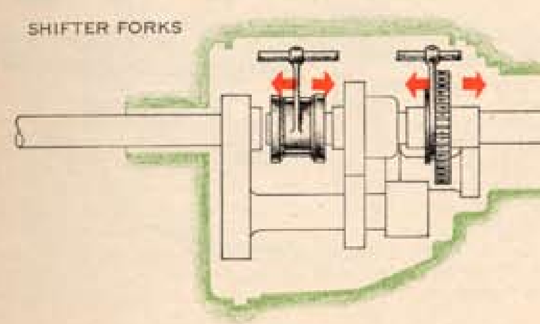
The other speeds we need are second and high. We get these by means of a positive clutch arrangement which slides between gears A and E. When it slides to the right it connects E to its shaft and we have second speed. When it slides to the left it connects the main shaft to the clutch shaft and we have direct drive straight through.

We should mention one thing here. In passenger cars the common practice is to use all helical gears in the transmission. Most trucks use spur gears, and we have shown them here for convenience. The helical gears are quieter and are preferred for that reason, but this does not affect the principle of operation in any way.

How do we shift these gears and clutches to get the different speeds? We have seen that we only have to move two things—the low speed gear and the double clutch. These both have grooves in them into which **shifting forks** fit loosely. The forks do not interfere with these parts turning around, but they can be used to slide them endwise.

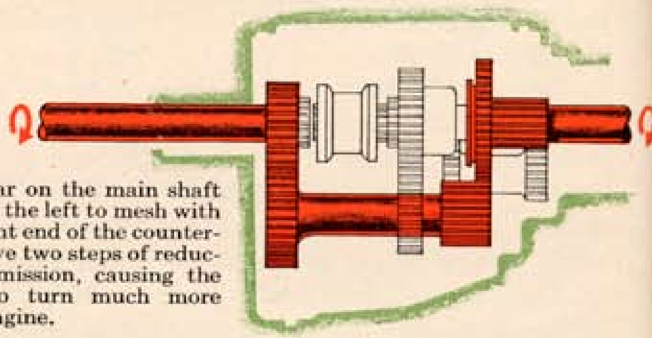
Then we connect the forks to the gearshift lever in the driver's compartment in such a way that he can select either one and move it in either direction. Thus with the one lever he can take his choice of any one of the four positions of the gears—five, counting neutral.

We have to disengage the main friction clutch when we shift gears. Otherwise there would be jerks and much



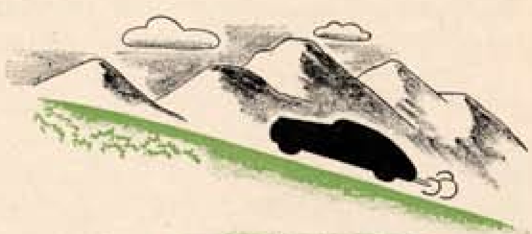
THREE SPEED TRANSMISSION

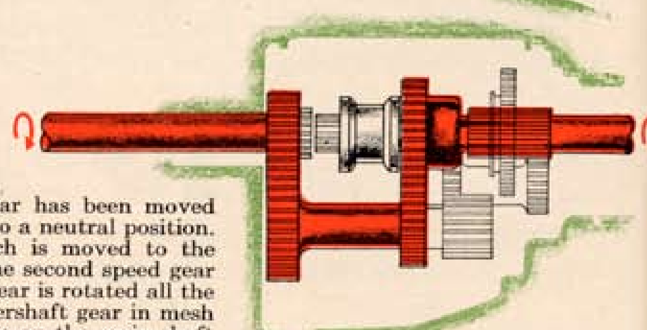
This shows how a three speed, constant mesh transmission operates in its various positions. The color indicates the path of the power through the transmission, from the engine on the left to the rear axle on the right. It shows which gears are actually working in each speed.



FIRST

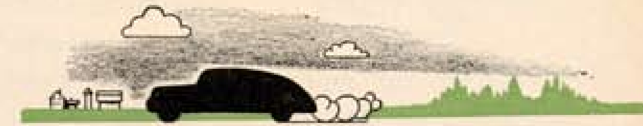
The low speed gear on the main shaft has been moved to the left to mesh with the gear on the right end of the counter-shaft. Thus we have two steps of reduction in the transmission, causing the propeller shaft to turn much more slowly than the engine.

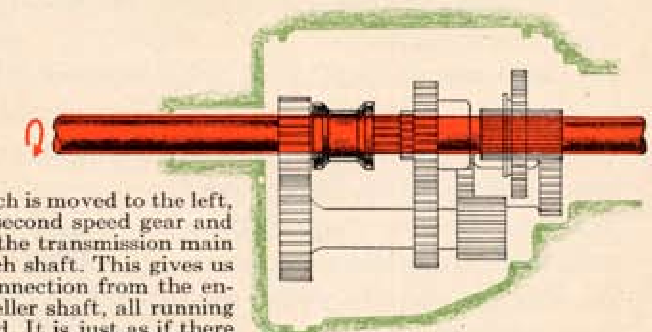




SECOND

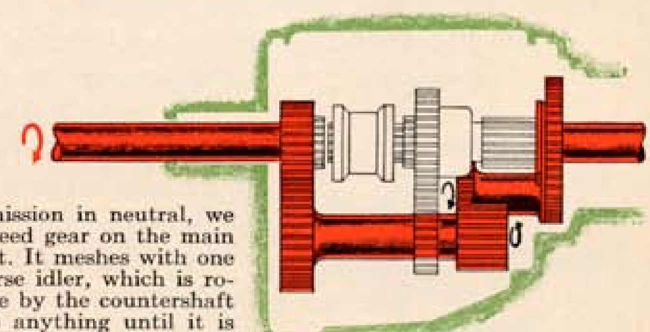
The low speed gear has been moved back to the right to a neutral position. The positive clutch is moved to the right to connect the second speed gear to its shaft. This gear is rotated all the time by the countershaft gear in mesh with it, but is loose on the main shaft and does not drive it except when the positive clutch connects them together.





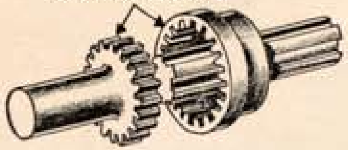
THIRD

The positive clutch is moved to the left, disengaging the second speed gear and then connecting the transmission main shaft to the clutch shaft. This gives us a direct, solid connection from the engine to the propeller shaft, all running at the same speed. It is just as if there were no transmission there.



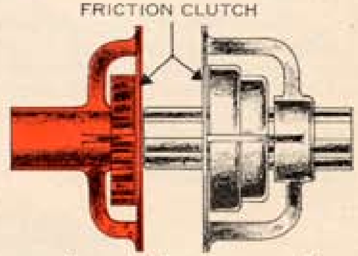
REVERSE

With the transmission in neutral, we move the low speed gear on the main shaft to the right. It meshes with one gear of the reverse idler, which is rotated all the time by the countershaft but does not do anything until it is connected to the main shaft in this way. It can be seen that the shaft to the rear wheels is now turning in the opposite direction.



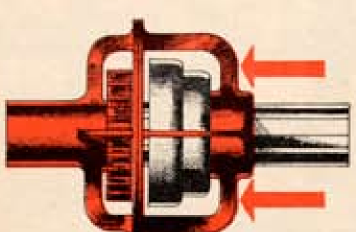
loud clashing of gears. Some gears are running and some are standing still, or they are running at different speeds. Also there is considerable pressure on the gear teeth when they are driving, so the gears do not slide apart easily. And of course it gives the clutch a chance to cushion the shock or jerk of suddenly changing the ratio between the engine and the rear wheels.

There has been a lot of work done to try to make it easier to shift gears. Probably the most successful result has been the development of gear synchronizers, or **synchronous transmissions.** This is a refinement of the constant mesh type we have described. Synchronizers are ordinarily used only for second and third speeds, inasmuch as that is when they are most needed. There are several types, but they all have the same object.



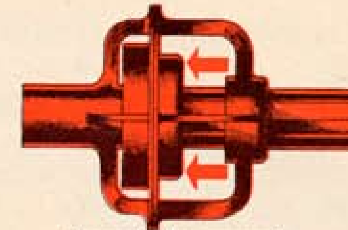
Completely disengaged.

Most of the trouble in shifting gears is because the gears or clutches are running at different speeds. If we could synchronize them, get them running at approximately the same speed before we tried to mesh the teeth, there would be little clash or clatter. That is just what we do. When the second and high speed clutch slides on the shaft—in either direction—it does not mesh with the teeth on the other half of the clutch right away. Instead a small friction clutch takes hold first. (The illustrations show only the general principle of it; the parts do not look anything like those shown.) This is a cone-shaped clutch, with metal faces, but it acts like the friction clutches we



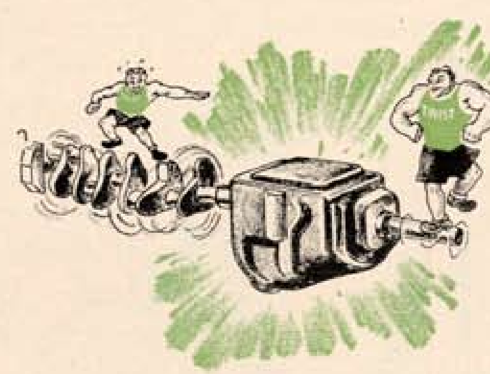
Friction clutch engaged, positive clutch still disengaged.

have described. It can slip enough to prevent a shock, but almost immediately it is solidly engaged. In doing this it has brought the speed of the gear up to the speed of the shaft. As soon as they are turning at the same speed, it is easy to push in the toothed part of the clutch which gives a positive connection. The first part of the motion engages the friction clutch, and the second part engages the positive toothed clutch. This arrangement enables even a new driver to shift gears without trouble.



Completely engaged.

All transmissions do not look just like those we have shown. Some have a greater number of forward speeds, particularly trucks, and the gears may be arranged in a different order on the shafts. There are some entirely different types which we are going to discuss. But most transmissions operate on this same principle. There are a number of gears which can be connected together in different ways to give us the different ratios we want. Except when it is in direct drive, a certain amount of torque comes in at the front end from the clutch shaft, and a different amount goes out the back end to the propeller shaft.



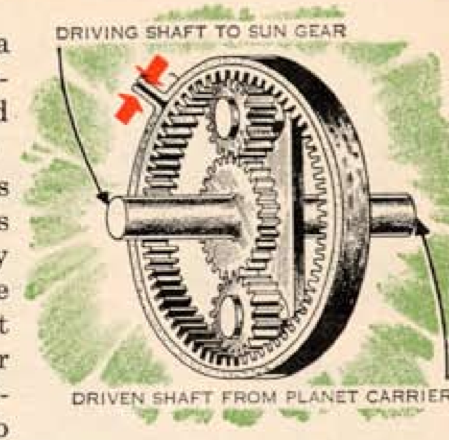
Planetary Gears

A great many people have heard of **planetary gears**, particularly if they have been driving cars for a long time. But they may think of them as an old-fashioned sort of thing. Because they gradually disappeared from automobiles, after being one of the earliest types used. But recently they have been revived, and once more we hear discussions of planetary transmissions. They are used in various arrangements in automobiles, and that is one of the interesting things about planetary gears—we can make them do a number of different things according to how we connect them into the power system. But first let us look at one and see what it is.

In its simplest form, it is essentially three gears. There is a **sun gear**, or pinion, in the center. Then there is a small **planet gear** meshing with it. (We show two of them here and usually there are three or four.) On the outside is the **ring gear**, an internal gear meshing with the planets. The planet gears are fastened together by the **planet carrier**. This holds them in place but lets them rotate. Just how these gears and carriers are fastened to the shafts depends on what we want the mechanism to do. We will explain one of the forms here, and others are shown on page 63.

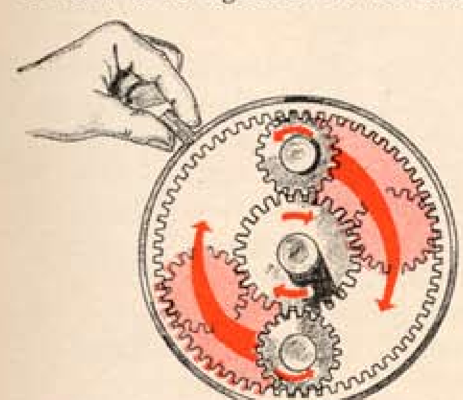
Suppose we connect the sun gear to the input, or driving shaft, and the planet carrier to the output,

or driven shaft. We put a brake band around the outside of the ring gear and hold it tight so it cannot move.



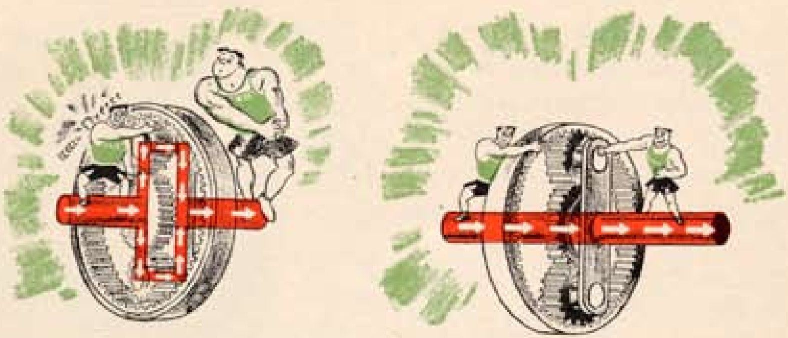
Then if the engine drives the sun gear, the planet gears must turn around. But they cannot stand still and rotate on their shafts because that would mean the ring gear must move, and we are holding that with the brake. So they have to move around the ring gear and the planet carrier moves with them. It is something like the differential we described. There are two motions to the planet gears. Each one is rotating about its own shaft, and at the same time they are all moving around in a circle on the teeth of the ring gear. This is where this type of gearing gets its name. The motion is much the same as the Earth and other planets about the sun. Each one rotates on its own axis, but they also continually circle around the sun.

The planet carrier, and thus the driven shaft, is turning much more slowly than the sun gear and drive shaft and in the same direction. Just what the ratio is depends on the size of the gears, and we will not go into the details of how it is figured. As an example, however, with the smallest practical planets the ratio can not be less than 2½ to 1. When the planets and the sun gear are the same size, the ratio is 4 to 1. This of course means that the speed is reduced to ¼, and the torque increased 4 times.



The planet gears travel around the stationary ring gear.

In order to shift into direct drive, we release the brake on the ring



gear and engage a clutch connecting the drive shaft directly to the driven shaft. If we wish, this can be done by clutching the planet carrier to either the sun gear or ring gear. In either case none of the gears can turn on each other, so the whole mechanism is locked and rotates all together without affecting the drive.

We mentioned that we can get various results with a planetary transmission by connecting it up in different ways. If we drive the ring gear and hold the sun gear still, we will still increase torque as we did in the case just described, but it will not be increased so much. By other arrangements we can increase the speed and reduce the torque, and by still other means we can get reverse. We have three units, any one of which we can hold stationary, and either of the other two can be the driving or driven member. So there are six possible combinations. They are shown on the opposite page. Practically all of them are used in automobiles in one way or another.

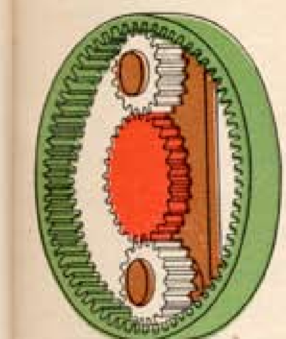
There are various modifications of this simple planetary gear. There are some with double planets of different sizes, and there are compound planetary gears, which consist of two planetary gear-sets with certain gears of one connected to certain gears of the other. These act in fundamentally the same way as the simple planetary, but following the power flow through them is rather complicated and figuring the gear ratio is not worth the trouble unless we are in the business of designing transmissions.

Planetary gears are used in automobiles largely as automatic or semi-automatic transmissions. In the next section we will show some of the ways they are used.

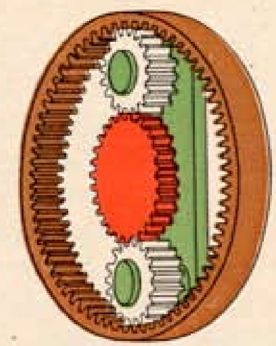
PLANETARY GEAR COMBINATIONS

There are three units in a planetary gear—sun gear, planet gears and carrier, and ring gear. To get various results we can hold any one of these units stationary, and either of the other two can be the driving or driven member. So there are six possible combinations. We show them here, with colors indicating the driving, driven, and locked members, and the labels telling what kind of gear results from each arrangement.

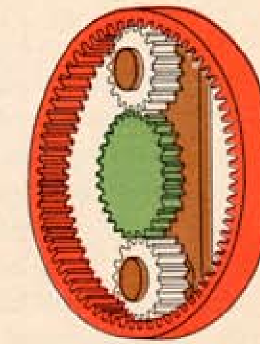
They are all planetary gears, but a number of different results are obtained by hooking them up differently.



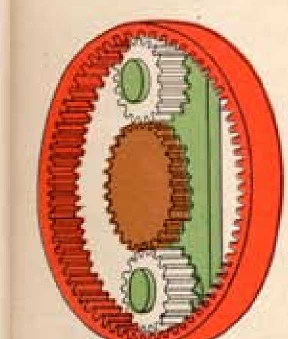
Reduction gear—less speed, more torque.



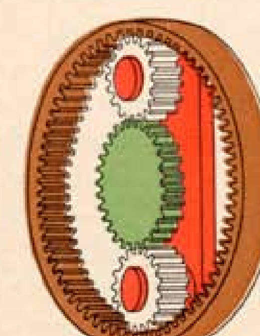
Reversing reduction gear—less speed, more torque, turns backward.



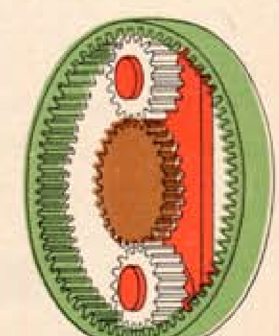
Reduction gear—less speed, more torque.



Reversing overdrive—more speed, less torque, turns backward.



Overdrive—more speed, less torque.



Overdrive—more speed, less torque.

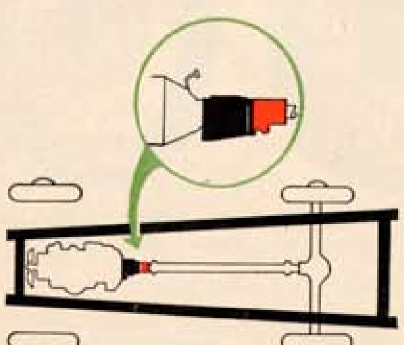
DRIVING **DRIVEN** **LOCKED**

Automatic Gear Transmission

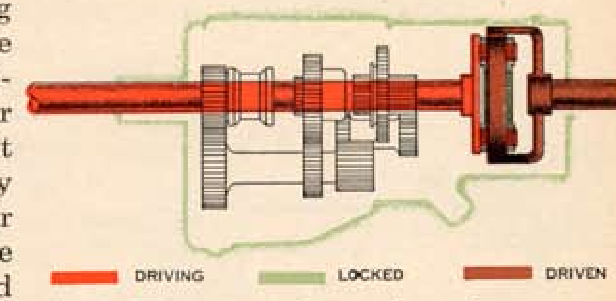
The name **automatic transmission** is used to cover a lot of different things. Ordinarily it means any arrangement which will change *by itself* the ratio between the engine and the wheels, change it without the driver having to do anything. Almost any transmission can be arranged to work automatically, or partially so. It is a question of the controls more than anything else. There must be something to think for the driver, to decide when the ratio should be changed. Various things have been used to control the time of shifting—car speed, engine speed, the torque required or load on the engine, and combinations of these. Automatic transmissions were invented almost as soon as there were autobiles, they have kept on being invented ever since, and what form they will take in the future is anybody's guess. All we are going to do here is point out one or two examples along this line which have had some commercial success.

While almost any kind of transmission can be made to work automatically, some are easier than others to use this way. Some get into a lot of complications. Planetary gears have been popular for this purpose, one reason being that they are truly constant mesh gears. We do not have to shift gears. We only have to hold one member tight in some manner.

