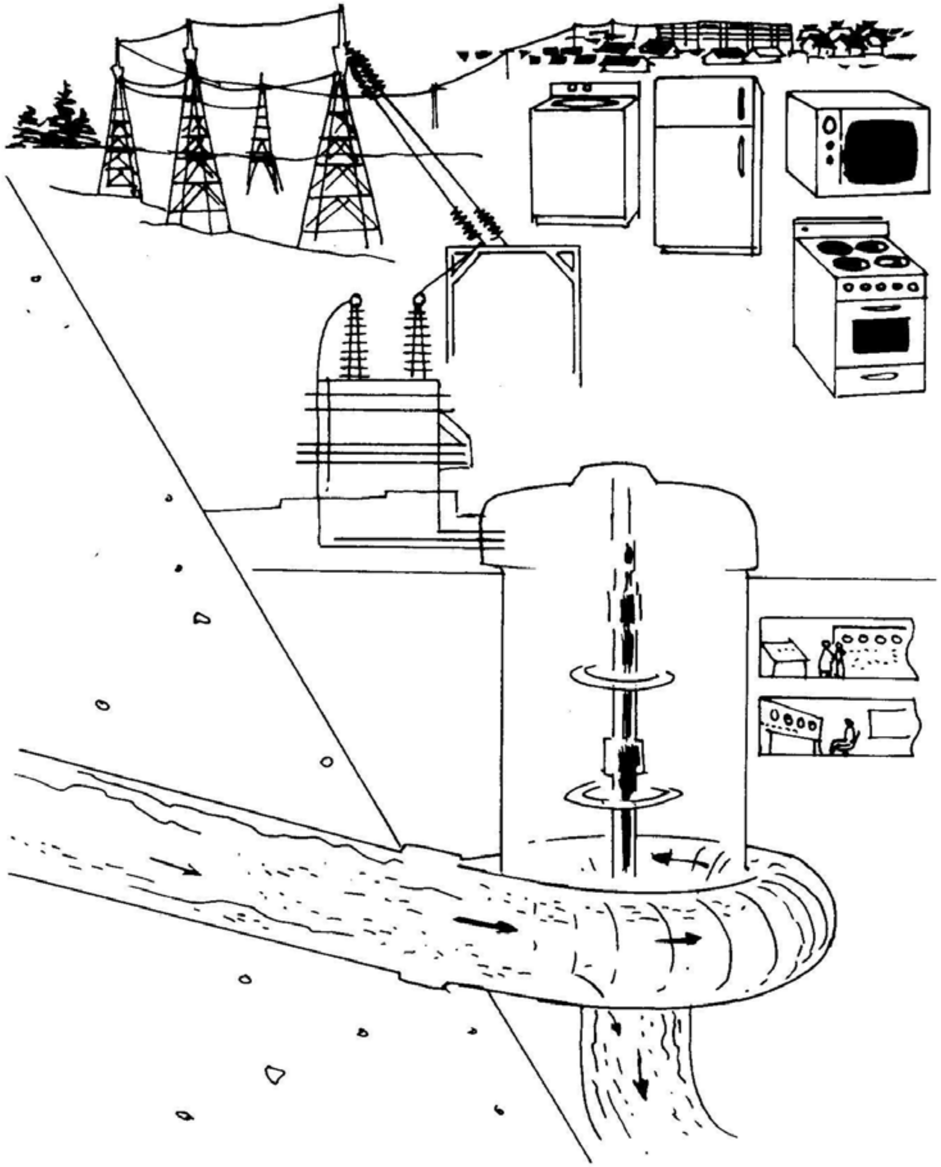
Machines and Work

Defined in the simplest terms a *machine* is a device that uses *force* to accomplish something. More technically, it is a device that transmits and changes force or motion into *work*. This definition implies that a machine must have moving parts. A machine can be very simple, like a *block and tackle* to raise a heavy weight, or very complex, like a railroad locomotive or the mechanical systems used for industrial processes.

A machine receives *input* from an energy source and transforms it into *output* in the form of mechanical or electrical energy. Machines whose input is a natural source of energy are called *prime movers*. Natural sources of energy include wind, water, steam, and petroleum. Windmills and waterwheels are prime movers; so are the great turbines driven by water or steam that turn the generators that produce electricity; and so are internal combustion engines that use petroleum products as fuel. Electric motors are not prime movers, since an alternating current of electricity which supplies most electrical energy does not exist in nature.

Terms like work, force, and power will be used frequently in this book, so it is necessary to define them precisely. Force is an effort that results in motion or physical change. If you use your muscles to lift a box you are exerting force on that box. The water which strikes the blades of a turbine is exerting force on those blades, thereby setting them into motion.

In a technical sense, work is the combination of the force and the distance through which it was exerted. In the case of the box



An electric generating system.

that you were lifting, work would be the force times the distance you raised the box. Work can be expressed mathematically in the formula: Work = Force × Distance. If you lift a ten-pound box to a table three feet high, you perform thirty *foot-pounds* of work. Note that the force is measured in terms of the resistance that must be overcome, in this case the weight of the box.

To produce work, a force must act through a distance. If you stand and hold a twenty-pound weight for any length of time, you may get very tired, but you are not doing work in the engineering sense because the force you exerted to hold up the weight was not acting through a distance. However, if you raised the weight, you would be doing work.

Note these two kinds of motion: linear and rotary. *Linear motion* is movement in a straight line; the technical term for this kind of motion is translation. *Reciprocating motion* is a linear motion that goes back and forth or up and down in the same path, like the movement of the pistons in a car. *Rotary motion* is movement in a circular path. To produce rotary motion it is necessary to have *torque*, a force that can cause a twisting motion called *torsion*. Torque is the kind of effort that you exert to open a twist-off lid on a jar. In many machines the problem is to change one kind of motion to another. In a car, for example, the linear motion of the pistons must be converted into rotary motion to make the wheels turn.