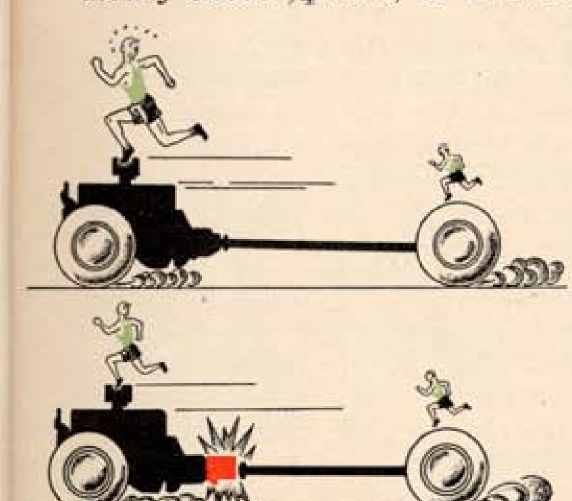
One use of planetary gears is in an automatic **overdrive.** This is not always thought of as an automatic transmission, but it really is. It is a two-speed transmission in back of the regular three-speed transmission, and it shifts automatically depending mostly on how fast the car is going. When we are cruising along the highway in the country, we do not need as much torque as when we are accel-



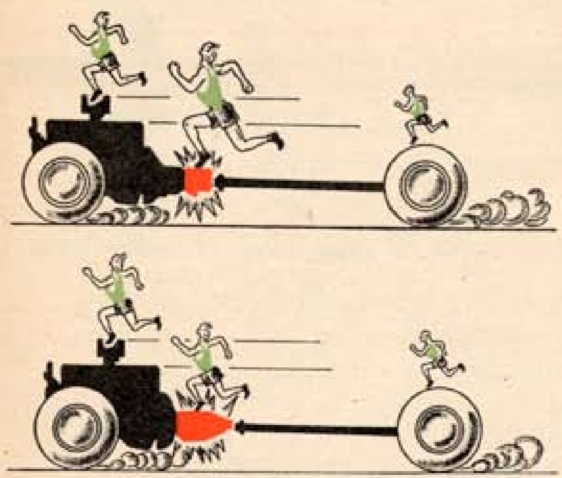
erating or driving in city traffic. We can afford to sacrifice some torque for speed. Or to say it another way, by changing the gear ratio we can get the same car speed with a lower engine speed. This means less noise and wear of engine parts, and usually less gasoline used. To do this we put a separate planetary transmission behind the regular transmission. At low speeds this is in direct drive and we do not even know it is there. We shift gears in the three-speed transmission in the ordinary way. But when we get above a certain speed in high gear, the planetary transmission comes into action. The sun gear is then grabbed and held stationary, power is applied to the planet carrier, and the ring gear is the driven member. As we can see on page 63, this gives us an overdrive. That is, we have more speed and less torque at the output shaft than we put into it. It is just opposite from first or second speed. We have come up from low gear to direct drive and now we go on through and beyond it. This ratio is usually about ¾ to 1; or in other words, for the same miles per hour of the car, the engine is turning only three-quarters as fast as it would in direct drive.



There are a number of control devices mixed up with this which make it much less simple than it sounds. There are means to shift it automatically at certain speeds, to keep it from



Overdrive reduces engine speed.



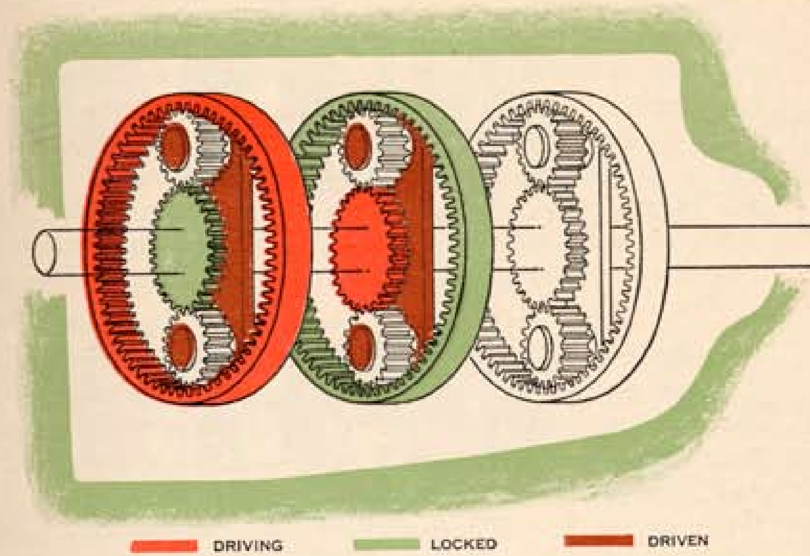
The final result is the same.

shifting when we do not want it to, to get back into direct drive even at high speeds, etc. Theoretically this can be used in combination with any gear of the regular transmission, giving us six speeds forward, but ordinarily it is used only with high gear.

We can get this same result by using a different ratio in the rear axle and going only to direct drive in the transmission. For example, if the rear axle—the ring gear and pinion—has a ratio of 4 to 1, and the overdrive ratio is $\frac{3}{4}$ to 1, the over-all ratio from engine to wheels will be 4 x $\frac{3}{4}$, or 3 to 1. Now if we have a rear axle ratio of 3 to 1, the over-all ratio in direct drive will again be 3 to 1. We should always bear in mind that the words **direct drive** and **overdrive** refer to the transmission only. There is still a reduction in the rear axle which we must take into account.

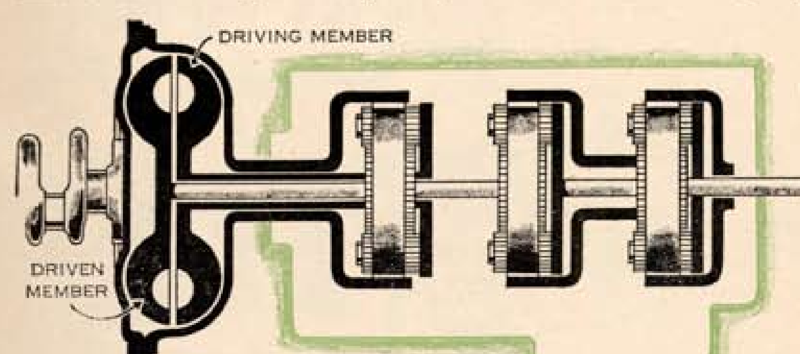
This general idea is used in one completely automatic transmission with which some cars have been equipped. It is a four-speed transmission, the top gear being direct drive, and a low rear axle ratio is used. A low axle ratio usually means slower pick-up or acceleration in high gear, so third speed is arranged so that it can be brought into use at almost any speed when more acceleration is desired.

The transmission consists of two planetary gear sets, one behind the other. Each planetary has two speeds, a reduction ratio and direct drive, but the reduction ratios are not the same. We can get the four speeds we want by choosing the proper ratios. In low gear, both planetaries are in action, giving us a double reduction. In second speed the front unit is in direct drive, and the rear unit alone



gives a reduction of about $2\frac{1}{2}$ to 1. In third speed we do just the opposite; the rear unit is in direct, and the front unit is working. This has a ratio of approximately $1\frac{1}{2}$ to 1. In fourth speed, both units are in direct drive, so engine torque flows straight through to the rear axle. There is also a reverse gear, which is a third planetary unit behind the other two. It acts in combination with the other two units to furnish a low ratio in the reverse direction.

A fluid flywheel is a very important part of this combination. It is located between the engine and the transmission, but the flow of power from the engine actually goes first to the front planetary unit, then to the fluid coupling,



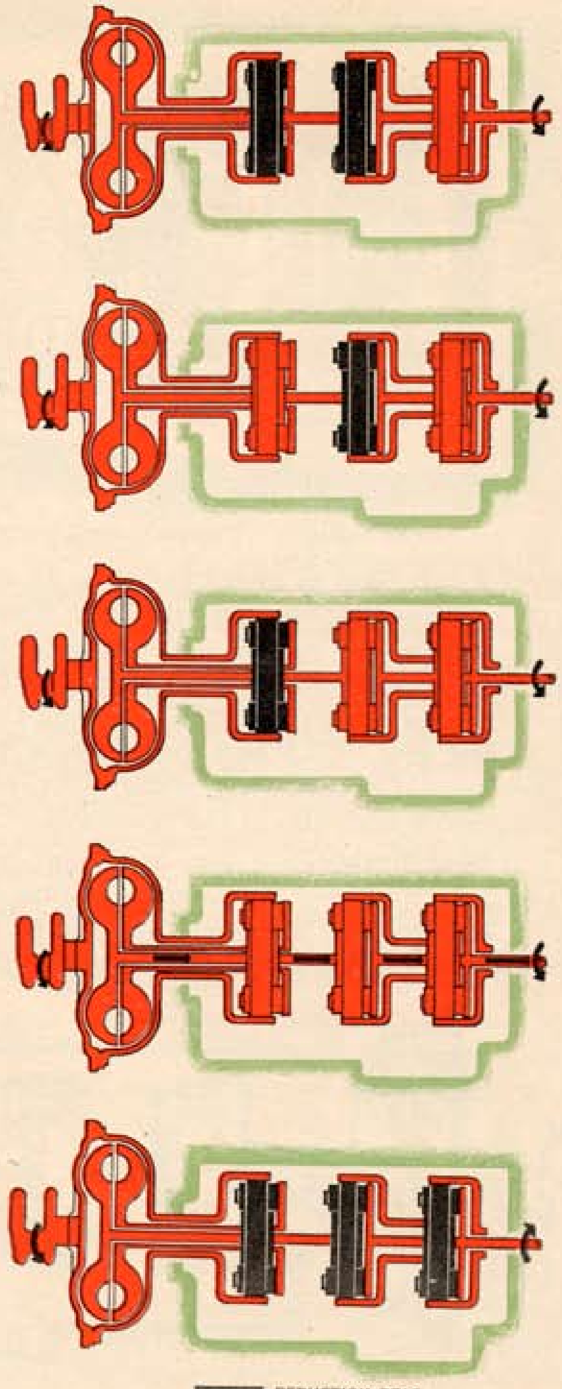
First Speed.
3¾ to 1

Second Speed.
2½ to 1

Third Speed.
1½ to 1

Fourth Speed.
1 to 1

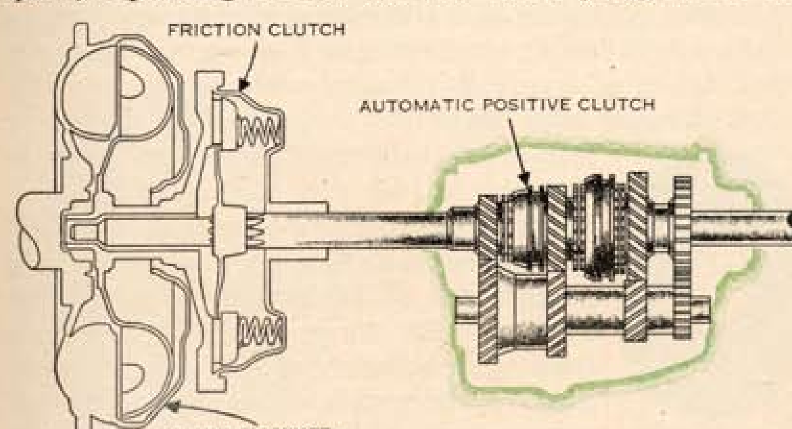
Reverse.
4¼ to 1



and then to the second planetary unit. The effect is just the same, however, except that the coupling runs at a reduced speed at certain times, which has advantages. There is no friction clutch. The transmission shifts from one speed to another under load, without being disconnected from the engine. This is possible because the fluid flywheel cushions the shock, and is one of the big differences between this and most other transmissions, even some which use a fluid flywheel.

The planetary gears are controlled by brake bands and friction clutches. A brake band holds the proper member stationary in each unit when it is in low ratio, and a clutch locks each unit together when direct drive is needed in that unit. Oil pressure makes these brakes and clutches work at the right time, depending on how fast the car is going and how far the accelerator pedal is pushed down. All the driver has to do is control the speed of the engine, and the gear shifting will take care of itself.

All automatic transmissions are not of the planetary type. We could use a conventional three-speed transmission if we wanted to, by adding the right kind of controls. We show here a four-speed transmission of the same general type. It would probably be called a semi-automatic transmission. If we place the shift lever in one position it shifts automatically back and forth between first and second speed, depending on how fast the car is going. With the



shift lever in another position it does the same thing between third and fourth. A fluid flywheel is provided, so the car can be started in third if desired and thus the driver does not need to do any shifting.

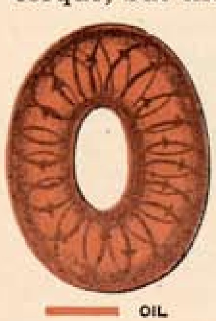
We will not try to explain the action of this transmission, but it is quite similar to that of the constant mesh type we described earlier. A positive clutch with synchronizers slides back and forth to make the shifts, but this is moved by a combination of vacuum and spring force instead of being shifted by hand.

As we said, these are only examples of automatic transmissions of various types. There are a great many others, but we cannot attempt to cover them here. We will show one more completely different type of automatic transmission, however, in the next section.

Hydraulic Torque Converter

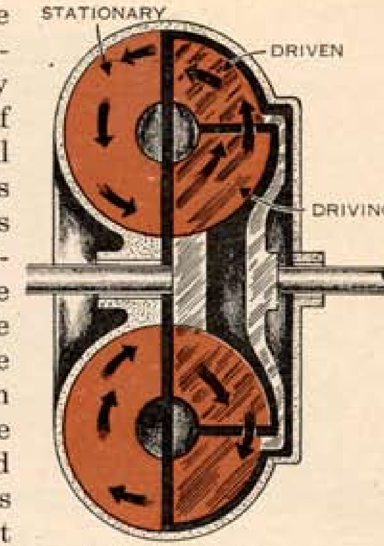
In our discussion of the fluid flywheel, we pointed out that it was simply a clutch, a hydraulic clutch, which could not deliver any more torque than was put into it. It is a very useful addition to a transmission, but it cannot replace the transmission because it is not a torque multiplier.

But we can make a torque multiplier out of it. In fact the first use of a device of this general type was for increasing torque. And since then there have been various designs of these so-called **hydraulic torque converters.** (There are other types of hydraulic transmissions which multiply torque, but the term "hydraulic torque converter" usually means the turbine type we are going to discuss.)

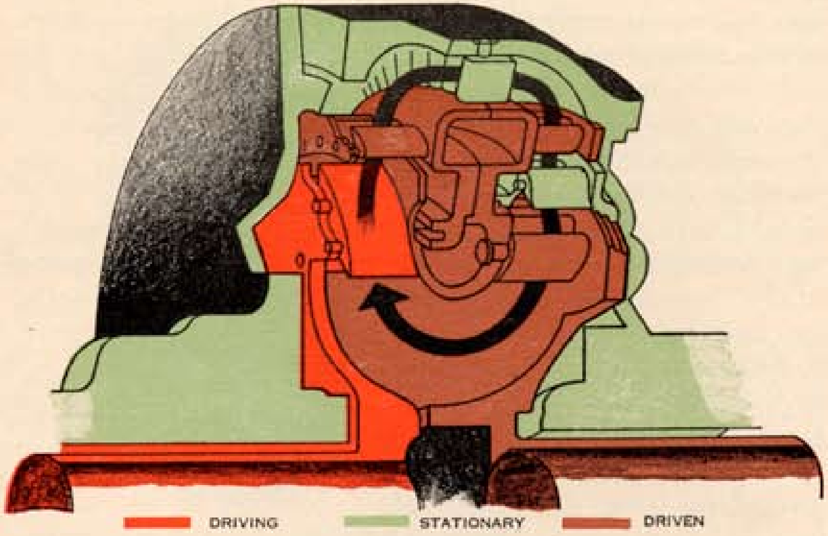


In principle, all we have to do to a fluid flywheel to make a torque converter is add another set of blades—*stationary* blades. You know the old rule that for every force there must be an equal and opposite reacting force. In transmissions this means that we cannot multiply torque unless we have

some solid point to push on. We usually say we must have a reaction member, some stationary part connected to the frame of the vehicle. In a conventional transmission the whole casing is fastened solidly and this holds the shafts in place. In the planetary we have to grab hold of one of the three members before we can multiply torque—we have to hold it stationary in relation to the frame. And we have the same situation here. In a fluid flywheel the whole thing turns around together. But if we put in a new part, a set of blades tied solidly to the frame, we have something to take the reaction, to furnish the reacting force. And then it multiplies torque.

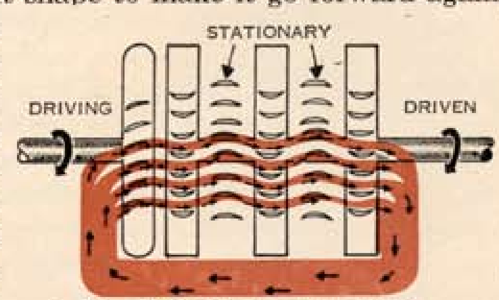


We show one fairly simple arrangement. The **driving element** and **driven element** take up one half of the doughnut, and the **stationary, or reaction, element** fills the other half. The whole thing is filled with oil, which circulates in the same manner as in the fluid flywheel, outward from the driver through the driven member and back toward the center through the stationary member. The blades are not straight and flat however. If we could spread the three members out flat and look down on them, we would get an idea of their shape and how the liquid flows through them. The impeller, or driving member, pushes the oil in the direction it is turning, and this oil hits the turbine or driven member and forces it to turn in the same direction. In doing this the oil bounces off the blades in the opposite direction, and if the reaction member were free to



turn it would turn backward. But it is held tight, so it straightens out the oil before returning it to the impeller and starts it moving in the forward direction again.

There are many ways in which these three units can be arranged, and it is not necessary that each unit have only one row of blades. One torque converter which has been quite successful in vehicles has three rows of blades on the driven member and two on the reaction member. If we lay these out flat as we did above, we can see how the oil circulates. The pump, or impeller, forces it against the first set of blades, which move forward. The oil has been deflected in a backward direction, but the stationary guide blades are of the right shape to make it go forward again, so it can drive the next set of driven blades in the right direction. Then the process is repeated once more. The turbine—that is, the three rows of blades—is one solid piece,

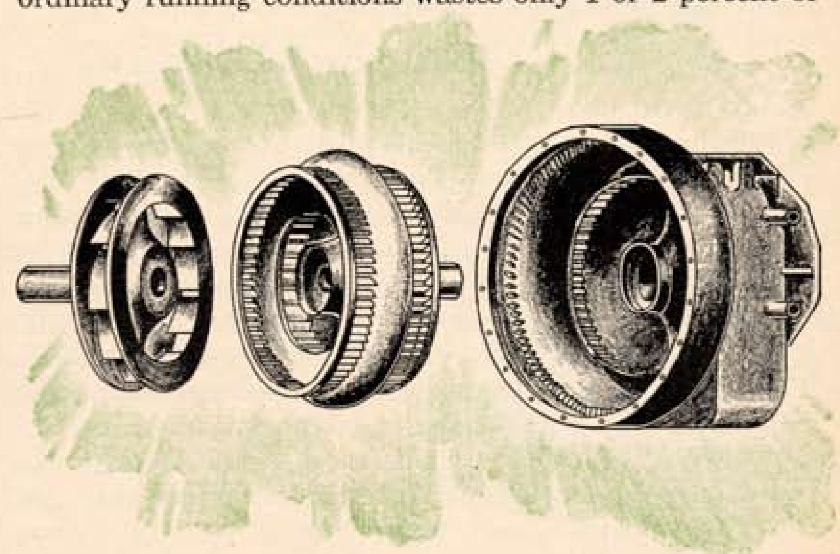


Simplified blade arrangement.

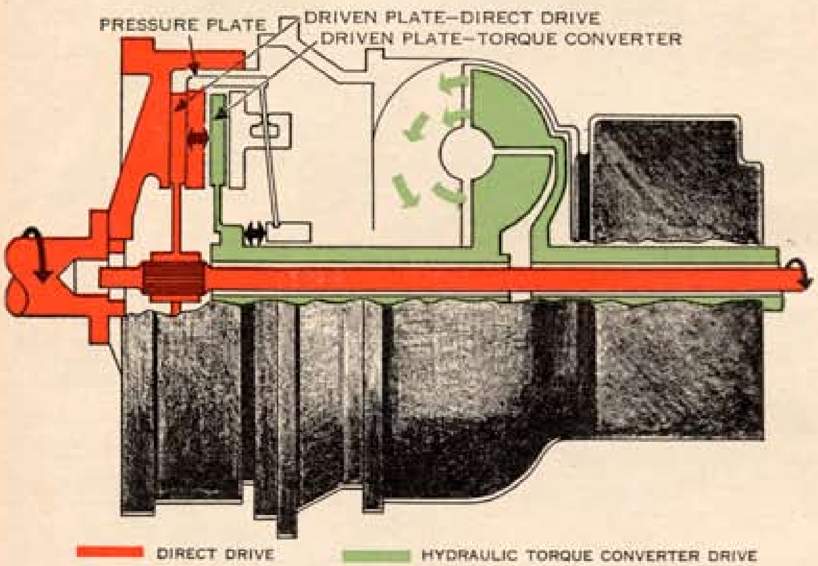
so the force on all three is added together to make the output shaft turn around, and thus drive the car.

A hydraulic torque converter is completely automatic in itself. It does not shift. It just smoothly changes from one ratio to another and to another in a continuous fashion, without definite steps. It is what we know as a continuously variable transmission. Where the conventional transmission changes like this, , it changes like this, . The type we have just shown, when working in a large bus, has a torque multiplication of 5 to 1 when the bus is starting to move. This gradually becomes less and less as the vehicle moves faster. With some designs we might eventually reach 1 to 1 or go even beyond, but as we shall see in a minute, we usually do not let that happen.

This sounds like a perfect way to drive a car—completely automatic in itself; nothing to shift, the advantages of a fluid flywheel combined with an automatic transmission. Why isn't it used on all vehicles? The answer lies in its low efficiency. That is, it wastes a lot of the power put into it. With all those blades, some stationary, some moving, there is a lot of churning up of the oil, and a certain part of the energy is lost in heat. A fluid flywheel under ordinary running conditions wastes only 1 or 2 percent of



the power, but present torque converters at their best waste 15 percent or more. And that best is only at one speed. As the speed increases and we approach a 1 to 1 ratio, the waste becomes more and more. We can stand some loss in efficiency during starting, where it is only temporary, but we cannot afford to run like that all day. We simply would be throwing away gasoline, and besides, all that heat would not be doing the torque converter any good.



There is one way to get around part of this trouble. The bus installation we showed is arranged to go into direct drive at a fairly low speed. This is a positive drive which eliminates the torque converter altogether. There is a double friction clutch at the front. When one side is engaged, the torque converter is working, for starting and getting up to speed. When the other side is engaged, there is a direct drive straight through, and the torque converter stands still. The clutch is shifted back and forth automatically at the best speeds. Thus except when starting up, the torque converter is not working and we do not have any power losses there.

Some people have also tried to get around this problem by using a hydraulic torque converter along with a transmission, such as a planetary gear arrangement. A great many combinations of this sort can be figured out—in fact so many that we will not go into any of them here. But it is one possibility for hydraulic torque converters in the future.

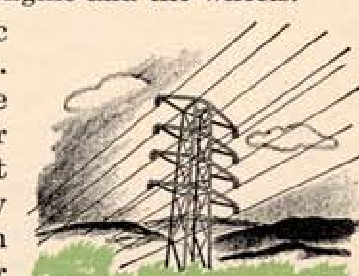
Electric Drive

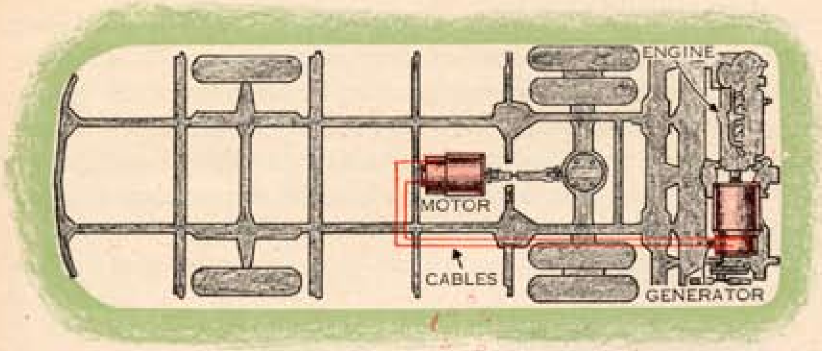
There is one other way of transmitting power in vehicles which is in common use. This is quite different from the others we have talked about, although it is for exactly the same purpose. It is the **gas-electric drive** or, what is more common now, the **Diesel-electric drive.**

Electricity is used for transmitting power in many ways and for many purposes. The network of wires spreading all over the country is simply for the purpose of getting power from one place, where it can be produced cheaply in large quantities, to a great many other places where it is going to be used. Some trains and trolley cars are driven this way, by electricity, from a central power station.

But that is not what we mean here by electric drive. And we do not mean the electric automobiles and trucks run by storage batteries, which used to be so common. What we are going to discuss are the vehicles driven by internal combustion engines in which an electrical system is used to replace the transmission and some other parts of the drive system between the engine and the wheels.

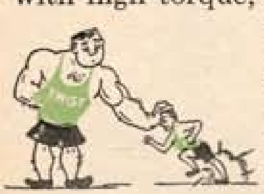
What we have is an electric **generator** and an electric **motor.** These are not little things like the generator and starter motor on our automobiles. These must handle all the power put out by the engine. (We might mention here that to the automobile or aircraft man an "engine" is an





internal combustion engine, and a "motor" is an electric motor.) The generator is connected directly to the engine, its shaft being fastened solidly to the engine crankshaft. These can be put any place in the vehicle. This system is used mostly in busses, and quite often the engine and generator are put under the rear seats, at the very back behind the axle. The motor is put some place where it can drive the rear axle, usually through a short propeller shaft just like any mechanical drive. The motor is connected to the generator by wires, or more accurately, by heavy cables. Thus the engine drives the generator, which produces electricity which makes the motor run. And the motor drives the axles and wheels in the regular manner.

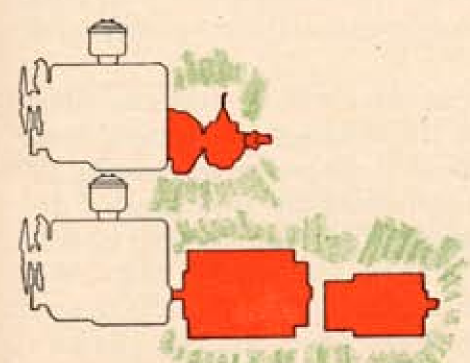
There are a number of different control systems used with this equipment, and we are not going to try to explain all the complications of the electrical circuits. In general this system does the same thing as any other transmission—it changes the torque on the rear axles up or down. And it does it more or less automatically. When the motor suddenly has to work harder, it slows down, and this reacts on the generator and changes what it is doing. The result is that when starting or on a steep hill the motor runs slowly with high torque, more torque than the engine is furnishing. Then when running along on level ground, the wheels do not need so much twist, the motor speeds up, and eventually acts just like an overdrive. The ratio has changed so that the motor now furnishes less torque than the engine



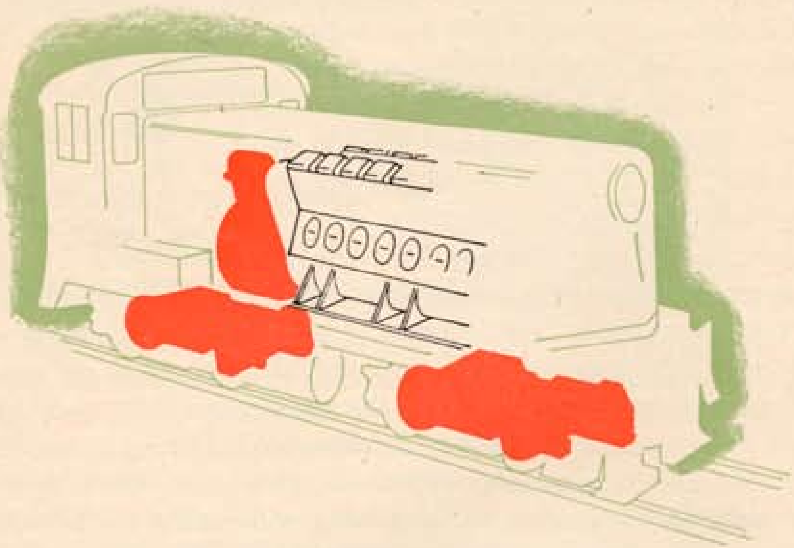
is putting out, but it is going faster. It is the same old story, speed versus torque. As one goes up, the other goes down.

This is all done by varying the current and voltage produced by the generator. Without explaining how or why, we will just say that when we have high current and low voltage from the generator, we have high torque and low speed from the motor. And vice versa; low current, high voltage means low torque, high speed. This means that if we want to we can keep the speed and power of the engine constant, and do all the changing of speed and torque electrically.

No clutch is necessary with a gas-electric drive. It is completely automatic; so it is very convenient for busses where there is a lot of stop and go driving. We can run the engine at some almost constant speed that is most desirable, and we can put the engine anywhere we want to, at any distance from the driver. But there are disadvantages also. It is not highly efficient. Changing from mechanical to electrical power and back again is wasteful. And the equipment is very heavy and expensive. For these reasons this type of drive has not been used to any extent on ordinary passenger cars up to the present time. For some service, however, such as in busses, it is worth this extra weight and cost.



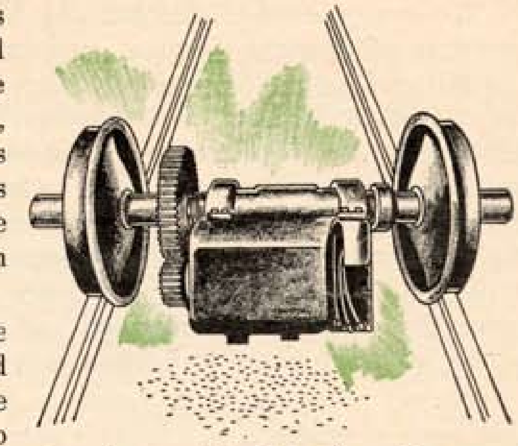
We have called this part of the book the Automobile Section, but we are going to stretch that a little. For the electric drive has had its greatest success in the railroad field. Diesel engines are being used more and more in this service, from small switch engines to



heavy freight locomotives. And these engines are just like any internal combustion engines in a car, they need a transmission. A train needs a lot of torque to get it started, and of course that is when the engine cannot furnish very much if connected direct. Mechanical and hydraulic transmissions have been used to some extent, but the electric drive is now practically universal in Diesel locomotives.

The system is essentially the same as we have already described. The Diesel engine drives a generator which furnishes electricity to a motor driving the wheels. The theory of it is just the same. There are differences, however, particularly in the size of the equipment and the arrangement or location of the pieces.

A Diesel engine in a locomotive will produce probably 10 times as much power as the ordinary bus engine. And this means that the electrical machines must handle 10 times as much power. A large generator is connected directly to the engine, but instead of having one large motor, this part of the system is split up into smaller units. We have one motor for each driving axle, which usually means two or four motors driven from one generator. These motors are mounted with one end right on the axle, the other end



supported on springs on the truck. A small pinion drives a large gear on the axle, which of course gives more torque and less speed just like the ring gear and pinion in an automobile.

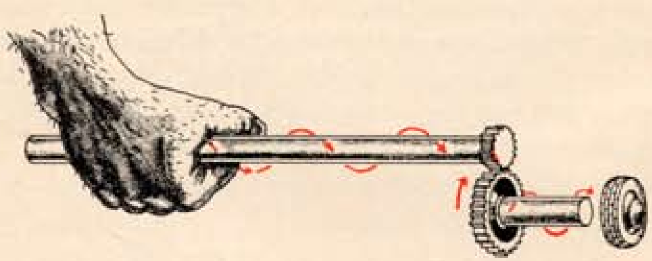
Sometimes there are two engines and two generators in one unit or car, and two or three of these units may be combined to form the complete power plant unit, or locomotive. Thus there may be as many as six engines and twelve or twenty-four motors for one train. These can all be controlled from one point by the operator.

The control system for such an arrangement is of course more complicated, but it works in much the same fashion as we have mentioned before. Except when starting, the engines run at constant speed, and all the necessary changes in torque and speed of the drive system are taken care of by varying the voltage and current furnished to the motors. This makes an easier job for the engines, as we can design the system so that they can run at their best speed, considering their power and fuel consumption.

* * * * *

We have shown all the common ways of transmitting power in automotive vehicles, including a short jump into the railroad field. We have seen that there are many different ways of doing it. There are various types of mechanical drives, several arrangements of hydraulic devices, and an electrical drive system with a lot of possible minor variations. But if we look at them more closely, we find that they are simply entirely different ways of doing exactly the same thing. In all of them we are just getting power from one place to another, and providing something which will change the speed and torque when necessary.

We get a certain twist from the engine and we carry that back to where it can apply a certain different twist to the wheels. To go a step further, we carry it back until it can apply a certain backward force to the ground, which makes the vehicle move forward. This last idea is better, because in the next section we get into the aircraft field, and we will find that with a propeller drive we cannot stop our story with the application of torque to the hub of the propeller. A lot of things happen beyond that point. But that is something for the next section.

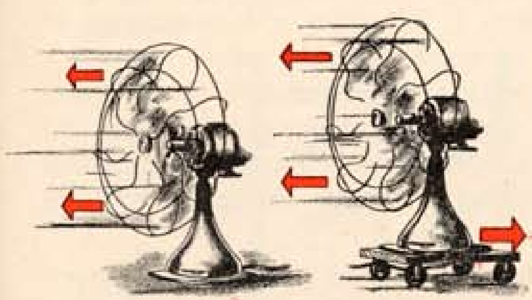


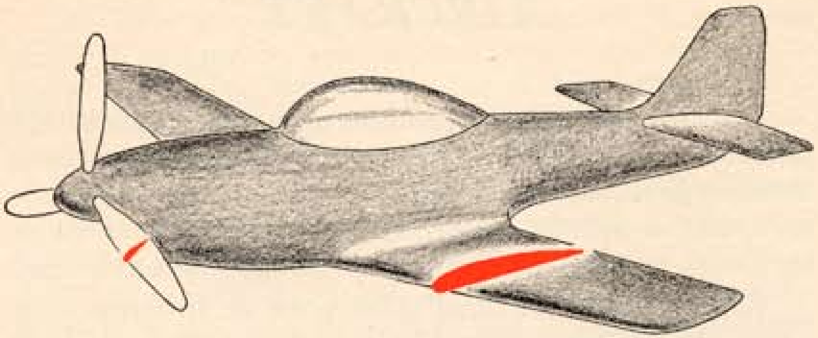
AIRCRAFT

In an automobile the wheels push back against the ground, and the reaction to that force makes the car move forward. In a boat the screw pushes back against the water, or to put it a little differently, it pushes a lot of water backward and the reaction makes the boat move forward.

Exactly the same thing takes place in an airplane. A large volume of air is pushed backward by some means, and the reaction makes the airplane go forward. It does not matter what pushes the air backward. It can be a large fan or **propeller** as in the usual airplane, or it can be a stream of hot air and exhaust gases as in the **jet propulsion** type. We will have more to say about jet propulsion a little later, but first let us look at the more common propeller arrangement.

We called it a fan—and that is not taking too much liberty. Suppose we take an electric fan, the kind of a fan we use to stir the air up in our house in hot weather. Ordinarily it stands still and blows the air forward. But if we put wheels under it, we will see it start to move backward immediately. It pushes the air in one direction and moves itself in the other direction. It may not move very fast, because it does not have much power, and it is not designed for just that purpose. A lot of other things are important in such a fan, for example, quiet operation. We would not want an airplane propeller whirring around in our bedroom when we were trying to sleep. Incidentally, most of the noise we hear from an airplane flying overhead is the propeller, not the engine.

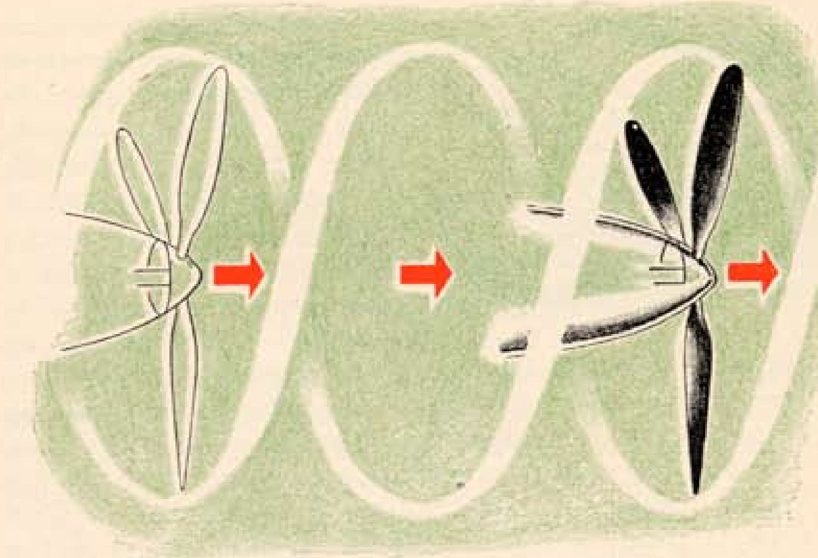




A propeller blade is very much like an airplane wing. If we take a cross-section of each—that is, cut it straight across and look at the end—we find they have about the same shape. The wing moves along in a straight line; the propeller blade is fastened at one end and whirls around. And they do the same thing. The wing in moving forward forces a big chunk of air *downward* and the reaction tends to push the wing and airplane *upward*. (This is an over-simplified statement which will be objected to by some people, but it is true as far as it goes.) The propeller is in a vertical position, so as it turns around it forces a lot of air *backward*, and the same kind of reaction moves the propeller and airplane *forward*. It is the propeller which wants to move forward, and it drags the airplane along with it, so we can see that it must be fastened securely to it.

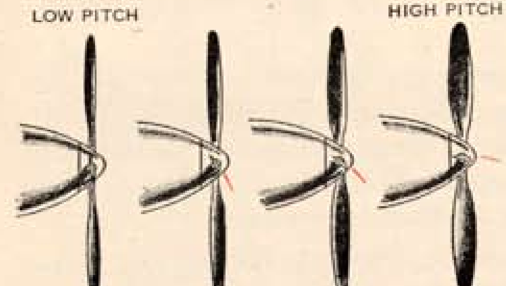
Another way to look at it is to say that a propeller screws itself through the air. For a propeller really is a screw, very much like the kind we talked about in the early part of this book. But instead of the thread going all the way around in a spiral, it is broken up into sections. If a screw were working in wood it would travel forward a certain number of feet with every revolution. In air there is some slipping, and a propeller doesn't travel forward quite as far as it theoretically should, but the principle is exactly the same. It screws itself into the air just like a wood screw goes into wood.

The distance it would move in one revolution theoretically, if it were screwing into wood, is called the **geometric**



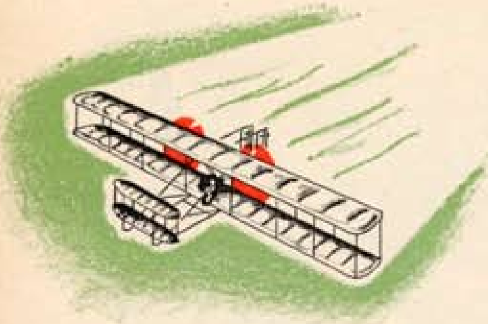
pitch, and is the same thing we talked about earlier in connection with screws. The distance it actually moves forward in the air is the **effective pitch**. This is not as great as the geometric pitch, and the difference between them is the **slip**. The slip and effective pitch vary with speed, air density, and other factors even though the propeller stays exactly the same.

While the pitch of a propeller is actually measured in terms of the distance moved, it is sometimes easier to think of it as the angle of the blades. When the blades are almost flat, it is in low pitch; it does not move forward very far in one revolution. When the blades are turned at a considerable angle it is in high pitch. It bites off a big chunk of air and moves quite a distance in one revolution.



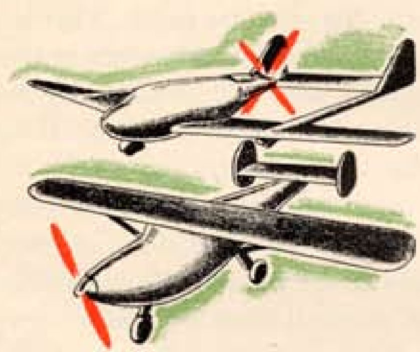
Pitch range—exaggerated.

In connection with this general subject, we might mention that



in England the correct name for a propeller is an **air screw.** This may sound queer in this country, but it is probably a more truly descriptive name than our own is.

We can put the propeller either in back or in front of the airplane. Usually it is found in the front, pulling the plane behind it. This is called a **tractor.** But there have been many airplanes with the propeller behind, pushing the plane, and some designers insist this is the better way. The first plane to fly under its own power, built by the Wright brothers in 1903, had the propellers behind. This type is called a **pusher.** Where the propeller is makes no difference in the way it works as long as it turns in the right direction; so that the plane will go forward, not backward.

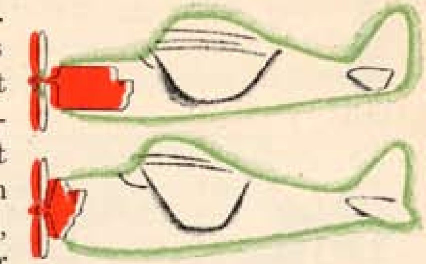


Propeller Drive

As we said earlier, some airplanes have nothing between the engines and the propeller but a single straight shaft. Essentially, the propeller is simply mounted on the front end of the engine crankshaft. This is true of practically all private planes of low or medium horsepower.