The *efficiency* of a machine is the ratio of the output of work to the input of energy given in terms of a percentage. No machine is 100% efficient because of *friction*, the resistance to relative motion that is produced by two bodies moving in contact with each other. There are many other reasons why energy is never completely utilized; heat is lost into the atmosphere or the full force of a stream of water cannot be brought to bear on a wheel. Friction is a factor in all mechanical devices. In some cases, it is a factor which mechanical engineers try to overcome, but in others, such as braking devices, it is a factor that they try to use to advantage.

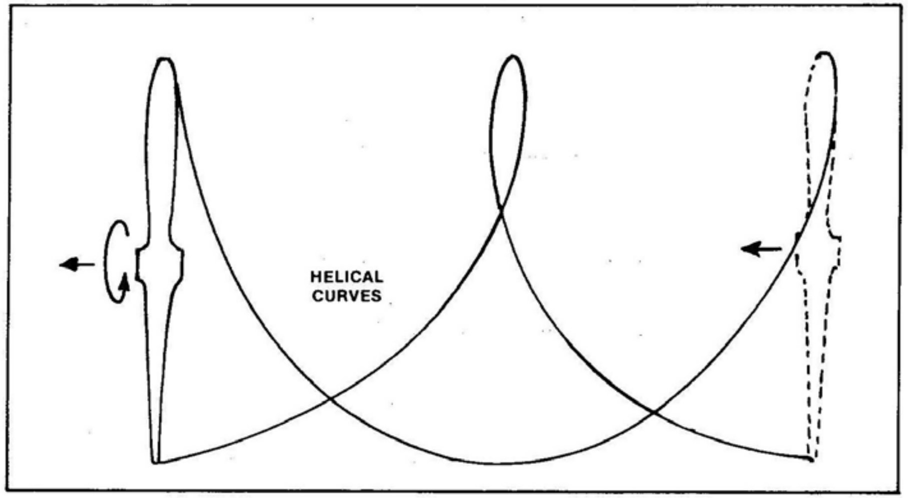
The ratio between output force and input force is called the mechanical advantage. If a device requires an effort of ten pounds to move a weight of twenty pounds, the mechanical advantage is two. Therefore the mechanical advantage is the resistance divided by the force.

Power is another term used in a special technical sense in speaking of machines. It is the rate or speed at which work is performed. If you raise a ten-pound weight a distance of twenty feet in two minutes, you are performing work at a rate of ten pounds × twenty feet × two minutes, or two hundred foot- pounds in two minutes. Since the rate is usually given in units of one minute, this is a rate of 100 foot-pounds in a minute.

In the English-speaking countries, the rate of doing work is usually given in terms of horsepower, often abbreviated hp. You will remember that this expression resulted from the desire of the inventor James Watt to describe the work his steam engines performed in terms that his customers could easily understand. After much experimentation, he settled on a rate of 33,000 foot-pounds per minute as one horsepower.

In the metric system power is measured in terms of *watts* and *kilowatts*. The watt is the power to do one *joule* of work per second. The joule is a small unit of work, approximately three-quarters of a foot-pound. One horsepower is equal to 746 watts. The kilowatt, a more widely used term, equals a thousand watts or approximately 1⅓ horsepower in the English system. The *newton* is a unit equal to the force necessary to accelerate one kilogram one meter per second per second.

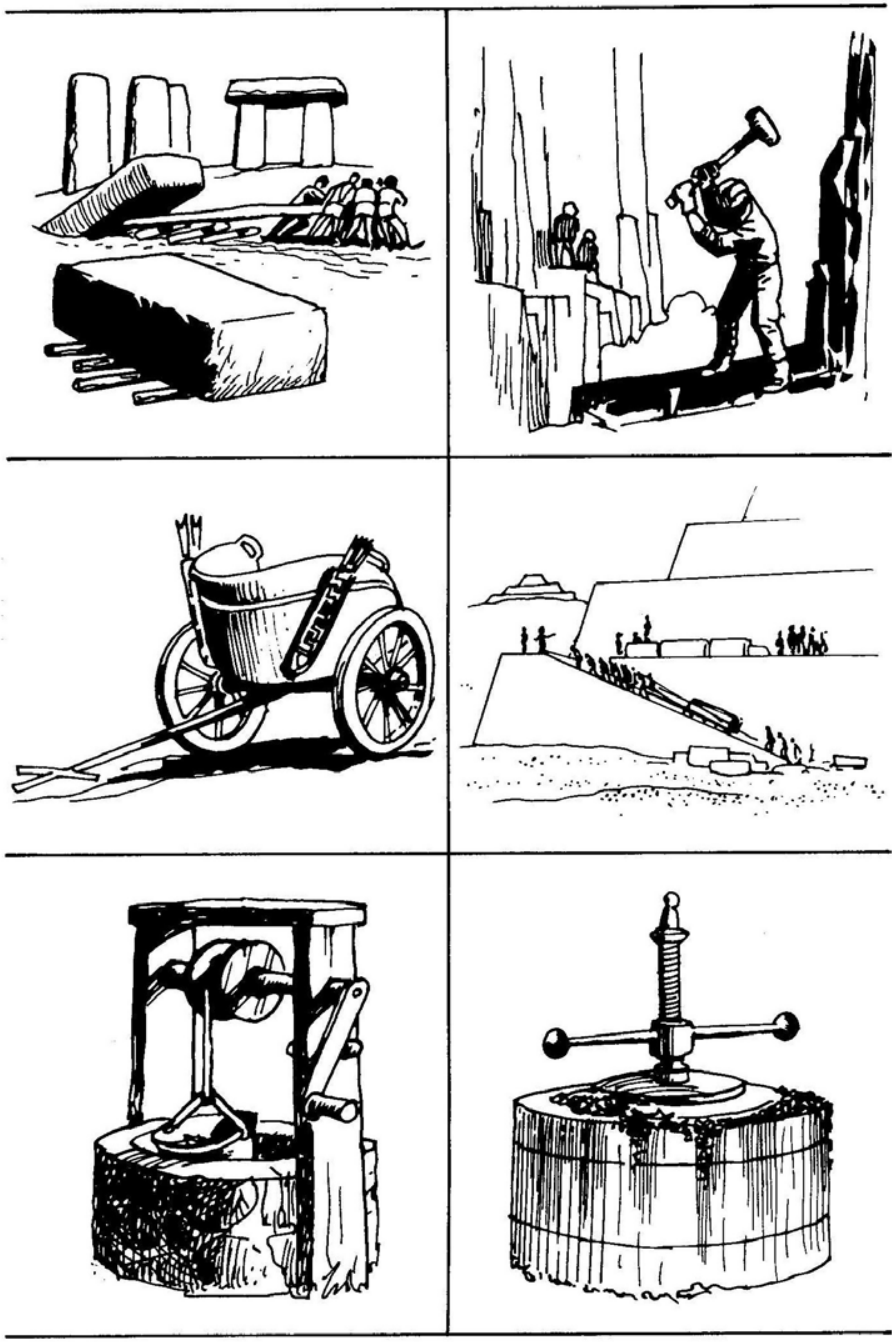
We are used to hearing the words watt and kilowatt in connection with electricity but we must remember that from a scientific viewpoint any kind of power can be quantified in the same terms. It is the work rather than the source of energy which is important; watts and kilowatts are used to measure power that results from mechanical as well as electrical energy.



The helical motion of a propeller.

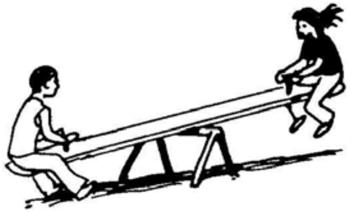
The Basic Machines

When a prehistoric man or woman used a stick to pry up a stone, the *lever* was invented. It is one of the six basic machines in the system of classification we will follow in this book. A lever is a rigid piece or bar, like the early person's stick, which turns on a point called the *fulcrum*. When force is applied at a second point, that force is transmitted to a third point where it can perform work. A children's seesaw is an excellent example of a lever. The point of balance on which the seesaw rests is the fulcrum; when downward force is applied to one end, the other end rises.



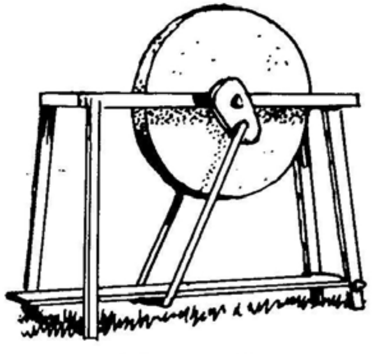
Ancient uses of basic machines.

The organized use of levers goes back beyond the beginning of recorded history. Levers were probably used to raise the huge blocks of stone from which Stone-henge was constructed. Perhaps the stones were raised by using tree trunks as levers until the stones toppled into place.



A seesaw—
a lever of the first class.

A wheelbarrow—
a lever of the second class.



A foot-treadle—
a lever of the third class.

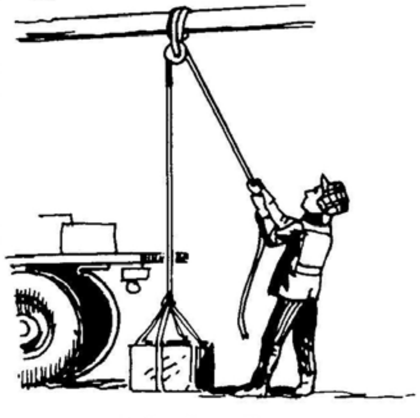
There are three classes of levers. The seesaw is a lever of the first class, with the fulcrum between the point where force is applied—*the effort end*—and the point where there is resisting force—*the load end.* The wheelbarrow is a lever of the second class, with the load between the fulcrum and the effort. The fulcrum is in front, the load is in the wheelbarrow itself and the effort is applied behind the load. A foot-treadle is a lever of the third class with the effort between the fulcrum and the load. The fulcrum is at one end, force in the form of pressure from the foot is applied behind the fulcrum, and the load is still farther beyond the point where the foot presses down.

We can observe that a seesaw will balance when a heavier person at the effort end is a short distance from the fulcrum and a lighter person at the load end is farther from the fulcrum. This is an illustration of the law of the lever: the effort force times its distance from the fulcrum is equal to the resisting force times its distance from the fulcrum when the lever is balanced. To gain more mechanical advantage, the distance between the point of effort and the fulcrum can be lengthened so that the effort is exerted through a greater distance. The fulcrum must exert an upward force equal to the two downward forces exerted on it—the downward force required to lower the effort arm and the downward force of the load.

The *wheel and axle* is the second basic type of machine. Like the lever, the wheel goes back to prehistoric times when someone probably discovered that it was easier to move heavy weights by sliding them on logs than by carrying them. The axle is a shaft on which a wheel can turn and the wheel and axle combination may have first been used sometime around 3,000 B.C. for water-raising devices. Its use for transportation evolved with the domestication of the horse. War chariots were the tanks of ancient times and wagons were the trucks.

In addition to its uses for transportation the wheel has endless applications. An early and important one was for the potter's wheel which permitted craftspeople to shape clay into controlled thickness for greater variety of forms and uses. Wheels were also put to work early for irrigation by raising water from streams or wells to divert it into artificial channels. Other early uses were for millstones to grind grain and for waterwheels that could transmit energy for many purposes.

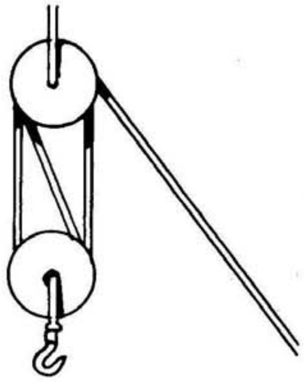
The potential of the wheel was increased by the development of the *crank.* The crank is a device which can transmit motion or can change rotary motion into reciprocating motion and the reverse. With the development of the crank, waterwheels could be put to work for essential purposes such as crushing rock or sawing wood.



A simple pulley.