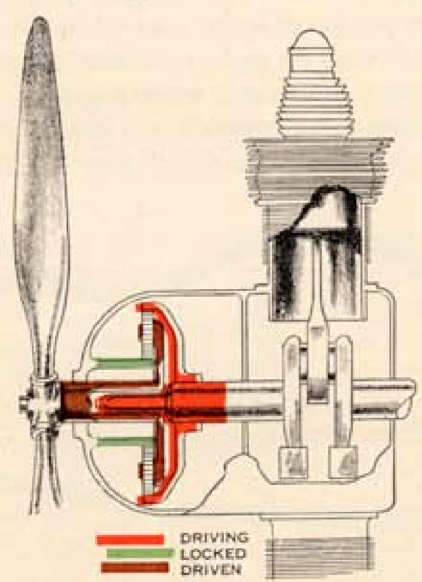
But when we get to the military aircraft or large transports, with engines of 1000 horsepower and over, we have

a different set of conditions. We must use large propellers with long blades to handle that much power, and large propellers are ordinarily run at slower rotative speeds than small propellers. This is logical, because the longer the propeller

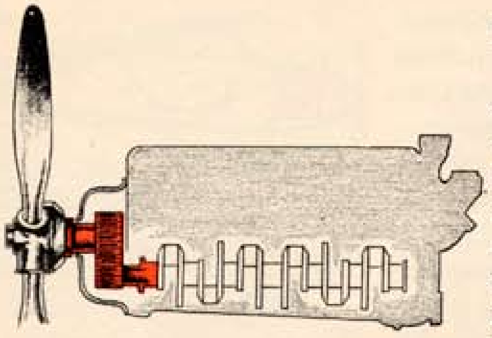


blade the faster its tip is going to move for the same engine speed in revolutions per minute. There are a lot of factors involved, some of which we will get into later, but it all adds up to the fact that the most efficient speed for the propeller is not the same as the best speed for the engine. We want the propeller to turn more slowly than the engine.

So we use a **reduction gear.** Somewhere between the engine and the propeller we put in a set of gears which lets the engine run fast enough to develop full power without over-speeding the propeller. The ratio is usually around 2 to 1, though it varies with different engines and different installations. Thus if the top speed of the engine is 3000 RPM, the propeller will never turn more than 1500 RPM.



On most of the large radial engines, a planetary gear is used. This is built-in by the engine manufacturer, and is practically part of the engine. It is built a little differently than the planetary gears we showed earlier, but it works the same. It is the type shown as No. 3 on page 63; that is, the engine drives the ring gear, the sun gear is held stationary, and the power is taken from the

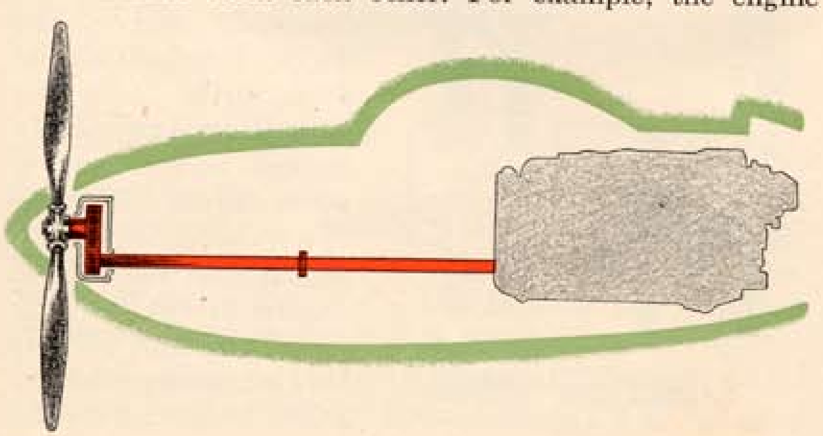


planet carrier.

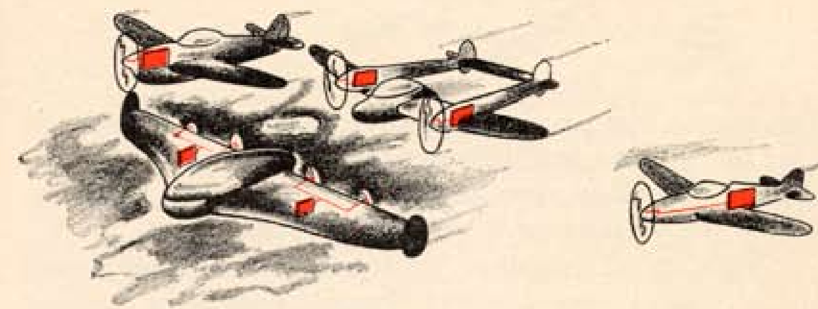
Some engines have simply two ordinary spur gears for speed reduction. This gives directly the ratio for which the gears are designed. It has a definite advantage in some cases in that it keeps the engine low and raises the propeller slightly for more ground clearance. Ground clearance may be the limiting factor in the size of the propeller.

There are some planes where the reduction gear is not combined with the engine, because the engine is located halfway back in the fuselage instead of in the nose. In these installations, a long extension shaft goes from the engine to a reduction gear in the nose. The reduction gear is exactly the same, but it has been taken off the engine and moved forward.

This sort of thing is possible with a liquid-cooled engine, because such an engine does not have to be located in front where the air can get to it. It can be put anywhere. There have been proposals for more complicated arrangements of this type in which the engine and propeller are separated even farther from each other. For example, the engine



might be in the fuselage with the propellers extending forward from the wings, being driven by shafts and bevel gears. Many things along this line are possible in the future.

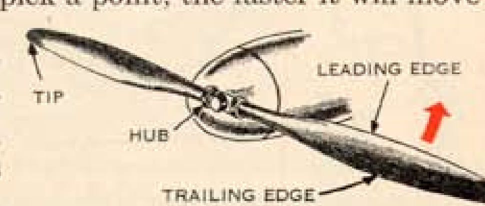


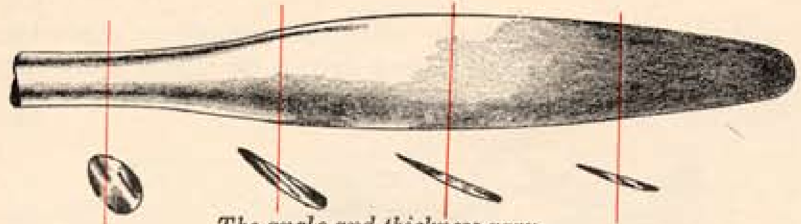
Propellers

We have already shown pictures of propellers and explained something of how they work, but before we go any further let's be sure we have a clear idea of the simple fundamentals.

A propeller has two or more **blades**, with a **hub** at the center which is fastened to the drive shaft. (One blade propellers have been built experimentally, but are not very practical.) The edge of the blade which strikes the air first as the propeller turns around is the **leading edge**. The other is the **trailing edge**. The **tip** is the end of the blade away from the hub.

The blades are set at an angle to the hub; that is, the leading edge is further forward than the trailing edge. The angle is not the same all the way from the hub to the tip, however. It is a greater angle near the hub. This is because that section does not move as fast as the tip. The farther out from the center we pick a point, the faster it will move for the same revolutions per minute. We try to design the propeller so that every point on it is working at its greatest efficiency.





The angle and thickness vary.

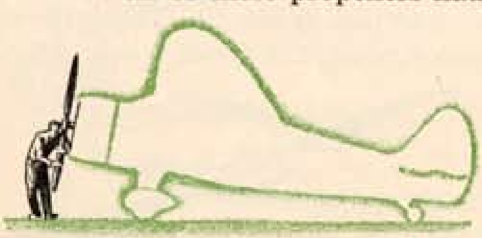
This means that we must have a comparatively large angle near the hub and gradually decrease it as we go out toward the tip. The blade must also be thicker near the hub than it is at the tip because it has to be stronger there.

Originally all propellers had two blades and were carved out of a solid piece of wood. Present propellers for light planes are much the same, though they are designed to be more efficient and are usually laminated, that is, made up of thin layers glued together, which gives more strength than a solid piece of wood.

Then the aluminum propeller came into use. The main advantage of this was that it could be made thinner for the same strength. This gave it higher efficiency, particularly in the larger sizes transmitting greater horsepower.

This also led to the **adjustable pitch** propeller. The aluminum blades were fastened in a split hub. The hub could be loosened and the blades turned to a different angle, to a higher pitch or a lower pitch. The main advantages of these were that the same propeller could be used for engines of slightly different horsepower, and that it could be adjusted to suit some particular condition that was most desired. It could be adjusted so that it was best for high speed, or for climbing, or for cruising at some particular altitude.

But all of these propellers had to be a compromise. A propeller is a fairly efficient device for transmitting power. It can deliver as useful power — **thrust horsepower** pulling the plane forward — over 85% of the

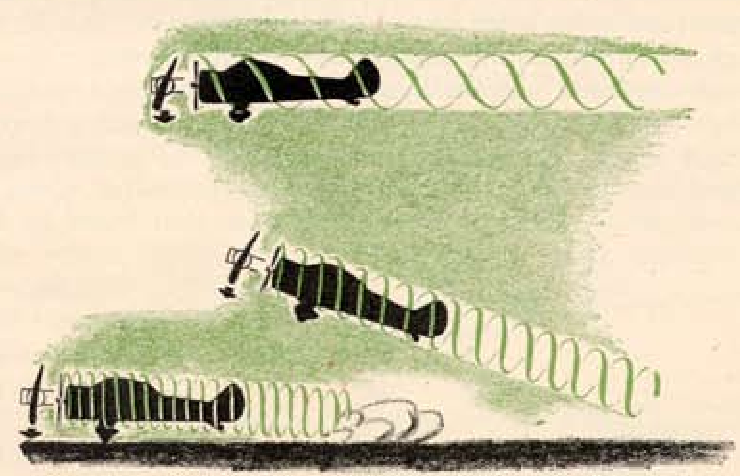


Ground adjustment.

power from the engine. But it does this only at one speed, one particular set of conditions. The same propeller cannot be equally efficient at high speed and low speed, at take-off and cruising, at climbing and level flight.

While it does not solve all the problems completely, a great many of these conditions can be taken care of if we can change the pitch of the propeller anytime we want to. If we can change the angle of the blades so that sometimes the propeller will bite off a big chunk of air and at other times it will spin around more freely, we will be much better off. When it is in high pitch, with the blades set at a large angle, the engine will have to work harder, for it is trying to push more air backward. In low pitch there will not be so much resistance to the propeller, so the engine can turn it faster and more easily. Sometimes we want it one way, sometimes another.

For take-off we want a fairly low pitch. The engine must be able to turn the propeller fast enough so that it (the engine) can develop its full horsepower. For example, suppose an engine can produce 1000 horsepower at 3000 revolutions per minute. But the propeller, due to the high angle of the blades, will let it turn only 2400 revolutions per minute. At that speed the engine can produce only about 800 horsepower, which of course does not give us as good performance as we would get from 1000 horsepower.

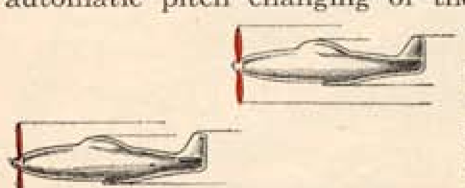


As the plane goes faster, we want a higher pitch. The faster the propeller moves forward in relation to its speed of rotation, the more angle we need on the blade. It has become easier for the engine to turn the propeller, and if we keep the same low pitch the engine will turn it too fast. This is not good for either the engine or the propeller. The pilot would have to close the throttle part way, and again we would lose power. But if we can increase the pitch of the propeller, we can keep the throttle wide open and make use of all the power available without hurting the engine by overspeeding it.

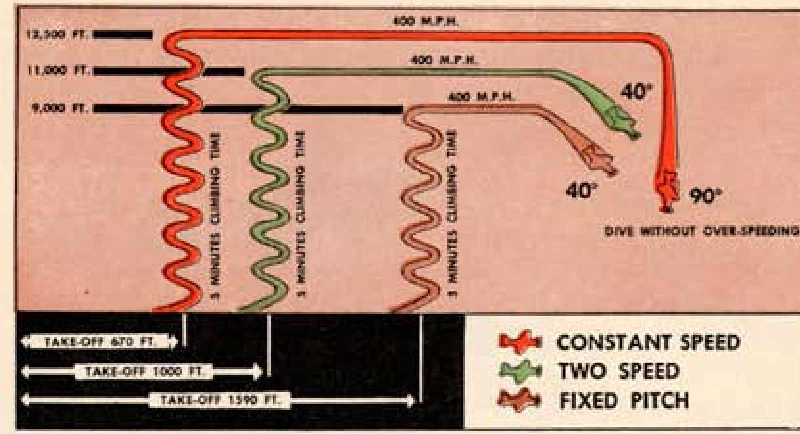
So the **variable pitch** propeller was developed. The blades were mounted in the hub in such a way that they could be twisted around during flight. The former type could be adjusted only on the ground. Now the pitch could be changed while the airplane was flying along, with no interruption in the operation of the propeller.

Some of these have a **two-position** control. There is a low pitch position and a high pitch position; and the pilot changes it from one to the other as he thinks best. It is ordinarily set so that the low pitch angle gives good take-off and climb, and the high pitch position gives good performance at high speed or some level-flight condition.

This has great advantages over the fixed pitch propeller, but it is far from perfect. Compromises are still necessary. On small, low powered planes, this is not so important, and even a fixed pitch propeller can give fairly good results for most conditions encountered. But on the high powered military planes and transports, the **constant speed** propeller control is a necessity. This is a variable pitch propeller which is controlled by a speed governor driven by the engine. The pilot can set it for any engine speed he wants, and then the engine keeps to that speed no matter what else happens. It is kept to that speed by the automatic pitch changing of the propeller. If the pilot opens the throttle, the pitch is increased. The engine is producing more power and making the airplane go faster, but the increased pitch of the



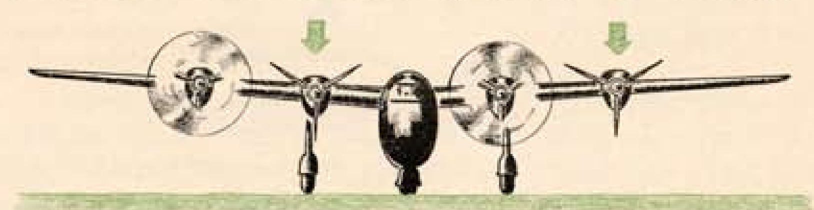
Throttle opened, pitch increases.



propeller blades holds the engine to the same speed. If the throttle is partly closed, the pitch decreases and the opposite takes place. Even in a steep power dive, the pitch increases enough to keep the engine from over-speeding. The pilot can reset the control for a different speed at any time.

This kind of propeller improves performance under all conditions. The chart gives a typical comparison between the planes which are identical except for the propellers. The propellers are all designed to give equal maximum speed in level flight.

Many multi-engine planes have **full-feathering** propellers. This means that the blades can be twisted beyond the ordinary highest pitch, so far that the leading edge is pointing directly forward. The blades are lined up with the line of flight of the plane, so that the air stream has no tendency to make the propeller go around—to "windmill."



"A variable pitch propeller is like an automobile transmission."

Low pitch

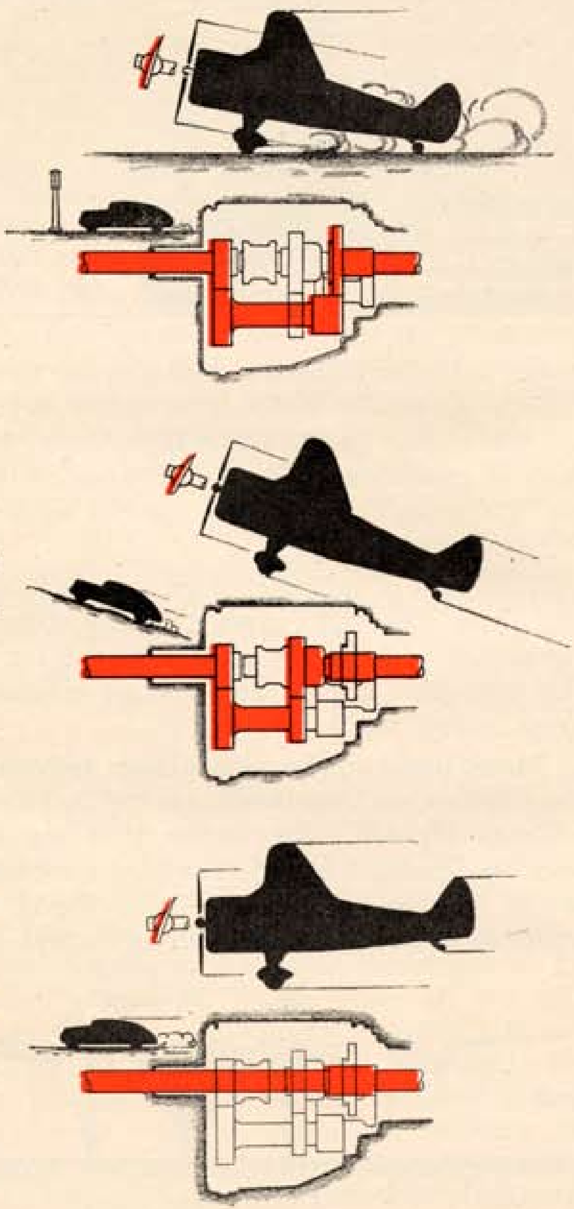
Low gear

Medium pitch

Second gear

High pitch

High gear



This is done in case of trouble with one engine, so that it can be cut out entirely. This makes it easier to control the plane and also prevents damaging the engine. With some types of engine trouble, it would soon be wrecked completely if the propeller continued to turn around, driven by the air stream. This feathering control operates very quickly.

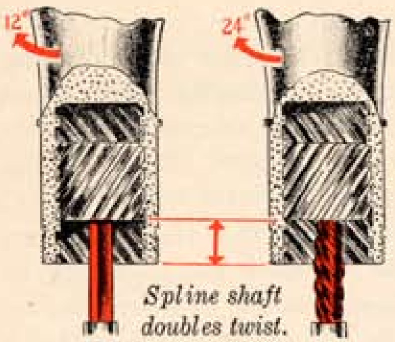
Some propellers are also designed so that the blades can be adjusted far enough to give negative pitch—to try to move the plane backward. This is useful in maneuvering large multi-engine planes on the ground or water, and can also be used as a brake after landing to shorten the distance required.

When we consider what the variable pitch propeller does, it is easy to see a resemblance to the automobile transmission. In starting, it lets the engine run fast enough to develop the power needed to get the plane in operation. When we have gotten up to speed and altitude it shifts to the proper position for level flight. It shifts down for climbing and up for diving. Some have a neutral and reverse.

But even from this brief comparison it is plain that it does a more complete job than the ordinary transmission. It is completely automatic—the pilot sets it as he wants to and then can forget it. It is continuously variable; that is, it moves gradually and smoothly from one point to another, with no definite steps or jumps. It can be set to give the best economy or the greatest performance. We could almost call it a perfect transmission within the limits of its range. Theoretically this could be done for automobiles also, but so far no practical mechanism has appeared.

We have tried to give some idea of what a variable pitch propeller does, and why. Now let us look at one and see how it does it. There are several designs of such propellers, some electrical, some hydraulic, and we will show here one of the hydraulic types.

In each blade socket, which is part of the hub, there is a piston and cylinder arrangement. But it is not a smooth piston sliding in a smooth cylinder, as we usually think of such a combination. There are splines in both piston and cylinder. That is, they have grooves which fit together and

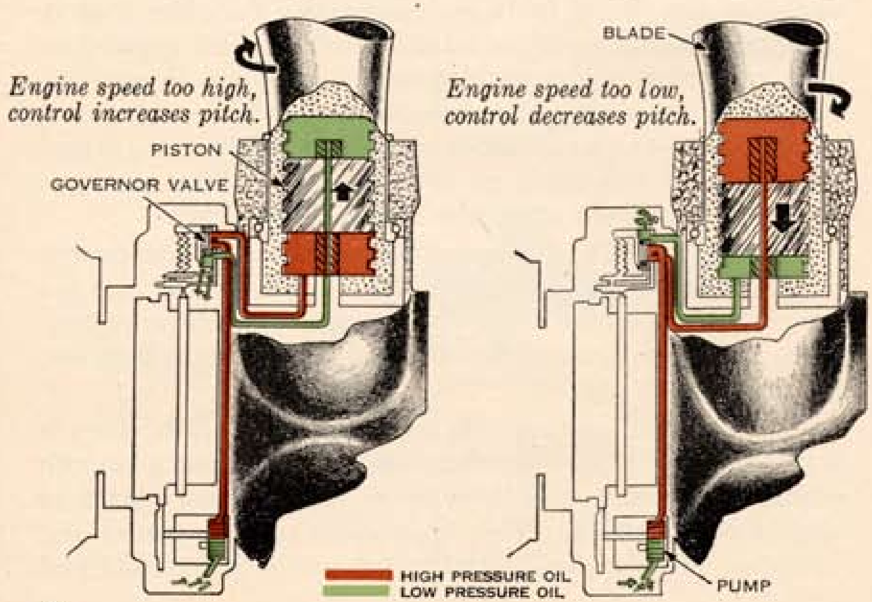


Spline shaft doubles twist.

run at an angle. Then when the piston moves up or down, the cylinder has to turn around, which turns the blade in its socket. And that, of course, is what we are trying to do.

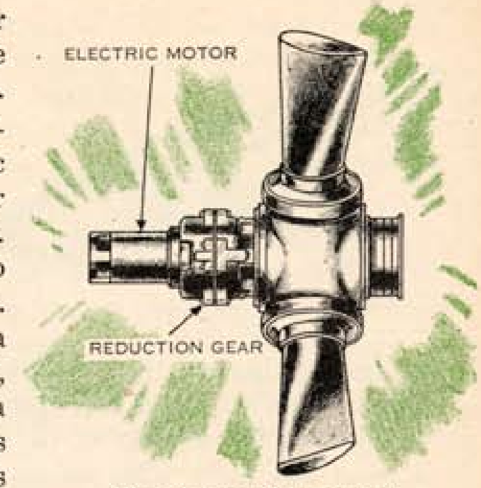
In actual practice the piston and the stationary shaft are also splined together with the same kind of angular grooves. This makes the piston turn as it slides, and doubles the turning movement of the blade.

The piston is forced in and out by oil pressure. A gear pump, which is driven from the propeller shaft, furnishes the pressure. The high pressure oil is directed to the right place at the right time by a distributor valve or governor. When the propeller starts to go too fast, this valve lets oil push the piston outward, which twists the blade to higher pitch. If the propeller drops below the speed which has been selected, the valve lets oil push the piston inward, which reduces the pitch and allows the engine to speed up.



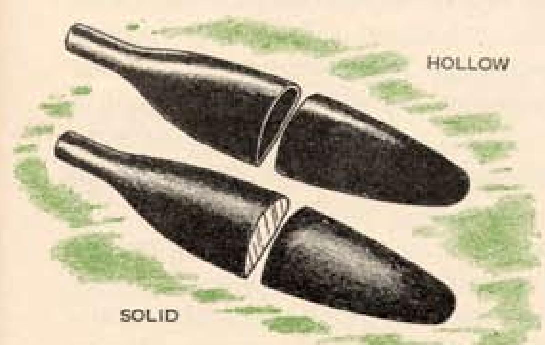
By adjusting this governor valve, the pilot can choose the engine speed he wants.

Another type of propeller control—the electric—includes an electric motor and a speed reduction gear. The motor is designed to run in either direction. The reduction gear is a two-stage planetary gear, the final drive being a bevel gear which meshes with pinions on the ends of the blades. A speed governor makes the electrical connections to start and stop the motor, which runs in one direction to increase the pitch angle and the other direction for lower pitch. It is not quite as simple as this sounds, but it does cover the high points.

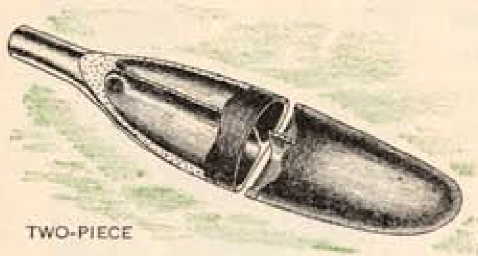


Electric propeller control.

Just a word about propeller blade construction. For large engines, most blades now are solid aluminum alloy or hollow steel. The latter type is sometimes made by forming a steel tube, squashing it down into the proper shape. Another way is to make it in two pieces. One piece is the main load-carrying member, being a strong forging with a reinforcing rib down the center. The other piece is more of a cover plate, which is brazed to the first piece. What is wanted, of course, is a propeller which is strong but light in weight.



The constant speed, variable pitch propeller solved a lot of problems, but it did not take care of everything. The propeller designer's main worry has been keeping up with the increases in engine power. Every



time the power of an engine goes up, the propeller used with it has to change accordingly. It would not be so bad if the airplane always stayed near the ground; it is the high-altitude flying that brings most of the trouble. The air becomes light and thin up there. The propeller does not have so much to bite on—there is less resistance to it. At 40,000 feet the density of the air is only one-quarter what it is at sea level. This means that a propeller which can handle 1000 horsepower at 40,000 feet must be about the same as a propeller handling 4000 horsepower on the ground. And with present supercharging methods, the horsepower at high altitudes has increased enormously.

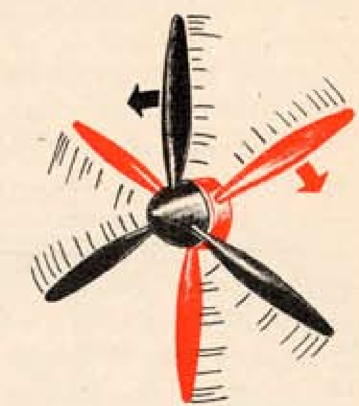
There are three usual ways to change a propeller so it can absorb more horsepower. There are some others but they are not so important.

First, we can increase the diameter, that is make the blades longer. This is about the simplest, but we have to bear in mind certain things. We must be sure there is enough clearance, so the propeller will not hit the ground or any part of the plane as it rotates. And we must consider the tip speed. The bigger the propeller, the faster the tips will travel. And when the tip of a propeller—or anything else—goes through the air at a speed approaching the speed of sound, some peculiar things happen. (The speed of sound is about 1,116 feet per second or 760 miles per hour at sea level.) In the case of a propeller, we will simply say that it becomes very inefficient at that point. So we may have to reduce engine speed or change the reduction gear if we go to a bigger propeller.

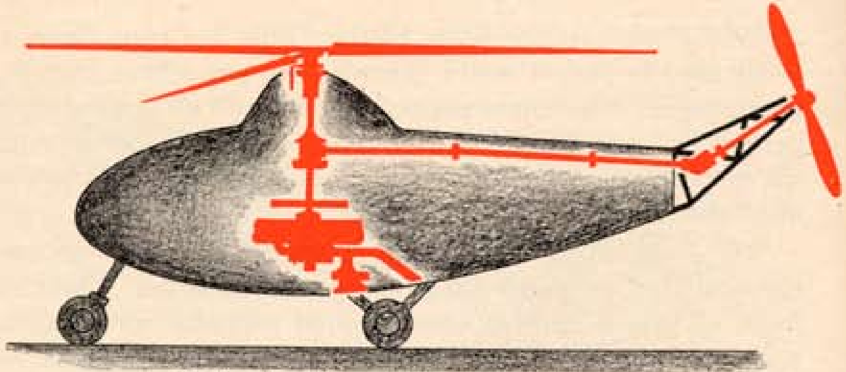
Second, we can make the blades wider. We cannot go too far in this respect, but within limits it is a good way to increase the horsepower capacity. Under certain conditions, wide blades are more efficient than narrow blades.

Third, we can use more blades. This has been done a great deal in recent years. Two-bladed propellers used to be universal. Now there are at least three on all large engine propellers, with four blades on many of them. Above four, we are likely to run into difficulties, and we would probably use **dual rotation** propellers.

In a six blade dual-rotation propeller, there is one three-bladed propeller rotating in one direction. Close in front of this is another three-bladed propeller rotating in the other direction. Thus we have a six-bladed propeller—only it is split into two parts. They are just alike, and each part has its own variable pitch mechanism. Some ingenious arrangements have been proposed for driving these two sets of blades, the most usual having the drive shaft for the front set running inside the drive shaft for the other set. Arranging six blades in this way is more efficient than putting them all into one propeller, and there is another advantage also. It eliminates the torque reaction. With one propeller there is always a reaction trying to rotate the airplane around the propeller instead of vice versa, and sometimes this can be very noticeable and annoying. With two propellers, turning in *opposite* directions, this cancels out, and greatly improves the general characteristics of the plane.



This principle has been used in some helicopter designs. We are not going to go into the details of that type of aircraft, but we will mention this one point. One of the big problems has always been this torque reaction. A helicopter has a large propeller or rotor fastened to the top of it, going around in a horizontal plane. It works exactly the same as a propeller on the nose of an airplane, but it is turned in the other direction so it pulls the plane up instead of straight forward. The trouble is that there is

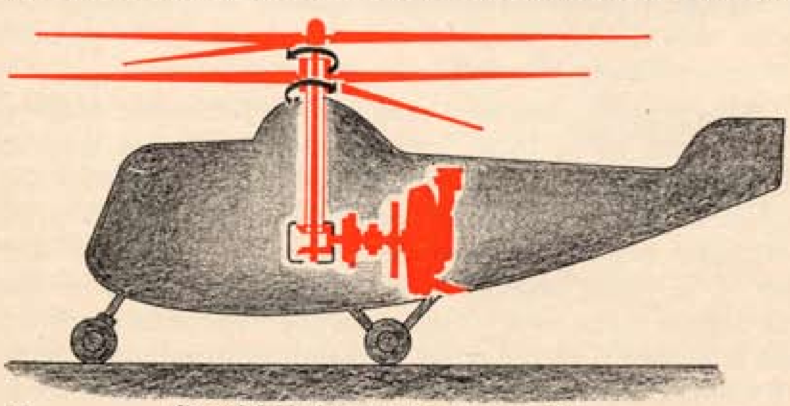


Helicopter with anti-torque propeller.

just as much tendency for the fuselage to go around the propeller as there is for the propeller to go around the fuselage. If we didn't do anything to counteract this, we would never know where a helicopter was going.

In some designs of helicopters we put a small propeller back on the tail to get away from this difficulty. The torque reaction of the main rotor is trying to push the tail sideways in one direction, and this small propeller is trying to push the tail sideways in the other direction. The controls are arranged in such a way that these forces are just equal so the tail does not move to either side.

Another arrangement which has been tried is the one we just mentioned—dual rotation propellers. Instead of one rotor on the top of the fuselage we have two, turning in opposite directions. This cancels out the torque reaction just as it does when dual rotation propellers are used on a

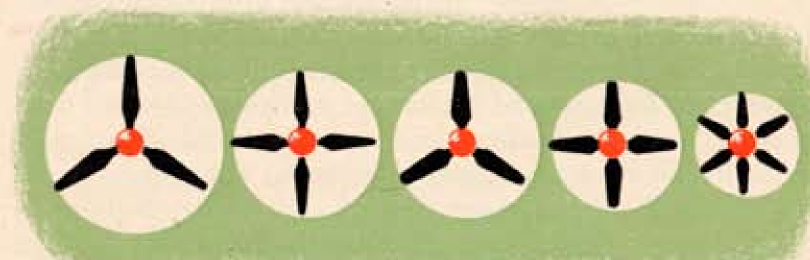


Co-axial blades cancel torque reaction.

conventional airplane, and there is no tendency for the helicopter to spin around.

Getting back to conventional airplanes and their propellers, we can see that there are a lot of things to take into consideration in the selection of the best propeller for a certain plane. And we have mentioned only the more important ones. The illustration shows an example of the possible choices of propellers for a single engine. All the propellers shown, from the large one with three narrow blades to the small six-bladed one, can handle the same horsepower. Which one should be selected depends on the plane, what it is to be used for, what flight characteristic is most desired, etc.

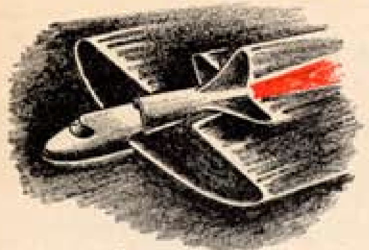
But in all this we should not lose sight of the basic principle. What we are looking for is the most efficient means to push a lot of air backward, and thus push the propeller and airplane forward.



These all handle the same horsepower.

Jet Propulsion

As we mentioned earlier, jet propulsion is another method of pushing a lot of air backward and thus making the airplane go forward. But it does it in a different way—a more direct way. In fact, it is so direct that there is no real dividing line between the source of power—the engine—and the transmission of power. They are really the same thing. So even though this book is supposed to cover the subject of power after it leaves the engine, in this particular case we are going to have to talk quite a bit about the



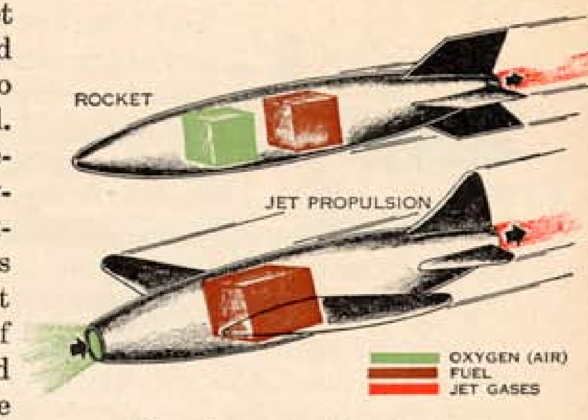
engine itself. In order to make any sense at all out of jet propulsion, we must tell a fairly complete story of the whole system.

The essentials of jet propulsion are simple and very old. Using the reaction from a jet of steam to make something move was proposed hundreds of years ago. The present variety, as applied to airplanes, takes a lot of air in at the front of the plane. It compresses this air and heats it to a high temperature by burning fuel in it. This makes it expand and push out the rear of the plane at high speed and the reaction to this push is what makes the plane go forward. In the conventional airplane, the propeller *pushes* a mass of air backward and the reaction gives it forward motion. With the jet plane, we *blow* a mass of air backward with the same results.

It is just like letting the air escape from a toy balloon. If we blow up a balloon without tying the stem, then hold it up and suddenly let go, the balloon will travel at a fairly high speed for a second or two. It will probably look as if it were going in all directions at once, but it is actually going in the direction opposite to the jet of air blowing out the stem. If we had some way of continuing to blow air out the stem, the balloon would continue to travel. A jet propulsion engine is one way of getting that continuous stream of air.

Before we get into more details of how it works, we will try to clear up two points which are not always understood. The first is the distinction between a rocket and a jet-propelled plane. We often hear the latter called a rocket plane, and there is some excuse for it. Both are propelled by shooting a jet of gases out the rear end. So in a broad sense a rocket is jet-propelled. But the way the two terms are used at present, the difference lies in the fuel and combustion

process. The rocket carries its own fuel and *also its own oxygen* to burn with the fuel. This could be something like black powder, which is an explosive containing its own oxygen, or it could be tanks of liquid fuel and liquid oxygen, which are combined to produce power. On the other hand, the jet propulsion plane carries its own fuel, but depends on the air—that is, the oxygen in the atmosphere—for combustion. It cannot work at all without air. It cannot fly above the limits of the earth's atmosphere any more than an ordinary airplane can. A rocket does not depend on air in any way. It can travel anywhere—or it could if it could carry enough fuel. It uses its fuel so fast that so far it has not been a very practical means of transportation. But if we are thinking about a trip to the moon, it will have to be a rocket, not a jet propulsion plane.



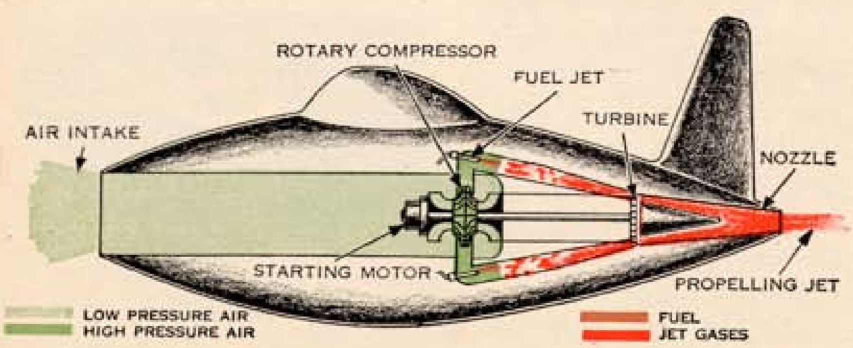
The other error which is so often made is thinking that the jet pushes against the atmosphere in order to push the plane forward. This is not the case. The jet does not push on anything outside the plane. What makes it go is the reaction between the jet and the plane itself. It is like the kick of a machine gun shooting a continuous stream of bullets out the rear end of a plane. In a rocket or jet propulsion system we are continuously forcing air or exhaust gases—instead of bullets—out the open end of a tube. There is the same

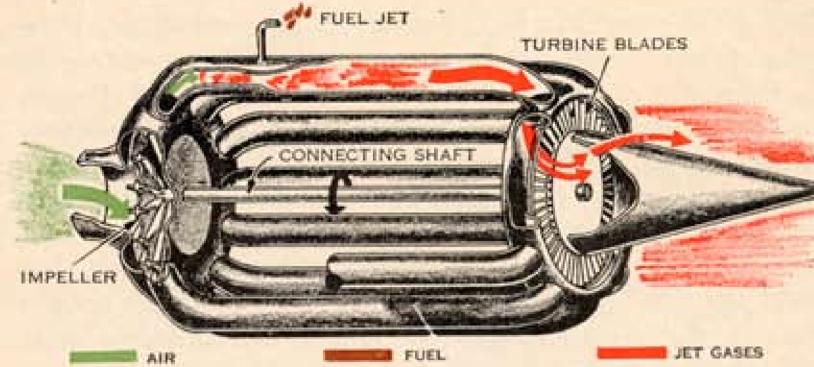
kind of kick or reaction on the closed end of the tube. It is the reaction of the force necessary to push the air out of the tube at that high speed. Getting a little technical, the force is equal to the mass of the air blown out, multiplied by its change of speed relative to the tube. Just as in any elementary problem in mechanics, F = MA, *force equals mass times acceleration.*

Now let us look at a jet propulsion system in more detail. The plane does not look very much different than usual. The main thing we notice is that there is *no propeller.* There is a big hole in the front instead. Then we notice there is a hole in the tail, too. It looks as though there were just a tube running straight through, open all the way.

But there is quite a bit of mechanism inside. First, there is a **compressor**—a supercharger—which takes the air coming in the front hole and compresses it, squeezes it together so the same amount of air takes up less space.

This compressed air is forced into a number of tubes, which we might consider the cylinders of the engine. In each of these is a **combustion chamber**, where an injector sprays a continuous stream of fuel into the air. This fuel combines with part of the air to form a combustible mixture, just as in any internal combustion engine. There are some means to start it burning and after that it burns continuously, as the temperature is high enough to ignite each new part of the mixture as it is formed. The burned mixture





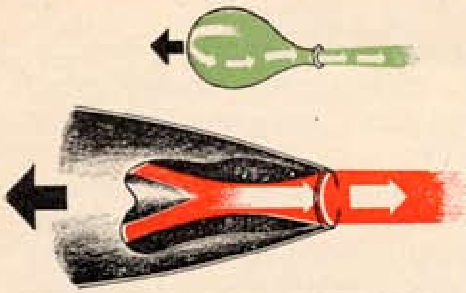
expands enormously, of course, and the heat also expands all the extra air, which is there, but is not needed for combustion. The pressure goes up a great deal, and the mixture of air and exhaust gases tries to get out as fast as possible.

But before it can get out, it runs up against an obstacle. This is a **turbine**, fastened on a shaft which runs forward to the compressor. The hot gases make the turbine go around at high speed, just like steam turning a turbine in an electric generating plant. This turns the compressor at the same speed, as the two are connected solidly to the same shaft. The turbine drives the compressor and nothing else. It has nothing to do directly with driving the plane.

Some of the energy in the hot gases is used up in driving the turbine, but not all of it, and the gases keep on pushing out the tube. The tube narrows down at one point to form a **nozzle**. This increases the speed of flow and the gases, still hot, shoot out into the open atmosphere at very high speed. This is the jet which drives the airplane through the air.

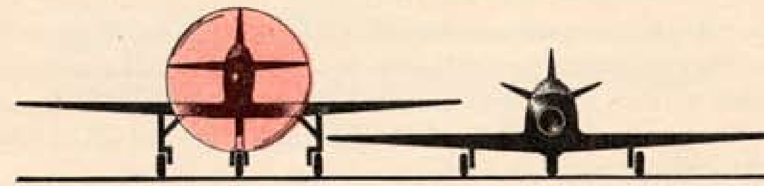
There must be an electric motor or something to rotate the compressor in order to start the whole system operating. After that the turbine drives the compressor. It is essentially the same thing as the turbo-supercharger used on some aircraft engines, except that there we are using waste exhaust gas from a reciprocating engine and here we are taking away part of the energy from the gases which are actually propelling the plane. And we are using a great deal more power; in fact, a fairly large percentage of the total power developed in the combustion chambers goes to drive the compressor. It handles more air and it must furnish a much higher pressure than an ordinary supercharger. The pressure must be greater than the pressure of the jet out the rear end of the plane because otherwise the jet would blow out the front as well as the back. In a rocket the front end of the tube is definitely closed; it is solid and the driving force pushes on it. Here we have a hole in the front end and the compressor pressure must plug up that hole.