The third basic machine is the *pulley.* In its simplest form it consists of a wheel with a groove around its outer surface through which a rope, wire, or chain can be passed. This simple device was used in ancient times for tasks such as raising water from wells or streams and hoisting sails onto ships. A pulley contained in a housing is called a *block.* When a fixed block is used with a movable block to which a weight is attached, downward pull on the rope will raise the weight. This device is called a *block and tackle.*

The block and tackle illustrated has a mechanical advantage of two. The mechanical advantage can be increased by different arrangements and combinations of blocks.



A block and tackle with
the mechanical advantage of two.

A pulley as a lever of the second class.

The movable pulley acts on the leverage principle; it forms a lever of the second class (like the wheelbarrow) with the fulcrum at the downward point of contact of rope and wheel, the load suspended from the axle, and the effort at the upward point of contact of rope and wheel. Increasing the number of fixed and movable pulleys increases the mechanical advantage.

The three remaining basic machines are so related to one another that they are sometimes grouped together. They are the *wedge*, the *inclined plane*, and the *screw*.

The wedge is a triangle with two chief surfaces that meet in a sharp angle or taper to a thin edge. Wedges are used for splitting open or pushing apart. They were used from very early times for such purposes as quarrying rock, plowing fields or cutting wood, as with an axe. A nail is a familiar form of the wedge.

The mechanical advantage of a wedge can be computed by dividing the length of the surface by the breadth of the wedge. A wedge twelve inches long with a breadth of three inches would have a theoretical mechanical advantage of four. However, friction is an important consideration in use of the wedge; in reality much of the advantage is lost. In fact, it is friction that holds a nail in place.

We have already mentioned the inclined plane as the probable method employed by the Egyptians for manipulating into place the huge blocks of stone in the pyramids. Early men and women knew that a weight could be pushed up a hill or a ramp of earth with less effort than would be required to move the same weight vertically. Many centuries had to pass before it was discovered that this mechanical device could be explained mathematically. The effort put forth in moving a load up an inclined plane is the same as the proportion between the height of the rise and the length of the inclined plane. If the rise is five feet and the length of the plane is twenty feet, the ratio is one to four. Therefore an effort equal to one-quarter of the load would theoretically be needed to raise the load. In actual practice, friction has to be overcome so a greater effort is required.

The inclined plane is an important factor that concerns civil engineers when designing highways or railroads. The mechanical engineer more frequently uses the screw, a spiral form of the inclined plane. The figure that results from wrapping the line of an inclined plane around a cylinder is called a *helix*.

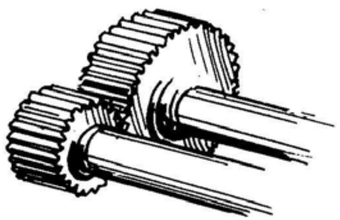
The screw was used in ancient times to press grapes for wine or olives for oil. In the Middle Ages it was important in the development of printing. Today we are most familiar with the screw as a fastener but it has numerous other uses. It is one of the most important devices for amplifying or increasing force. A familiar adaptation is the screw *jack* used to lift automobiles or any great weight through a short distance. The screw is also a major means of changing the direction of motion.

Both the screw and the helix have so many adaptations in modern machines that it is impossible to list them but one in particular is extremely interesting: the helical motion of a propeller on a boat or an airplane moves the vessel or plane ahead as though it were screwing its way through the water or air!

Machine Components

Essentially all machines are variations or combinations of the six basic types described in the previous unit. There are a number of different kinds of *mechanisms* or components that transmit motion or change it in one way or another. Modern machines and their components have become so complex that a branch of the science of mechanics called *kinematics* evolved in order to study mechanisms and their actions. Regardless of the original input and final output of most modern machines, it is their mechanisms that give them their great versatility and flexibility.

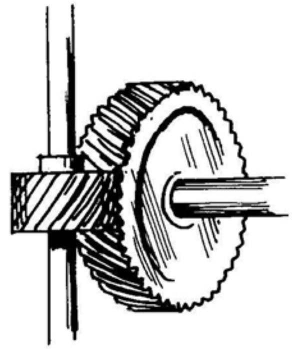
Gears play such an important part in machines that they have become the symbol for machinery. They are wheels with teeth that engage or mesh with each other so that they work in pairs to transmit or change motion. They are frequently used to reduce or increase the speed of a motion and they can also change the direction of motion. The line around which a wheel rotates is its axis; gears can change *axial motion*.

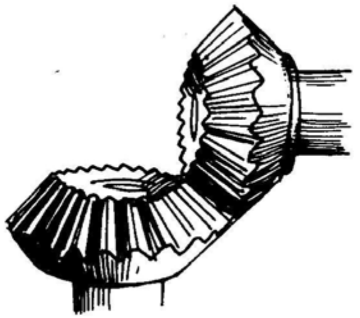

Spur gears engaging.

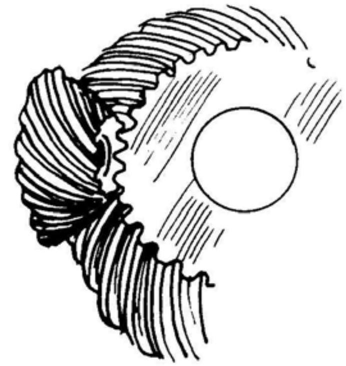
By classifying gears according to the shape and arrangement of their teeth we discover four basic types. The simplest and most common is the *spur gear*. Spur gears have teeth that are straight and parallel to the axis. One member of a pair or series of gears receives input motion, usually from a shaft. The teeth of the first gear mesh (engage) with the teeth of the next one, passing the motion (energy) along. If the two gears have the same number of teeth, the velocities will be inversely proportional to the number of teeth. That is, if the first gear has sixty teeth and the second gear has twenty, the second gear will turn three times as fast as the first. Spur gears are used for transmitting motion along parallel axes rather than for changing direction.

In *helical gears* the teeth are at such an angle to the wheel that they form helices. There are often two sets of teeth on each gear with the teeth at equal but opposite angles; this variation is called a *herringbone gear*. These gears are particularly useful for transmitting power at high speeds. They are also used to change the direction of motion, most frequently when the axes are crossed through a 90° angle.

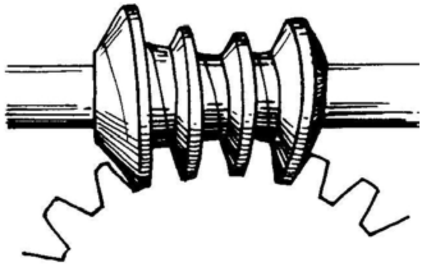
A bevel is a surface that is slanted at an angle in relation to another surface. In a *bevel gear* the teeth are slanted in relation to the plane of the wheel. Bevel gears are useful in changing the direction of motion, the change being in proportion to the angle of the beveled surface. One variation is the spiral bevel gear which has the same relationship to bevel gears as helical gears have to spur gears. With a bevel gear one tooth at a time has to bear the entire load but in the spiral configuration more than one tooth always remains in contact.


Helical gears engaging.


Spiral bevel gears engaging.

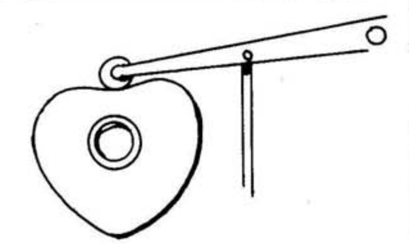

Bevel gears engaging at an angle.

The fourth basic type is called the *worm gear*. Basically a pair consists of the gear itself, a wheel with teeth which meshes with a worm —a screw which is a helix wrapped around a cylinder. A variation is a worm shaped in an hour-glass figure. Worm gears are used primarily for changing the direction of axial motion.

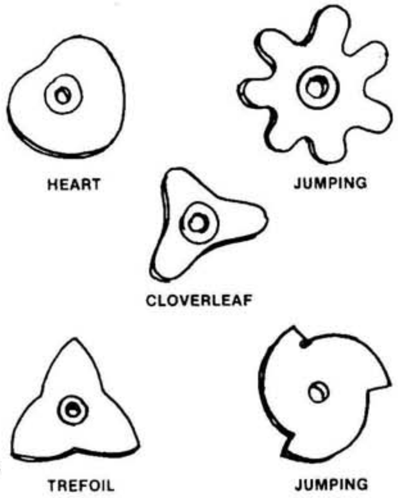

An hourglass worm meshing with a gear.

Another type of gear mechanism is the *rack and pinion*. The rack is a straight bar with teeth and the pinion is a small spur gear.

Gear devices can be used in a variety of shapes and combinations. They are essential elements in tiny devices like watches and in large ones like automobiles. Without the gears that transmit motion to the driving wheels we could not have the kind of transportation that exists today. In their variations on the basic machines gear mechanisms are key elements that produce enormous versatility.



A heart-shaped cam with follower.

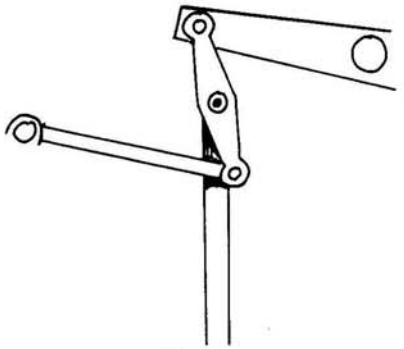


Different shapes of cams.

Another kind of mechanism is the *cam*. Like the gear, it consists of a pair of components; the cam itself is the input member and the *follower* is the output member. The cam is attached to a rotating shaft; it transmits motion to the follower. Cams come in many different shapes — there are heart-shaped cams, clover-leafed cams, elliptical cams and others. By means of these different shapes cams can change rotating into reciprocating (back and forth or up and down) motion or into oscillating or vibrating motion. The follower is usually a rod or shaft.

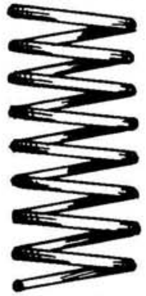
Cams can transmit exact motions at specific times in a cycle. They are therefore useful where the timing of complex motions is important. They are in automobile engines to raise and lower the valves and in sewing machines to control the movements of the needle.

Another kind of mechanism is known as a *linkage*; it is a series of at least three rods or solid links that are connected by joints that permit the links to pivot. When one link is fixed the other links can move only in paths that are predetermined. Like cams, linkages are used to change the direction of motion, to transmit different kinds of motion, or to provide variations in timing in different parts of a cycle by varying the lengths of the links in relation to each other.

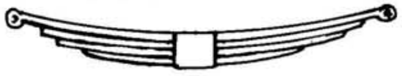


A linkage.

The *spring* is a mechanism that is used in a wide variety of machines; it is frequently an elastic helical coil that returns to its original shape after being distorted. Springs are essential components in watches; in some cam mechanisms they hold the follower in place; they are found in scales and they help to cushion an automobile ride. There are many variations on the basic coiled or spiral spring, including the *leaf spring* which is made of strips of elastic material and springs that depend on the compression and expansion of air.

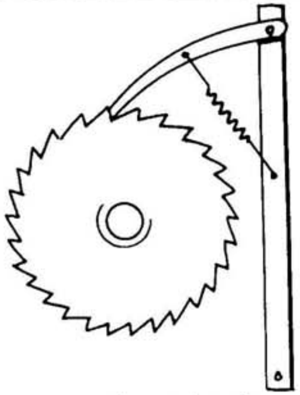


A spiral coil spring.



A leaf spring.

A *ratchet* is another paired mechanism consisting of a wheel with teeth and a pawl which drops into the spaces between the teeth. The ratchet mechanism is used to prevent a motion from being reversed or to change reciprocating into rotary motion.



A ratchet and pawl.

This is a brief introduction to the complex world of machine components. The infinite number of combinations and variations in which these mechanisms can be combined is the heart of the work of a mechanical engineer.

Friction

Friction reduces the efficiency of machines but it is also indispensable. When you try to walk on ice, slipping and sliding and perhaps falling down, you realize the importance of friction. Ice has a low *coefficient of friction* and that is what makes it so difficult to walk on. Without friction it would be impossible to walk at all and our trains and cars could not move.