So, jet propulsion is just another way of making an airplane go by forcing a lot of air backward. But is it any better than doing it with a propeller? How does it compare with the conventional engine-propeller combination?



The engine itself is not as efficient as the reciprocating engine ordinarily used. That is, it takes more fuel to produce the same power. This will no doubt be improved in the future, as more work is done on design and materials— particularly materials to stand higher temperature. The efficiency of propulsion, or in other words, the effectiveness of the stream of air in making the plane go, depends on the speed. It improves as the plane goes faster, as the speed of the plane approaches the speed with which the jet leaves the plane. But in taking off and at low speeds the efficiency is low.

Why use jet propulsion then? What advantages make it worthwhile? It does not have to use high octane gasoline; it can use kerosene or anything along that line. Because there is no propeller we can use a very short or low landing gear on the plane which is convenient. In some ways a jet propulsion engine is simpler than a conventional engine and offers a possibility of saving weight. But these are incidental reasons. The real crux of the matter is in just one

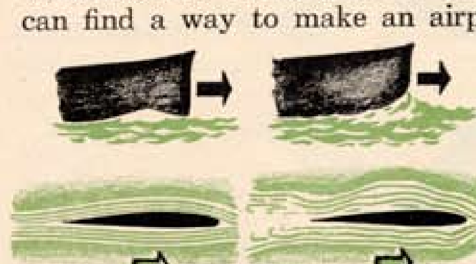


A propeller must have ground clearance.

word—*speed*. A jet propulsion plane can travel at speeds practically impossible for a propeller-driven plane.

The reason for this goes back to a problem we just touched on earlier. It has to do with the peculiar things which happen when an object moves through the air at a speed greater than the speed of sound. We do not have space to go into it here, but will simply say that air does not behave as it does at lower speeds. It does not flow around an object in the usual way; it piles up in front of it instead. It is something like a wave piling up in front of a boat in the water. But it is worse because the air has no upper surface for the wave to rise up into; it has to be pushed ahead by the object. The result of all this is a sudden, very great increase in the amount of power needed to drive the object.

An airplane does not have to actually reach the speed of sound to have this trouble affect it. The air flow is irregular over certain parts of the plane and is speeded up. The propeller is rotating as well as going forward and it is usually the first to feel the effects of this so-called "compressibility" of air. At speeds around 400 miles per hour there may be a sudden dropping-off in propeller efficiency, while the rest of the plane is unaffected. Therefore, if we can find a way to make an airplane go without using a propeller, we can increase its top speed considerably. And that is what jet propulsion does.



The smooth flow changes at high speeds.

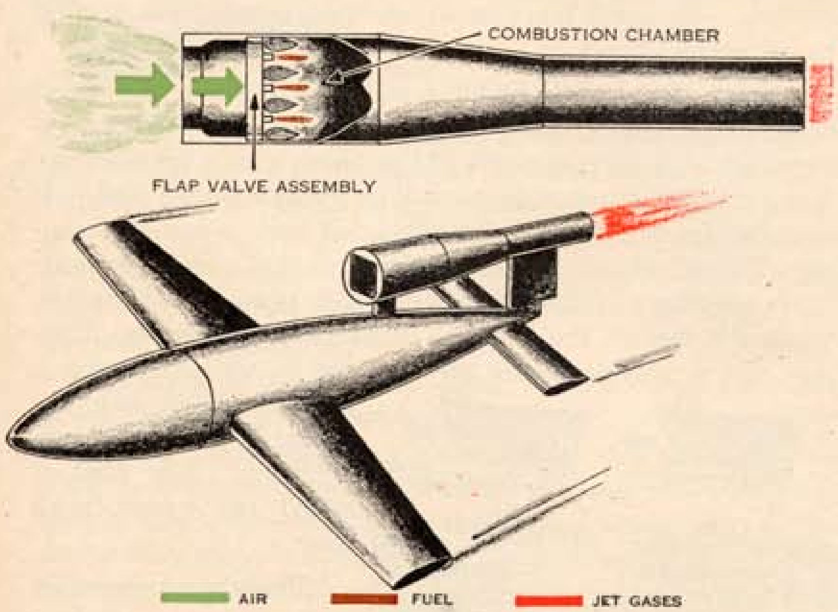
The advantages of jet propulsion are especially noticeable at very high altitudes. The speed of sound is less, due to the extreme cold, which limits the propeller still more, and with the lower air density it is difficult to keep the engine power from dropping off. The jet-propelled plane does not have the first trouble and the power and efficiency of its engine may actually increase at high altitude.

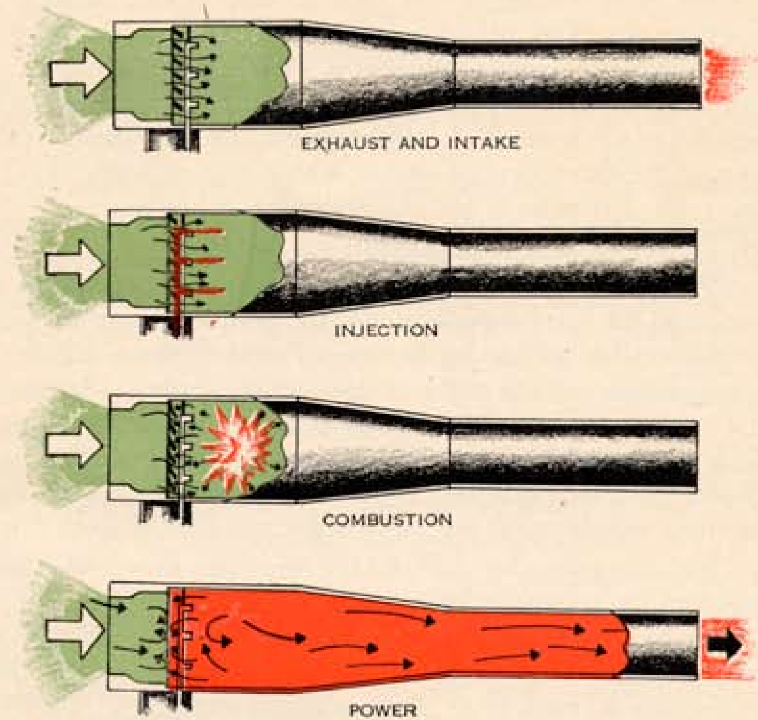
Thus at the present time, jet propulsion is aimed directly at the field of high speed, high altitude flying.

Before we leave this subject, we will mention briefly a different type of jet propulsion. This is the type used in the robot bombs of 1944.

The main features of this are that its action is intermittent instead of continuous, and that it has no compressor or turbine. The air is forced into it and compressed slightly by its motion through the air.

Let us assume that it is already moving at a fairly high speed. Air is forced into the tube through the flaps or shutters in the front opening. Fuel is injected into the slightly compressed air and ignited in some way. This raises the pressure immediately, which pushes the flaps down and closes the





front end of the tube. The hot gases then push against this closed end and shoot out the back open end just as in the previous system. When the pressure inside the tube has dropped far enough, the flaps in front are forced open again by the outside air, and the same cycle is repeated. There are about 45 explosions per second; in other words the whole cycle takes only 1/45 of a second.

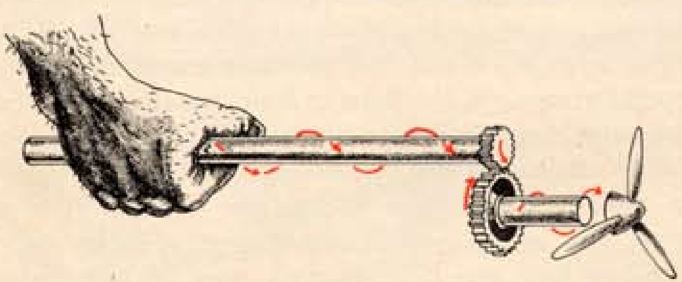
This is a comparatively inefficient system, and very wasteful of fuel, but it is a simple way of doing what we have mentioned so often—pushing a mass of air backward and thus making the plane go forward.

We have discussed two general methods of making an airplane go. The broad principle is the same in both of them, but the way in which it is used is quite different. In one case we have an engine turning a shaft and propeller which pushes a mass of air backward. In the other case we have a different kind of engine which acts directly in blowing back a stream of hot air and exhaust gases.

What is going to happen in the future?

We don't know. In some quarters, great things are expected of jet propulsion. Other people swear that the propeller can never be beaten. There is some talk of a combination of the two in the same plane—a propeller for low speed, low altitude work, and a jet for high speed, high altitude flying. One thing we can be sure of. The most effective, most efficient system will survive, and each method will be used on the job for which it is best fitted.

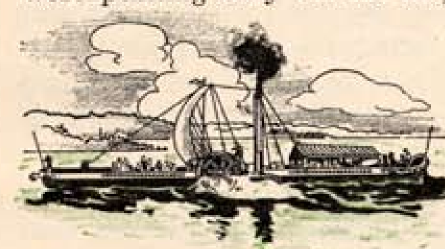
But suppose we leave the airplane now. We have touched on transportation on land and in the air, but we still have one more medium—the sea. In the next section we will show how the internal combustion engine is used in the marine field, how power makes a boat go through the water.



MARINE

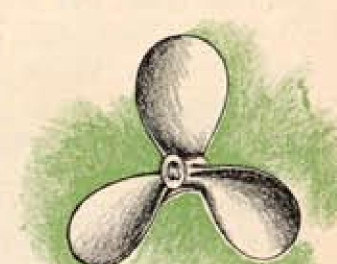
A lot that we have said about airplanes also applies to boats. The principles of making them go are very much the same, but because water is different than air, we find some differences in the way the principles are put to use.

Most of the earlier power ships used paddle-wheels to move them through the water. The side-wheelers had a big paddle-wheel on each side partly under water, so that when the paddles were moving backward they were pushing on the water and when they were moving forward they were pushing only on the air, with little effect. We can see a resemblance to the wheels of an automobile, which push backward on the ground and thus make the vehicle go forward.

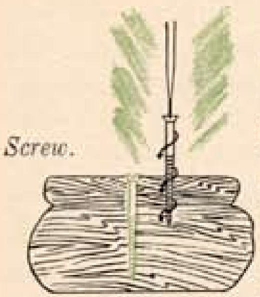


But we get closer to it if we compare it to an airplane. We have mentioned several times that an airplane moves forward because the propeller is pushing a lot of air backward. A boat moves forward because something is pushing a lot of water backward. The paddle-wheels are pushing a stream of water back on each side of the boat, and the reaction to that push makes the wheels—and the boat—move ahead.

When we get to most present day ships the resemblance is even clearer, because they use propellers just like airplanes do. These propellers are a different shape because they are working in water instead of in air, but they work just the same way.

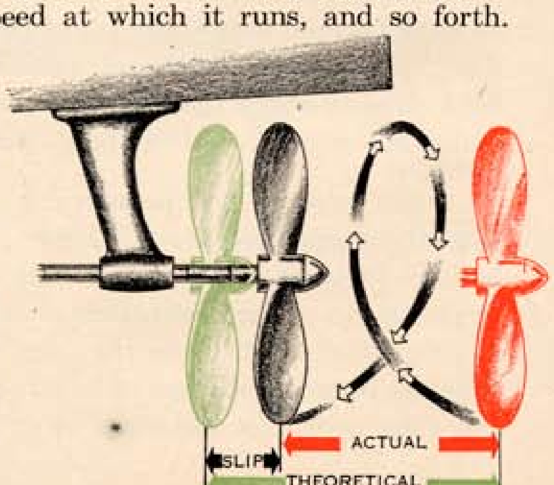


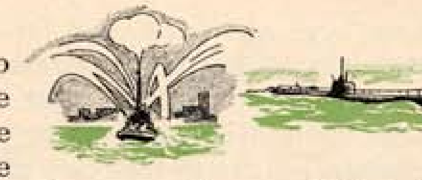
Screw.



They are often called **screws**, or **screw propellers**, and that is a good name for them. A propeller actually is a section of a screw, and it screws itself through the water just like a screw goes into a piece of wood. It moves a little bit forward with every revolution. It does not move forward quite as far as it should theoretically, because water is not solid like wood. It gets churned up by the propeller and the hull of the boat, and the propeller slips. And **slip** is exactly what we call it. Slip is the difference between the distance the propeller *should* move in one revolution (if water were solid) and the distance it actually *does* move in one revolution. It is the same situation we had with the airplane propeller—geometric pitch minus effective pitch. The slip varies depending on the kind of ship, the ship speed, engine speed, and so forth, and in figures may range from 10% to 50% or 60%. In other words, the screw may actually move almost as far as it should theoretically, or it may move less than half that far.

The shape and weight of the hull have a lot to do with the speed and efficiency with which we can make a boat go through the water. Each ship has a natural speed at which it will run most efficiently. All these things make a difference in our choice of drive mechanism and propeller —the size, shape, speed at which it runs, and so forth. There are some general rules about these things which we will get into later, but a lot of it is a "cut-and-try" problem. Quite often we cannot figure out on paper the best propeller for a new ship, and sometimes two or three are tried before the most efficient one is found.

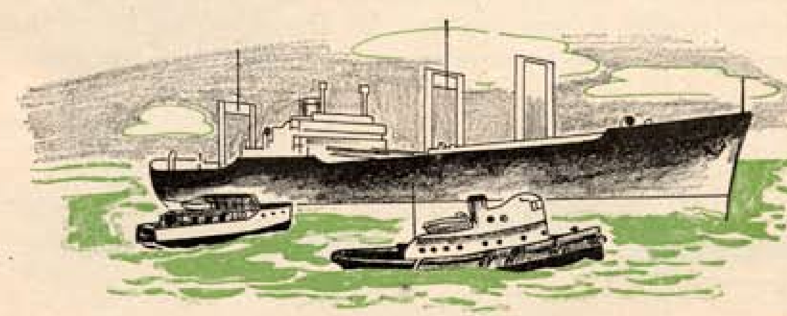




But before we get into any more details on the propeller, let us look at the rest of the system. We know we must have an engine someplace, and that it is an internal combustion engine. Steam engines and steam turbines are used a great deal for marine service, but as we stated in the beginning of this book, we are limiting ourselves here to internal combustion power transmission. That is a big enough subject by itself. In the internal combustion field we have gasoline engines and Diesel engines, but we will not try particularly to distinguish between those classifications. A number of gasoline engines are used in small boats, but in the larger sizes the Diesel engine has a vast majority. These larger sizes usually have a more complex system of power transmission and consequently we will pay more attention to them, so most of the information in this section will be on Diesel engine installations.

Diesel engines are used on a lot of different kinds of boats—passenger and cargo ships, ferries and tug boats, yachts, many military and Government vessels, and various others. This means different kinds of jobs to do, and thus different arrangements for hooking up the engine to the propeller.

All through this subject of marine drive systems we will find that we cannot be as definite or thorough as with the automobile—or even the airplane—because there is too much variation in the field. There are vessels of all

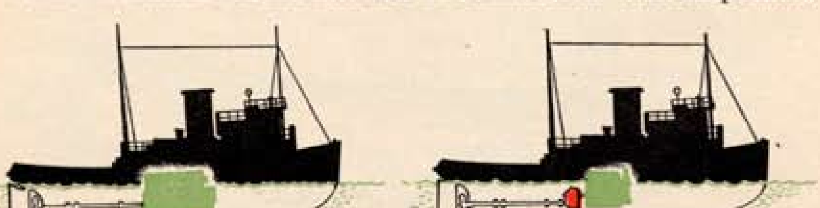


sizes, large and small, and for all sorts of purposes. And there is much less standardization even in ships of the same size. There are more different ideas of the proper way to build them. We cannot cover them all in a book such as this, but will try to take care of some of the fundamentals. But we must remember that the examples we show are examples only, and may be only one out of many ways of doing that particular job.

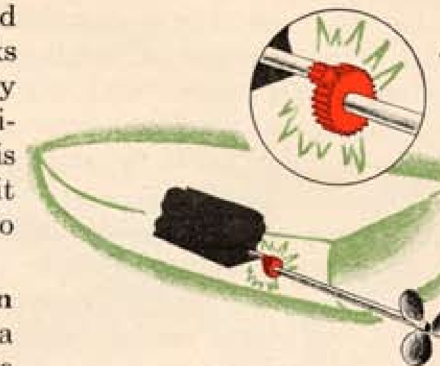
Propeller Drive

The simplest way to connect an engine and a propeller is to join them solidly together with a straight shaft, and that was the first arrangement commonly used. The propeller turned at the same speed as the engine, and turned all the time the engine was running. In order to make the boat back up it was necessary to reverse the engine itself; that is, we could change the timing of the valves and ignition so that the crankshaft would revolve in the opposite direction.

This arrangement worked all right on certain jobs, though it was rather clumsy and sometimes inefficient. But it ran into trouble when engines began to change, when we started to build engines to run at higher speeds. By running engines faster we can get more power from them, or—what is really the same thing—we can get the same power from a smaller, lighter engine. The old, heavy Diesel engines with a top speed of less than 200 revolutions per minute were fine for this system, but when we went to higher speeds it was too fast for the propeller. It is the same situation we mentioned in connection with airplanes.



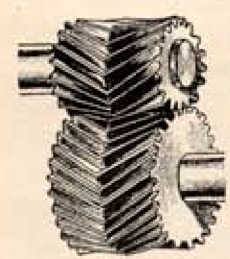
So we add a reduction gear.



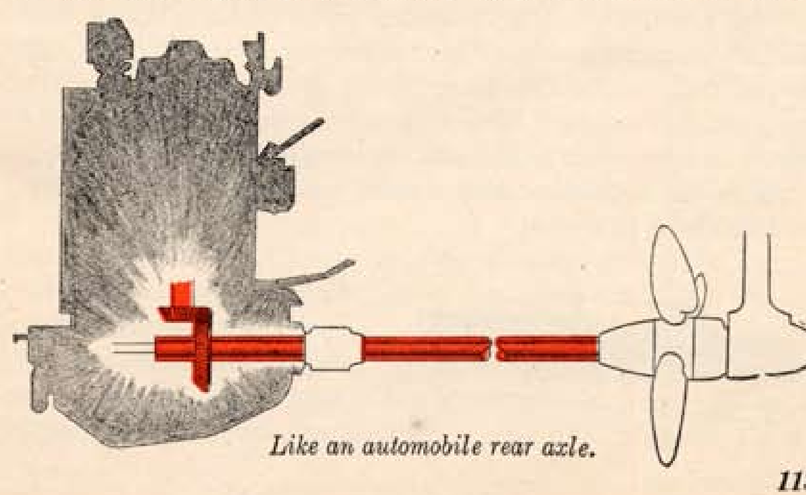
Each propeller has a speed range in which it works best. The best speed may vary according to conditions under which it is working, but in general it is lower than we want to run the engine.

So we add a **reduction gear.** By that we mean a *speed* reduction gear. We can put a little gear on the engine shaft and a big gear on the propeller shaft. This lets us run the engine fast and the propeller slow. Usually the ratio is around 3 to 1 or 4 to 1.

Various types of gears have been used for speed reduction. For large engines and heavy loads, herringbone, or double helical, gears are most popular because they eliminate side thrust. They are likely to be much wider than we usually think of gears, in order to spread the load over as great an area as possible. But they of course do just the same thing as the simple spur gears we showed above.



One recent installation which is somewhat unusual uses a bevel gear arrangement very much like an auto-



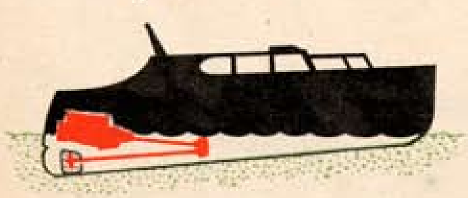
Like an automobile rear axle.

mobile rear axle. The engine stands up on end, the crankshaft being vertical. A small pinion is fastened at the bottom which meshes with a ring gear on the propeller shaft. Thus we turn the power around a corner and get our speed reduction at the same time.