There are three different kinds of mechanical friction: *static, sliding*, and *rolling*. Static friction is the resistance to motion between two bodies in contact but at rest. The resistance of static friction is greater than that of sliding friction which is resistance to continued motion after one body has started to move. Rolling friction occurs when resistance is reduced to its lowest degree by rotary motion not on the same axis.

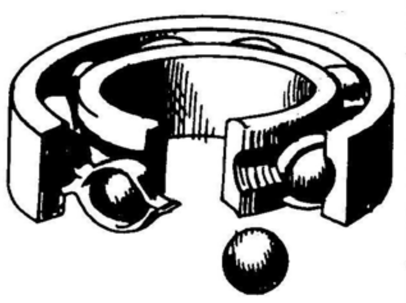
Ice has a low coefficient of friction.

Note these three kinds of friction at work: it takes a stronger effort to put a box into motion (static friction) then it does to keep it moving across the floor once started (sliding friction); if there are rollers under the box it takes still less effort to keep it in motion (rolling friction).

One way to reduce friction in machines is through the materials for the parts that contact each other. The *coefficient of friction* is the constant ratio of the friction to the force pressing the surfaces together. Coefficients have been equated for different common materials using the three types of friction. Steel on steel or glass on glass have high coefficients but some new substances have much lower coefficients. One of these is *babbitt metal*, an alloy made of tin, copper, and *antimony*; another is *teflon*, a plastic containing fluorine that is sometimes used in cooking utensils.

Another way of reducing friction is by means of *lubrication*, applying oil or grease to the points or surfaces where the parts of a machine contact each other. Petroleum products are the principal modern lubricants; some of them include *polymers*, the long, heavy, complex molecules that occur in plastics.

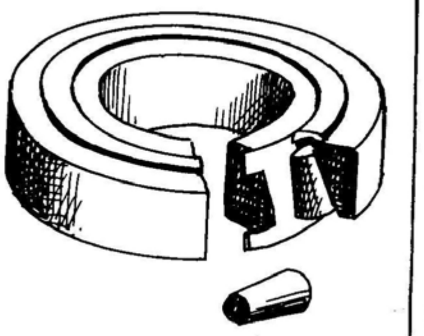
A vital mechanism for reducing friction is the *bearing* which basically is a device that bears the friction of parts in motion. Often one of the parts will be moving and the other will be stationary. Logs used to move heavy stones in early times were the primitive form of a bearing. They were efficient because they changed sliding friction to rolling friction, thereby decreasing the effort necessary to move the stones.



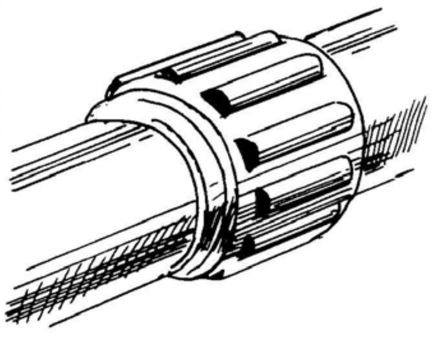
A ball bearing and cage.

Reducing friction between the parts of a machine is the principal purpose of bearings. Different types have been designed for use at various points of contact to fit the kinds of motion at work. Probably the most familiar are *ball bearings* which are used in many machines. Small balls are fitted into a *cage*, a container that separates them. Cage and bearings are then sealed, often in a lubricant, between rings which are called *races*. The entire assembly is a ball bearing.

Another familiar type is the *roller bearing*, a modern version of the logs that were used as primitive bearings. Roller bearings contain small cylinders on which the bearing races can roll. They are usually fitted with the same kind of holding cage and races as ball bearings. In order to sustain pressure from different directions, bearing rollers are sometimes *tapered* or shaped like cut-off cones



Tapered roller bearings.



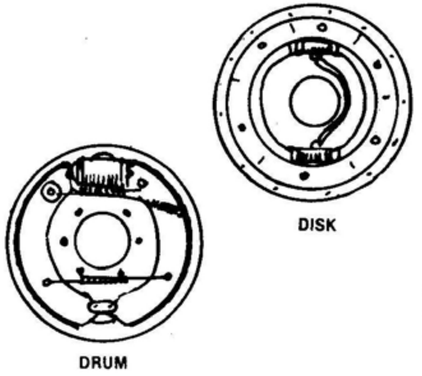
A roller bearing and cage.

and set at an angle to the races. A variation is the *needle bearing* with cylinders of very small diameter. Needle bearings need not be contained in a cage or between races. Their advantage is greater load-carrying capacity with more friction than ball bearings of comparable size.

A modern development is the *non-contact bearing* in which there is contact between the machine parts only at rest; when in motion they are separated by a thin layer of gas or fluid. This prevents wear between the moving parts. Non-contact bearings have been developed for such complex and sophisticated systems as missile guidance. The possibility of using cushions of compressed air in transportation systems has been discussed frequently in recent years.

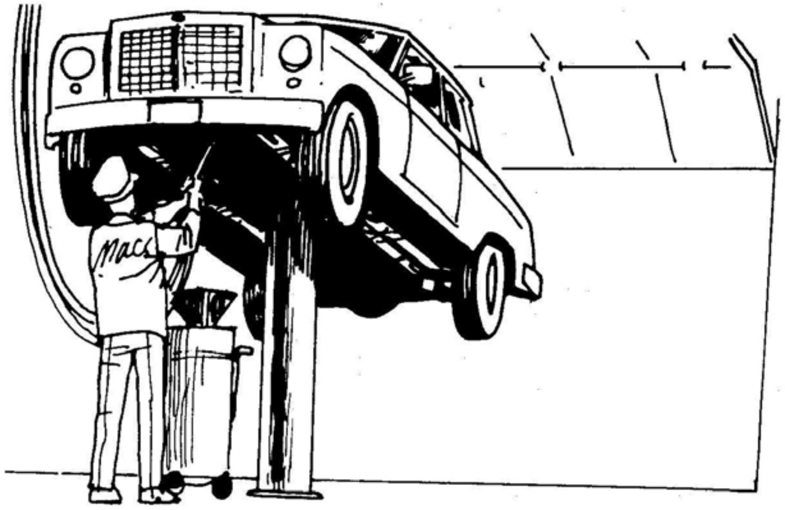
While bearings are used to minimize friction other mechanical devices put friction to work. The car that rolls without acceleration is gradually brought to a stop by friction. A long gradual stop is far from suitable, however, to traffic conditions where speed must be controlled and where sudden and frequent stops are necessary. *Braking devices* put friction to work to provide the necessary control over motion in automobiles and other kinds of machines.

The most common types of brakes ordinarily consist of a rotating component that is brought into contact with a friction component designed so that the mechanical energy is changed into heat which is dissipated into the air. The friction material may be metal, ceramic, or a substance like asbestos. Old-fashioned automobile brakes were made of a steel band that could be pressed down against the outside of the brake drum. When they got wet, however, their friction coefficient was often dangerously reduced, a condition known as *fading*. This led to the development of *drum brakes* with a friction lining on the inside of the drum. These are less likely to fade. A still more recent braking device is the *disk brake*. It consists of metal disks that turn with the wheel and can be brought into contact against friction pads.



A drum brake and a disk brake.

Another mechanism necessary for road vehicles is a *clutch* device so that the motor shaft can be connected or disconnected from the wheel shaft while the motor is running. The type in common use today is the *disk clutch* in which connection is made by applying pressure so that pairs of disks lined with friction material are brought into contact or released to increase or decrease power to the output shaft. In many cars pressure comes when the driver steps on the clutch pedal; with some automatic transmissions pressure is applied automatically through fluids as speed changes. Any kind of clutch depends on friction.



Lubricating a car.

Steam Engines

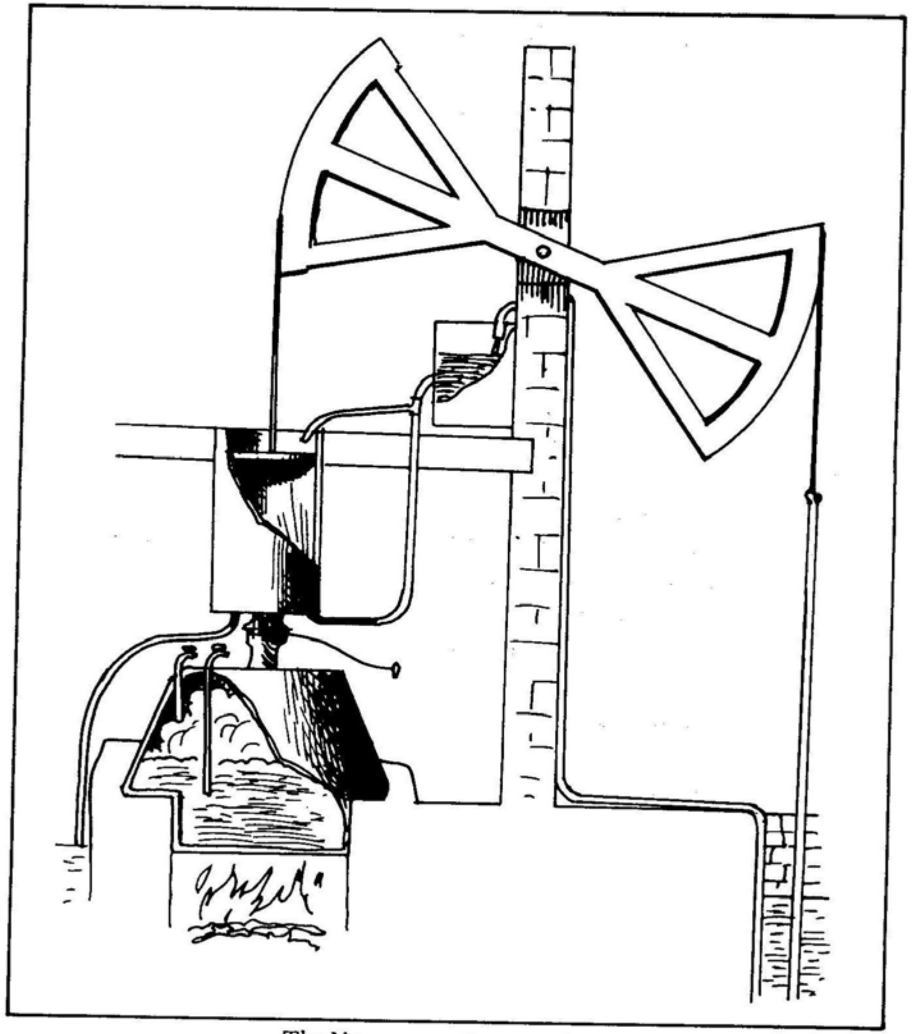
Steam was used to provide power for a kind of mechanical toy in ancient times by an ingenious Greek inventor named Hero of Alexandria. But it was not until the end of the seventeenth century that steam was harnessed for machines that could perform work. The development of these machines is usually regarded as the beginning of the Industrial Revolution. The first steam engines were designed for the practical purpose of pumping water out of mines; the first one to be sold commercially was called the Miner's Friend.

When water is boiled it creates a volume of steam greater than the original amount of water. This greater volume can burst a *boiler* unless it is released. When the vessel is cooled the steam *condenses* rapidly so that it returns to its liquid state. The result is a *partial vacuum* in the vessel that contained the steam. It was this vacuum that was put to work by Thomas Savery and later Thomas Newcomen in the earliest practical steam engines.

In the Savery engine steam from a boiler entered a container. When the container was filled cold water was poured over it thereby creating a partial vacuum that sucked water up into the container. When the container was refilled with steam the water was forced up to a higher level. The *valves* that controlled the admission of steam to the container as well as the cold water to cause condensation had to be worked by hand on this engine.

The Newcomen engine was an important advance over the Savery engine. The *piston* was attached by a chain to a *walking beam*, a heavy lever that worked on the seesaw principle. The other end of the walking beam was attached to a shaft that worked a pump deep in a mine. When the piston was at the top of the steam-filled cylinder, water was shot into the cylinder condensing the steam. Atmospheric pressure forced the piston down, simultaneously raising water from the mine. Steam was allowed to fill the cylinder and the piston moved up to the top, ready for another stroke.