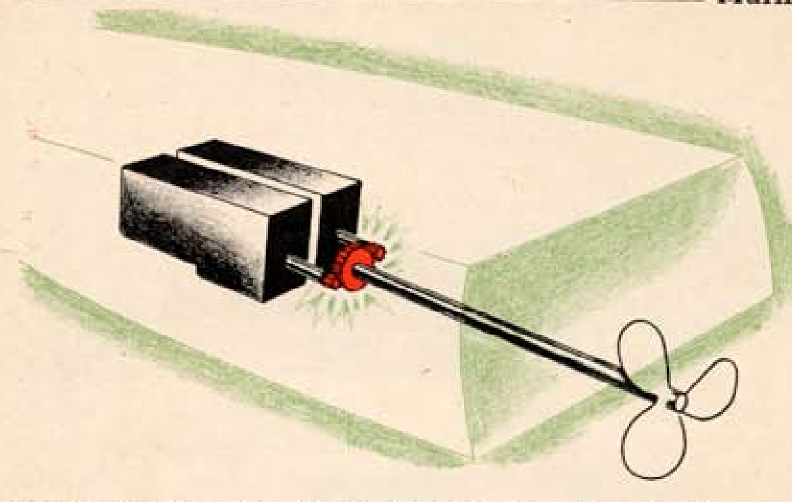
Any of these arrangements adds weight and complications to the system. But the advantages more than make up for it. As a definite example, take a small cruiser with a 100 horsepower engine running at 3000 revolutions per minute. We would use a propeller 13 inches in diameter. With a 3 to 1 reduction gear, keeping the propeller down to 1000 R.P.M., we could use a 24 inch propeller. The increase in overall propulsion efficiency from this larger propeller at slower speed would more than make up for the additional cost and complication by a wide margin.

And there are some other advantages in getting rid of that direct, solid connection between engine and propeller. It lets us locate the engine in places we couldn't put it before. It doesn't have to be directly in front of and in line with the propeller. We can often save space, or at least we can put the engine in a more convenient place which will give us more usable space. Just as an example we can put the engine in the stern of the boat, with a shaft running forward, and gear it to another shaft which runs backward again to the propeller at the rear. This gives us much more space to use in the center of the boat.

The arrangement we just described of the vertical engine with pinion and ring gear is another example of what can be done along this line. There are a lot of different ways we can arrange the engine, reduction gear, and propeller, and it usually depends on the particular conditions —where we want the most space, what the boat is to be used for, and so on.

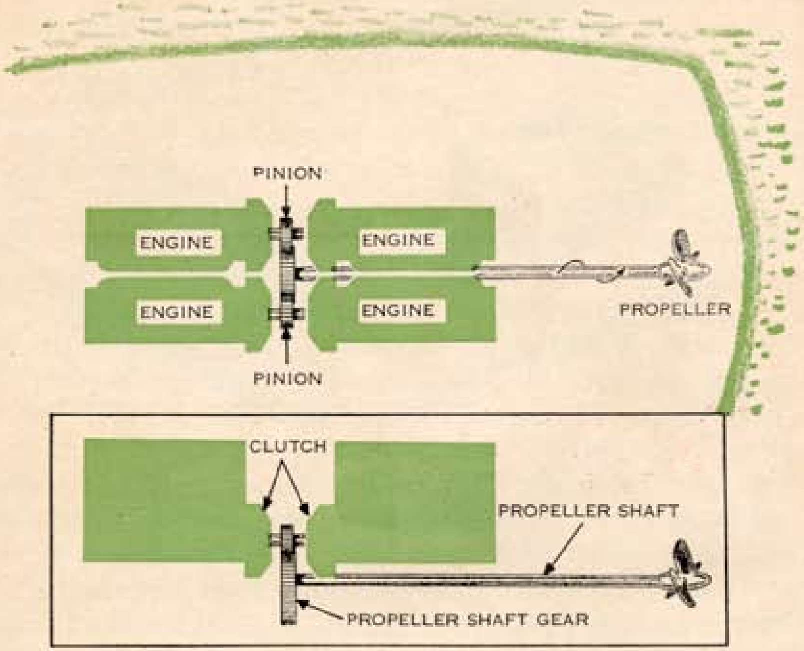


There is another thing which is made easier by the use of a reduction gear—or at least some kind of gearing—between the en-



gine and propeller. That is the use of more than one engine to drive a single propeller. Quite often it is easier and more practical to have two or more engines drive one propeller than it is to have one great big engine. If we are going to have a set of gears in the system anyway it is a comparatively simple matter to add another gear. Then we have two engines and two gears driving one gear which is fastened to the propeller shaft. The engines are turning in the same direction. One gear is exerting a force downward on one side of the propeller shaft gear, and the other is exerting a force upward on the other side. So they are both twisting the propeller in the same direction, and the torque of the two engines is added together. If the gears on the engines are small and the gear on the propeller shaft is large, we have our reduction gear and at the same time a means of hooking up two engines to one propeller.

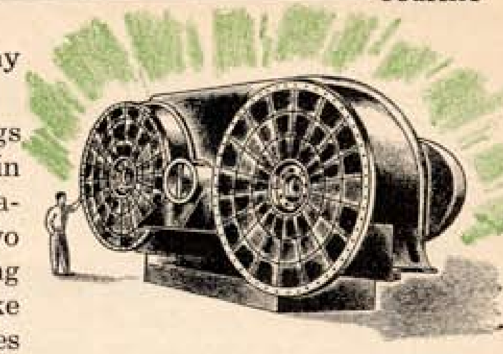
Two engines are not the limit for this system. One arrangement which has been used a great deal by our Navy is known as the "quad". It consists of four Diesel engines fastened together driving one propeller. It is essentially the same as we showed above, with two more engines added on the other side of the gear box. The gearing is in the middle, with two engines driving each pinion, or small gear. These gears are moved up toward the top of the large gear, so that the propeller shaft can pass under



one pair of engines. Each engine has its own clutch, a friction disc clutch just about like that in an automobile. This allows any engine to be disconnected and stopped at any time without interfering with the operation of the others.

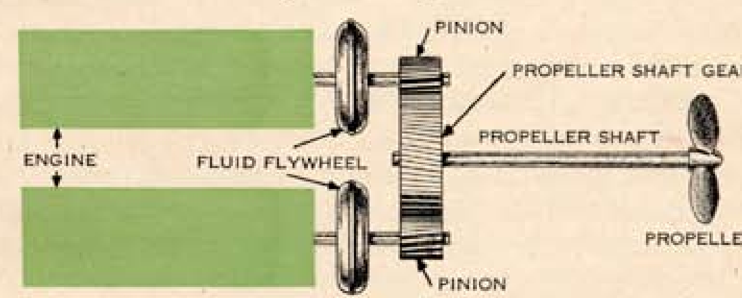
The quad was used partly because engines were needed at once and this type of six-cylinder Diesel could be obtained in a hurry and the larger engines could not. It might not be done this way under ordinary circumstances, but it did prove to be very satisfactory. The way in which the engine had been designed at an earlier date made it possible to put four of them together in a very compact unit.

Many installations of a Diesel engine and reduction gear make use of a **hydraulic coupling** or **fluid flywheel**. This works exactly the same as an automobile fluid flywheel, but may be a lot bigger. Some of them are almost twice the height of a man. It is placed between the engine and reduction gear, and prevents torsional vibration of the engine from reaching the gears. It also protects the system



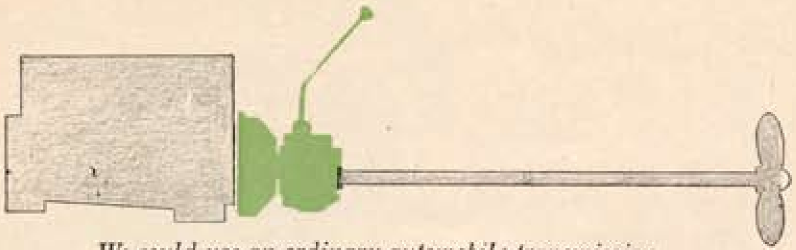
from damage due to any sudden shock loads.

Hydraulic couplings are especially valuable in multiple engine installations, where we have two or more engines driving one propeller. They make it easier for the engines to share the load equally, and prevent any trouble in one engine from interfering with any other engine. Many of them have an arrangement for changing the amount of oil inside the coupling, which means that the amount of slip—and thus the speed—can be changed. When the oil is entirely removed, the engine is completely disconnected from the gear and propeller, just as if there were a friction clutch in the system. Thus one engine can be shut down for repairs or service, while the ship continues under the power of the other engine or engines.



Reverse Gear

A boat must be able to back up. It is like an automobile in that respect. In both cases we do practically all our traveling in a forward direction, and if we always had plenty of space around us we could probably get along all right without any way of reversing. But we have crowded streets, garages, parking in small spaces, and such things, and with



We could use an ordinary automobile transmission.

boats we have to maneuver them into docks and we often get them into places where the only way out is by going backward. Also the only brake we have on a boat is the propeller trying to push it in the opposite direction. So we must have on a boat something corresponding to the reverse gear in an automobile transmission.

There are several ways we could do this. We have already mentioned one in describing the direct-connected propeller. There we stop the engine itself and make it run in the opposite direction. This gives us the result we want, and has been used widely in ships, but it has some disadvantages. It is easier to build an internal combustion engine which always turns in the same direction, so usually we build them that way and put something behind the engine to give the same effect.

Reverse gears are made up of various combinations of gears and clutches. We could take an ordinary automobile transmission and put it between the engine and the propeller. We would need a clutch to disconnect it from the engine while we shifted gears, and with this combination we would be able to go forward or backward, or stand still in neutral.

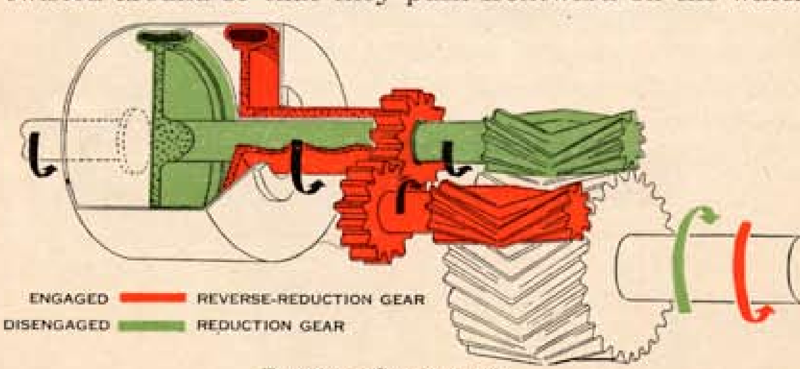
We could arrange this transmission to give the speed reduction we wanted also. The reverse gear is often combined with the reduction gear, though not in the way we have just mentioned. We show one arrangement which is commonly used. The engine drives the outer case of a double clutch. When the first clutch is engaged and the second clutch is released, the power flows from the engine to the first clutch, which drives an inner shaft passing straight through the first set of gears without being con-

nected to them. This shaft drives the pinion on top of the larger gear, and so we have simply an ordinary reduction gear driving the propeller in the forward direction.

To get reverse we release the first clutch and engage the second one. The power then goes by way of the second clutch to drive the hollow shaft which is fastened solidly to the first gear. This drives the second gear which in turn drives the lower pinion meshed with the large reduction gear. As the arrows show, the large gear is turning in a direction opposite to that in the first case, so the propeller is turning in a reverse direction. Thus we always have the reduction gear in operation, but whether or not the reverse gear is working depends on which clutch is engaged. When both clutches are released, the engine is disconnected from the rest of the system and we have no drive in either direction.

There are otner types of reverse gears, including some using arrangements of planetary gears. And there are other ways of getting the same result without using gears to make the propeller shaft go around in the opposite direction. One of these ways is to do it electrically. We will discuss this in the next section, in which reversing is just one feature of the electric drive.

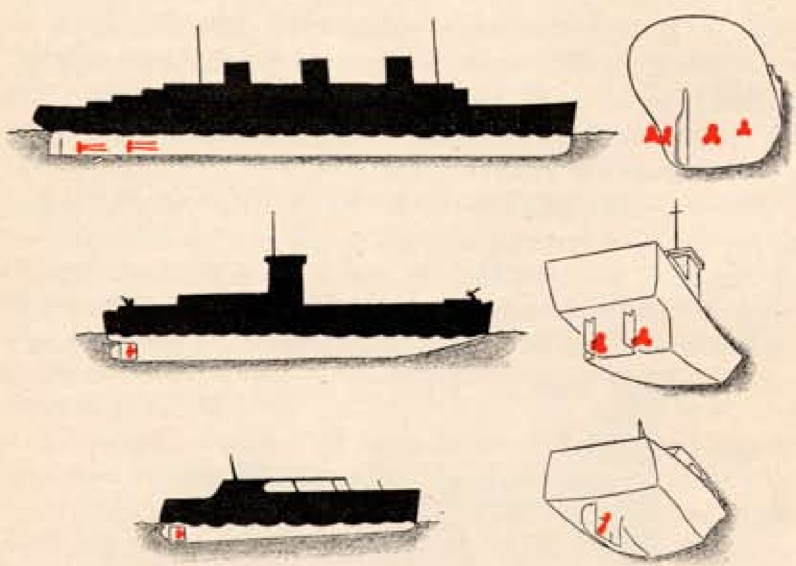
We will also discuss a little later another way of doing it—by using a reversible pitch propeller. In this case we always turn the propeller in the same direction, but we twist the blades around to a different position. They are twisted around so that they push frontward on the water



Reverse-reduction gear.

instead of backward. Thus they try to make the boat go backward instead of forward. But we will see more details of that in the section on propellers.

We might mention here that a ship often has more than one propeller. Many of them have two, and some even more. This ordinarily means two or more complete systems of engine or engines, reverse and reduction gears, propeller shaft, and propeller. One ship using the quad had two propellers, so in this case we actually had eight engines driving the vessel. With two propellers, they are arranged to turn in opposite directions; that is, one goes clockwise, the other counter-clockwise, when they are both driving the ship forward. They can be used to assist in steering and maneuverability by reversing one propeller while the other is kept in the forward position. This gives somewhat the same effect as pushing on one oar and pulling on the other in a row boat.



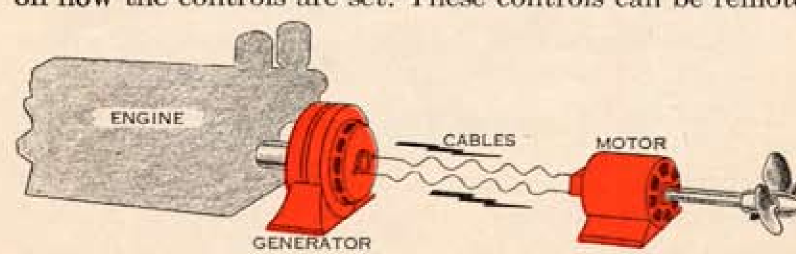
Electric Drive

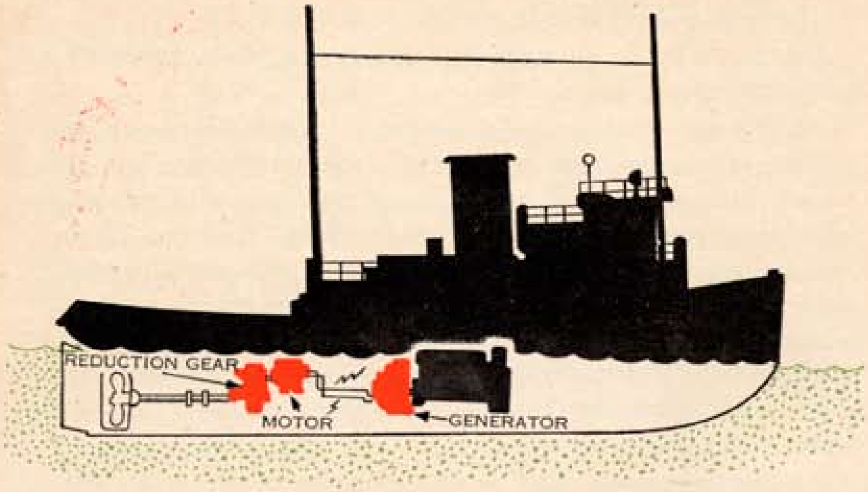
Another way to connect a Diesel engine to a propeller is by electricity.

The **Diesel-electric drive** used on many ships is essentially the same thing we talked about for busses and railroad locomotives. There is no mechanical connection between the two—nothing but wires. A large electric **generator** is fastened solidly to the engine. As the engine drives this around it produces electricity which is carried by large wires, or cables, to an electric **motor**. This motor is connected to the propeller shaft, and as the electricity from the generator causes the motor to run, it of course turns the propeller.

The generator and motor may be of the alternating current (A.C.) type, but we are more likely to find direct current (D.C.) used. The speed of the motor varies according to the voltage furnished to it by the generator—high voltage, high speed—low voltage, low speed. We won't try to go into details of the electrical control system, but will simply say that means are provided to change the voltage of the generator any time we wish to. Thus the speed of the propeller and the speed of the ship can be easily controlled, and the controls can be put anywhere on the ship.

The same thing holds true for reversing the ship. Instead of having any kind of gearing to make the propeller shaft rotate in the opposite direction, the electrical hookup is arranged so that the propelling motor can be run the other way. The engine and generator always run in one direction, but the motor can run either way depending on how the controls are set. These controls can be remote,





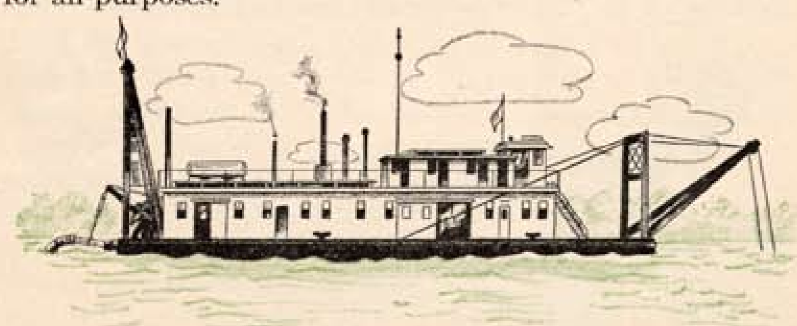
so the whole system can be run from the bridge or pilot house or any other place on the ship selected for it. Thus one man can stop or start the ship, back it up, make it go faster or slower—all without having to relay messages to and from the engine-room.

We often have a reduction gear even with this electric drive. It is placed between the motor and the propeller. The main reason for it is that if we can run the electric motor faster and reduce the speed behind it, we can use a smaller, lighter motor for transmitting the same horsepower. And it also gives more flexibility in arranging multiple motor installations. There are all sorts of different combinations used with the electric drive just as with the mechanical drive—two engines and generators with two motors geared to a single propeller, one engine with two motors and two propellers, four engines with four motors geared to one propeller shaft, and various others.

The Diesel-electric equipment for ships is heavy and expensive, just as we found out earlier in connection with land transportation. But the equipment it replaces is quite heavy, too, and it has a number of advantages. The engine or engines can be located anywhere in the ship, even up on deck if there were anything to be gained by it. And they can be put in any position, that is they do not have to

be lined up with the propeller shaft. The only thing which is really necessary is that the motor be in the right position and in line with the propeller. For the rest of the equipment we can lead the cables any place. This is a big help to the ship designer in laying out the ship, as he can arrange things so they will be most efficient for the particular job the vessel is supposed to do. There is no long propeller shaft, which sometimes wastes space which would otherwise be useful. The electric drive does not save on weight or space, but it allows us to make better use of the space, which usually means more money earned by the ship regardless of its business.

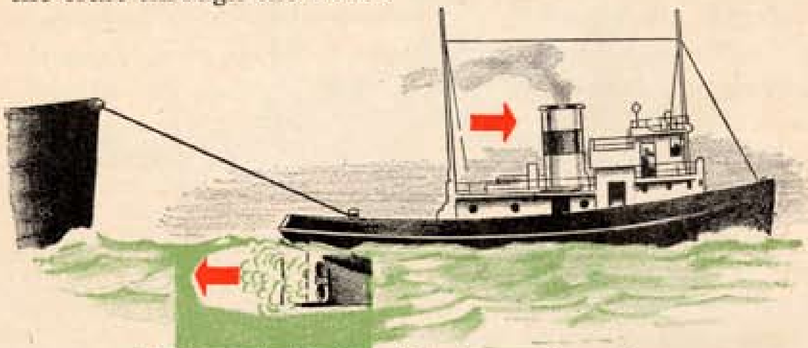
Another advantage of this type of drive is that it means we have a complete power plant on board which can be used for many things beside propelling the ship. Many of the smaller auxiliary loads can be handled by the generators while they are driving the ship, but the greatest value is on jobs where the auxiliary load is high when the ship is at rest. No separate power plant must be provided for handling cargo, as the full power of the engines is available when the ship is at the dock. Fire boats, dredges, and some fishing boats can make full use of this arrangement, as their greatest requirements come when the engine is not needed for propulsion. The main engines are really acting also as auxiliaries, and the controls are set up in such a way that they can be switched from one to the other very quickly. It usually means that the vessel is better equipped for all purposes.



The main engines act also as auxiliaries.

Propellers

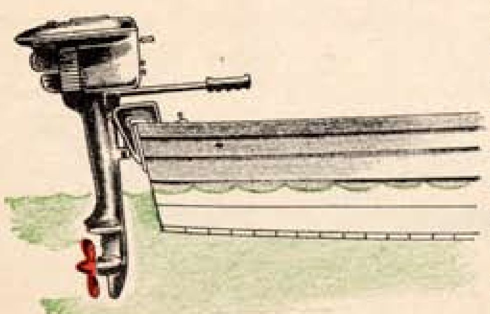
A propeller is sometimes defined as a device to convert torque into thrust. That is, it takes the twist produced by an engine and changes it into a straight-line force pushing the craft through the water.



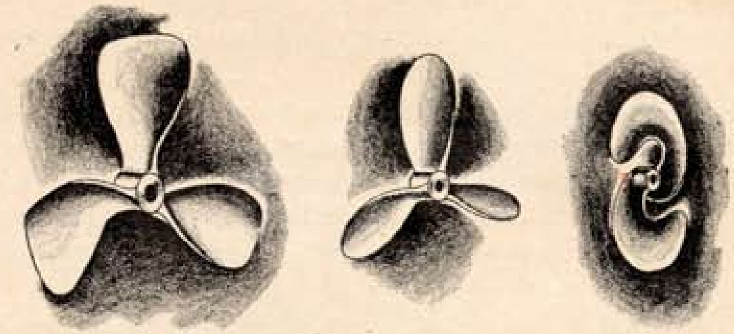
Water pushed backward, boat moves forward.

It can do this because it is really a screw. It screws itself through the water, and in so doing it pushes a lot of water backward. The reaction to this push makes the propeller and boat move forward. The shape of the blades is what makes it a screw. They are set at an angle and curved, so that while each blade is traveling through the water sideways it is at the same time giving a push at right angles to this.

Most propellers have three blades, but two and four blade propellers are also common. The two blade variety are only on small, high speed craft or sailboats with auxiliary power; the four blade type on large ships. Some are made solid, with the blades and hub all one piece. Others are built-up, the individual blades being set in and fastened tightly to the hub. There are a great many different shapes of blades. Probably



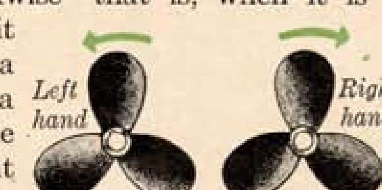
Two-blade propeller.



most of them are elliptical, but even here there is a lot of variation, as some of them are long and skinny while others are short and almost circular. Which type should be used depends on what type of service it is going to be used in. For example, a heavy work boat with a slow speed engine would probably have a propeller with rather square-tip blades, which would give more working area out near the tip. A faster boat with faster engines might have a thinner blade, with its greatest width nearer the center of the blade. Many blades are unsymmetrical and some very queerly shaped. The one on the right in the illustration is made particularly for waters with lots of weeds or driftwood; it does not get tangled up or damaged so easily.

If we saw a blade in two and look at the cross-section, we find just about the same shape we found when we cut across an airplane wing or airplane propeller. Marine propellers used to be more or less symmetrical in cross-section, but lately the trend has been toward the airfoil shape.

Propellers are usually classified according to three things—direction of rotation, diameter, and pitch. If we stand behind a boat and look at the propeller, a **right hand** propeller will turn clockwise—that is, when it is driving the ship forward. If it turns counter-clockwise, it is a **left hand** propeller. Ordinarily a single propeller, or one on the center-line of the boat, is right hand. With two or more pro-



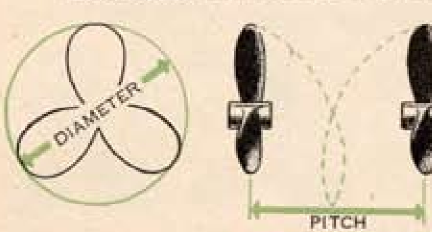
pellers, the one on the starboard (the right side looking forward) is usually right hand, and the one on the port (the left side) is left hand.

The **diameter** of a propeller is of course the diameter of the circle passing through the tips of the blades. Everything else being equal the larger the diameter the greater the horsepower it can handle. Or to put it the other way, the greater the diameter the more horsepower is required to turn it at the proper speed.

The **pitch** is just what it was in airplane propellers. It is the distance the propeller would travel forward in one revolution if it were turning in something solid like wood where there was no slip. Both the diameter and the pitch are usually measured in inches, and when we speak of a 20″ x 24″ propeller, we mean a propeller 20 inches in diameter which with no slip would move forward 24 inches with each revolution.

It is not an easy job to select a propeller of the right size and pitch for a certain boat. The mathematics of propeller design are complicated to say the least. There are several ways to figure theoretically what a propeller will do under certain circumstances, but we will not get into that here. Even with a full understanding of the theories we can not always pick the best propeller for a particular job. But by a combination of theory and practical experience we can usually come close to it. At least we can tell which way to change things in order to make them right. And by means of this combination of theory and practice, the design of propellers has improved continually, and today they can do many things considered impossible a few years ago.

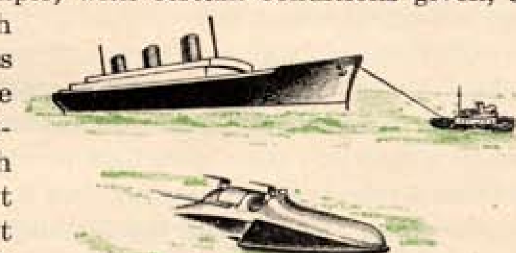
The main reason it is hard to pick the best propeller for a certain job is that there are so many factors involved. There are eight things which must be taken into account, and they are all more or less mixed up together. That



is, each one affects one or more of the others, and if we change one we usually have to change something else. These eight items are:

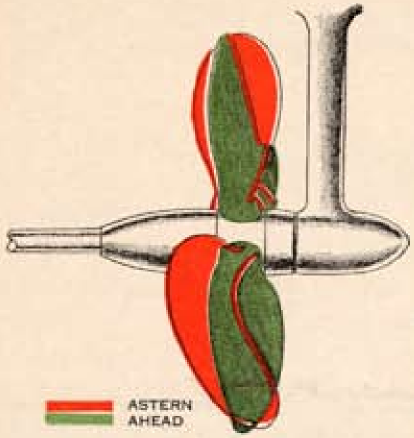
Engine horsepower
Engine (or propeller shaft) speed.
Shape and weight of ship.
Ship speed.
Slip.
Propeller diameter.
Propeller blade area and shape.
Propeller pitch.

Usually some of these are definitely established and cannot be changed very much, such as the design of the hull and the engine power. Others can be estimated from experience; for example, with certain conditions given, a man familiar with this sort of business could tell you that the slip would be approximately 20%. With this we can start figuring the right pitch for the propeller from the engine speed and the desired ship speed, or we can estimate the speed of the ship with a certain propeller. If the propeller turns so many revolutions per minute and the pitch is so many inches, we can multiply these together and find how many inches the propeller will move forward in a minute. This is the theoretical figure, however, and we must take away 20% for the slip. This gives us the actual ship speed in inches per minute, which can be changed over to the more usual miles per hour.



Propellers work under widely varying conditions.

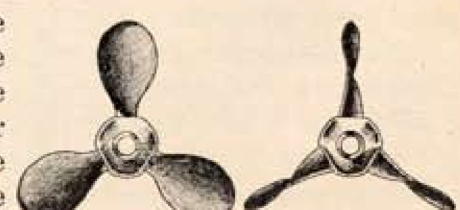
The diameter and blade area of the propeller will probably be chosen according to the horsepower of the engine. But it is not as simple as all that. If we reduced the pitch we could use a propeller of greater diameter, perhaps keeping the same blade area by changing the shape. If the hull was light and easy pushing, the slip would be



less and we could use a propeller with greater pitch, or we could run the engine faster. If we used a smaller propeller or reduced its pitch, we might be able to run the engine faster and produce more power. And so on, and so on. We can see that there are lots of different ways we can do this, and that each of them probably means a compromise of some sort. As is usually the case in such matters, we have to sacrifice a little in one direction in order to get something else we want.

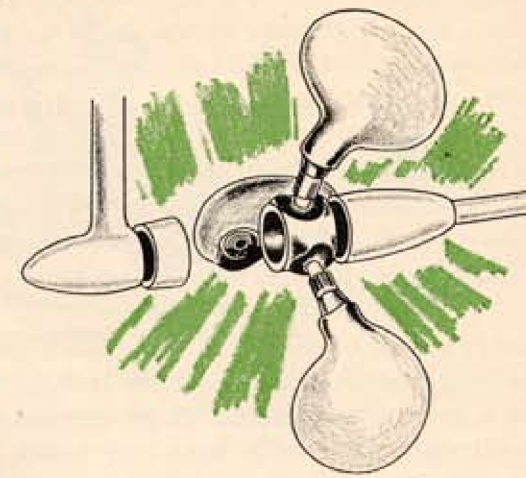
There is one way we can avoid some of these compromises. That is by using a **variable pitch** propeller. Variable pitch or controllable pitch propellers are just what they are in airplanes—they have blades which can be turned or twisted to change their angle. Thus it changes their "bite" on the water and changes the distance traveled forward in each revolution. And when the blades are twisted far enough they reach a point where the propeller begins to exert a thrust in the opposite direction, and tries to reverse the motion of the boat.

Such propellers have been used for a number of years, but they were mostly small, two-bladed propellers on small boats and sail boats with auxiliary power. Some of them were primarily reversible pitch propellers, having only forward and reverse positions, and used in order to eliminate a reverse gear. In sail boats the main reason for them was to feather the blades—that is to turn the blades so their edges were straight forward in order that they would offer little resistance when sails were being used rather than the



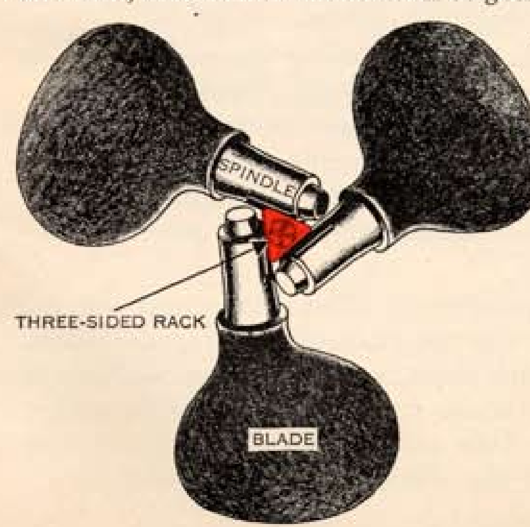
Feathering propeller.

engine. These did not try to take full advantage of the variable pitch principle, and little was done with them in the larger sizes. Probably the biggest reason for this was that many people thought they would not stand up properly, that maintenance costs would be high.

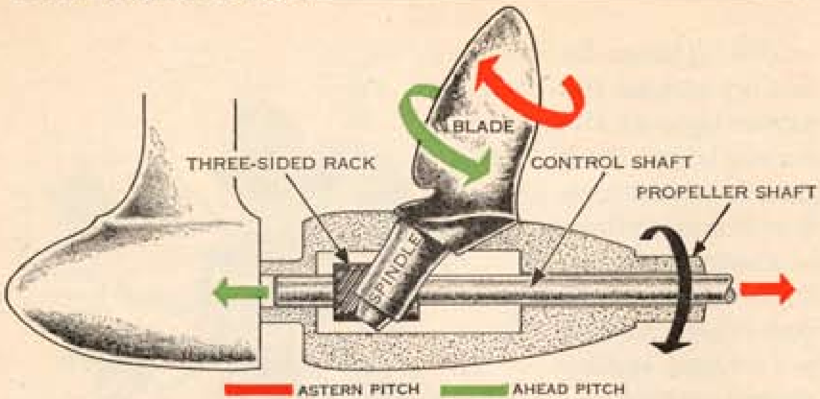


In recent years, however, there has been more interest in this subject. A larger controllable pitch propeller has been designed and has been used successfully on several Navy craft. This is a three-bladed propeller which can handle well over 1000 horsepower.

The **blades** are of course separate from the **hub.** The shafts or spindles of the blades are inserted into the hub, and are nested together in such a way that they form a triangular opening in the middle. These shafts have teeth on them, and a three-sided rack or gear fits into the opening and meshes with the teeth. Then when the rack moves backward or forward it twists the shafts and changes the pitch of the blades.



The rack is on the end of a long shaft which runs right through the center of the hollow propeller shaft



and turns with it at all times. It is moved back and forth by a large screw driven by an electric motor, so it can be controlled electrically from any point to which wires can be run.

One of the biggest advantages of such a propeller is of course that we do not need a reverse gear. The engine, propeller shaft, and propeller all turn in one direction all the time. We simply reduce the pitch of the propeller all the way to zero, or neutral, and then keep on twisting the blades until the pitch is in the opposite direction. The blades are then at such an angle that they push water forward and the propeller moves backward. It is much the same as if we had two propellers on the same shaft and could choose either one at any time; one would push the boat forward and the other would push it backward.

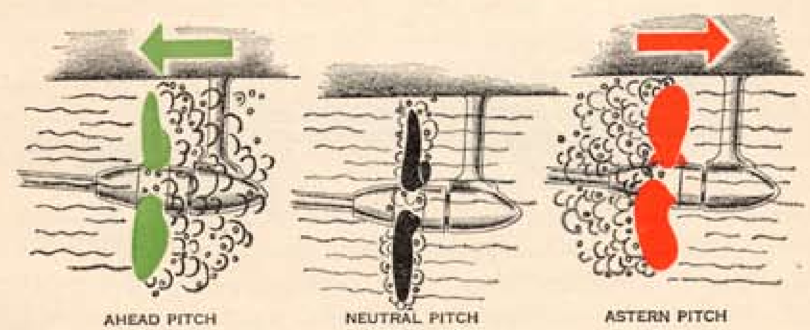
One of the first places this propeller was used was with the engine we mentioned earlier which stands on end, the crankshaft vertical. Light weight was very important in this installation, and by using the reversible pitch propeller and the ring gear and pinion, a great deal of weight was saved over the conventional reduction and reverse gear arrangement.

But there are a number of other advantages we get from being able to change the pitch of the propeller whenever we desire. It means there is one less thing we have to worry about or compromise on in selecting our propeller. And it means we can take care of different conditions we may run into without the efficiency going way down.

For example, suppose we chose a propeller with a certain pitch and diameter which would be best for the peak horsepower of the engine. But then at part load that would not be the best combination of pitch and diameter. We want to change something. It would be hard to change the size, but with this propeller we can change the pitch. We can increase the pitch to give us lower engine speed and less fuel consumption. It is much like the overdrive in an automobile—we can get a certain ship speed with a lower engine speed by increasing the pitch of the propeller.

Sometimes we need a very slow ship speed—slower than we want to run the engine. With a low pitch of the propeller we can go very slowly with the engine running at a convenient speed.

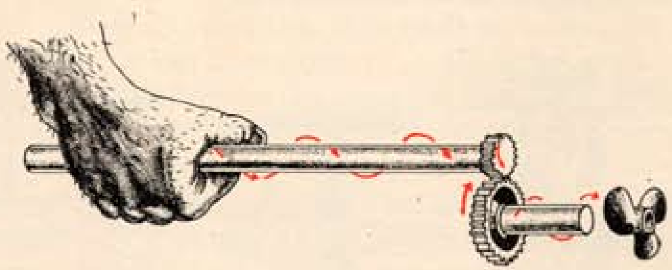
We can use the same propeller on different ships if we can vary the pitch. And we can change the pitch according to the load, or the job there is to do. This is especially helpful to something like a tug boat, which may have no load one minute and be straining at an ocean liner the next. So there are advantages to a variable pitch propeller in the water just as there are in the air.



We have just hit the high spots of marine propulsion systems, and probably not all of those. There is such a variety in this field, mainly because ships are usually designed individually. They are not turned out in mass production with hundreds of thousands built just alike as we do with automobiles.

But the principles do not vary so much, and the individual pieces are much the same. It is a question of combining and arranging them in different ways, and deciding how many of each we want. It is something like children's building blocks. Using the same pieces we can make a castle, or a tower, or a castle with a tower on it, or two towers on it, and so forth.

It all depends on what we need or want for the particular purpose. After we decide how many engines we want, how many propellers, what speeds we can use, then the pattern for putting them together is fairly well established. As always, what we are trying to do is take the power from the engine and use it to move the vehicle in the most efficient way for its particular job.



TRANSMISSION AND ENGINE

We have looked at the three fields of transportation. We have seen how the internal combustion engine is used to propel vehicles on land, in the air, and on the sea. We have found that there are different problems in each case, that each field has certain things which must be taken into consideration. Certain characteristics are important in one case and do not matter particularly in the others.

In the automobile we have wheels doing the driving. We must use the power of the engine to turn those wheels and push the car forward. And it must do that over a wide range of conditions. An automobile must be able to go fast and slow with equal ease. It must start from rest and accelerate quickly. It must go up hills and down hills, on mud roads and smooth pavement. All this means that we need a lot of flexibility in both engine and transmission.

In an airplane we have a propeller instead of wheels. The engine turns a propeller to make the plane go. And any mechanism we use for this must be light in weight. It is desirable to keep the weight down in any vehicle, but it is especially important in an airplane and is the one thing always kept in mind when working in this field. What seems light to an automobile or marine engineer may be ridiculously heavy to an aircraft designer. There is another consideration also which affects only the aircraft field. That is altitude, and particularly the thinning out of the air as we go up. If it were not for this we would have a much easier time selecting a propeller and deciding on other features of the system.

A boat also uses a propeller. But it is working in water instead of in air, so we have quite a different problem. The principles are much the same, but the shape of the water screw is different and we have some new factors to consider. Long life is as important as light weight in the marine field, which influences our design. And we have multiple engine installations to complicate matters.

So each field has its own peculiarities. But at the same time we can find much in common. We have an engine furnishing power in the form of a twisting force, and we must transmit that twist to a point where it can turn the wheels or propeller. That is the first requirement—simply to get that power from one place to another—and we have to do that in all cases.

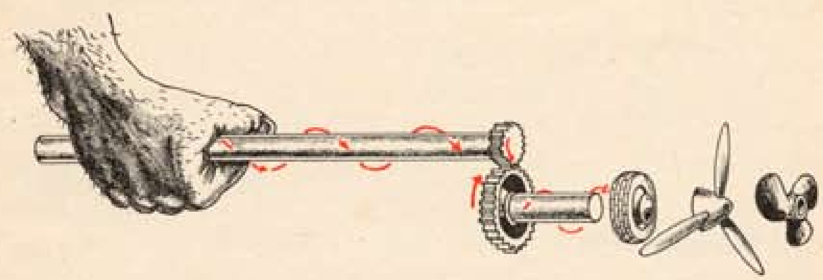
But we also change that power while we are transmitting it. And we find that we do much the same thing whether it is in an automobile, boat, or airplane. *We increase the torque and decrease the speed.* We run the wheels or propeller at a slower speed than the engine, but with a greater twisting force. Usually we do it with gears, but we may do it hydraulically or electrically. But the final result is the same—torque becomes larger, speed smaller.

The real reason behind this lies in the fundamental characteristics of the internal combustion engine. It is a *high-speed* engine. That is, to get the most power out of a given-size engine, it has to run fairly fast—at least faster than we want the wheels or propeller to turn. We can not run an engine at a slow speed and get the torque or twist we need to propel a vehicle efficiently. So the easiest thing to do is just what we have described—run the engine faster and use some sort of a transmission to reduce the speed and increase the torque.

Thus our power transmission system is largely dependent on the type of engine we use it with. It is the over-all effect of the engine-transmission combination that we are interested in. If new types of engines should be developed in the future, our transmission system will change accordingly. What way it will change depends on how the engine changes. We have seen that in a jet propulsion system the source of power, the transmission of power, and the vehicle propelling force are all mixed up together. There isn't any rotating, twisting force; the power is a direct thrust as it comes from the engine. There really isn't any transmission.

On the other hand the gasoline turbine, which is related to jet propulsion and which many people consider the most promising future power plant, goes a step in the other direction. This has a rotary motion and furnishes a twisting force just like a piston-type engine, but it runs much faster. It turns at even higher speeds. So with this we will have to use more gears instead of less—or something equivalent to gears.

Transmission systems will undoubtedly change whether or not engines change. And they will change for the better. They will be more efficient, quieter, smaller, more automatic or more convenient for the operator. Progress due to research and invention will be apparent in this field just as in every other. But the fundamental purpose will be the same—to take power from the engine, deliver it to the proper place and in the proper form, and use it in the best way to make the vehicle go. That is power transmission, on land, in the air, and on the sea. That is how POWER GOES TO WORK.



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"A POWER PRIMER" is a companion piece to "Power Goes to Work". It covers the internal combustion engine in the same manner that this book covers the transmission of power after it leaves the engine.

There is a simple explanation of the fundamental principles of the internal combustion engine, and then a section on each of the types in general use today—automobile, aircraft, and Diesel. The objective is to strip these engines of their technical mysteries, and show in simple words and many pictures that they are all basically the same—that they all operate on the same basic formula, which is simply the proper combination of air, fuel, and ignition.

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