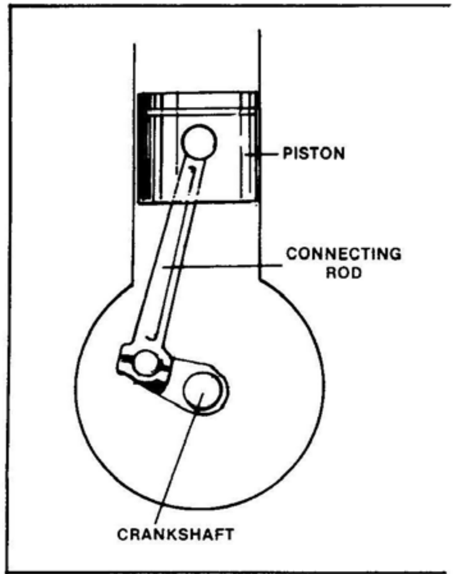
After the Newcomen engine had been in service for a time, it was discovered that the valves that controlled the steam and cold water could be automated—that is, they could be attached to the walking beam in such a way as to turn them on or off by the action of the beam at certain points during the cycle.



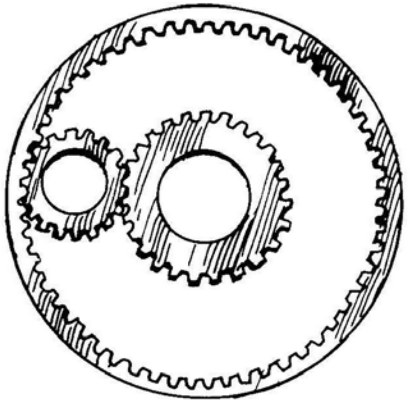
The Newcomen steam engine.

The next important figure in the development of the steam engine was James Watt. He is often credited with being the inventor of the steam engine but what he did in fact was improve on the preceding machines. Watt's contributions were of enormous importance in the history of machines and mechanical engineering. One great disadvantage of the Newcomen engine was the amount of fuel it used because so much heat was lost through the alternate heating and cooling of the cylinder. Watt's solution was to separate the cylinder and the condenser so that the cylinder could be kept hot and the condenser cool at the same time. Watt's engine was a great success since it used only one-third as much fuel as the Newcomen engine.

James Pickard, who had been employed by Watt, took the next big step in the development of the steam engine. This was to change the reciprocating motion of the piston to rotary motion that could turn wheels. Pickard attached the piston to a connecting rod that turned a *crankshaft* to produce rotary motion.



Pickard took out a patent on his crankshaft design so Watt had to evolve other devices to produce rotary motion. One of his ideas was the arrangement called *sun-and-planet gears.* A smaller gear (the planet) rotates around the outer face of a larger gear (the sun).



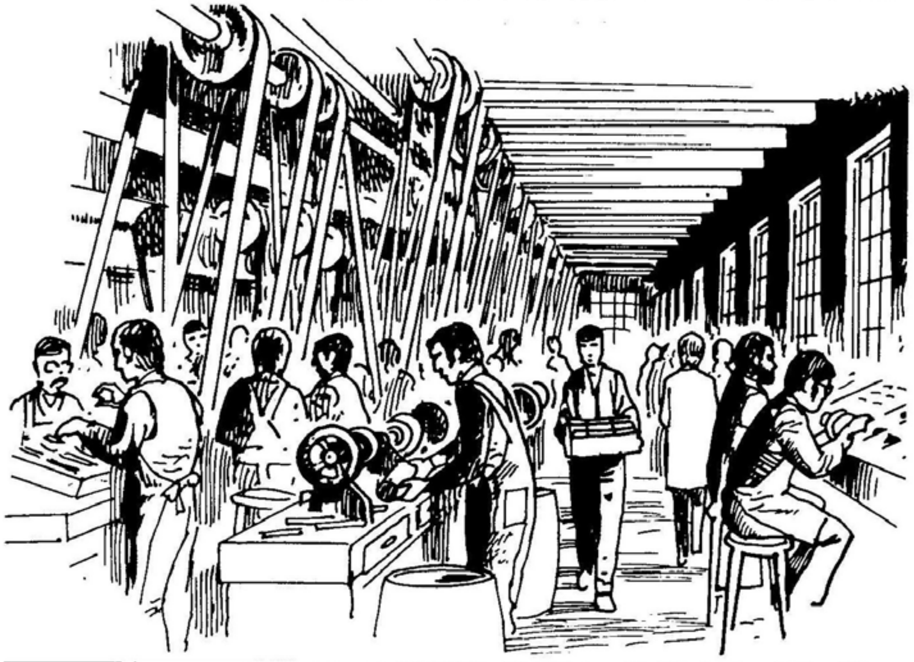
Sun-and-planet gears.

In these early days of steam engines the technical accomplishments we take for granted were difficult to achieve. Machining of parts was not exact and it was impossible to build boilers that could withstand steam at high pressure. In Watt's day it was the vacuum created by condensing steam that actually performed work. As boilermaking improved it was possible to superheat the water and thus increase the steam pressure. This, in combination with *safety valves*, made steam engines far more efficient by putting the pressure to work.

The nineteenth century was the age of steam. The machines of Savery, Newcomen, Watt, and their successors were used not only for pumping water out of mines but for an increasing number of in-


An early steam locomotive.

dustrial advances. Many early applications were in the manufacture of textiles but inventors were soon at work on the problem of using steam engines for transportation. By the middle of the century trains with steampowered locomotives were becoming the world's most important form of transportation and steamships had become common on inland waterways. Before the end of the century the difficulties of building transoceanic steamships had been solved. Thousands of factories manufacturing hundreds of products used steam power. A familiar sight at the end of the century was the factory or workroom with a whole network of belts that provided drives for other devices such as lathes, drill presses, and sewing machines. These belts were a cause of frequent industrial accidents.

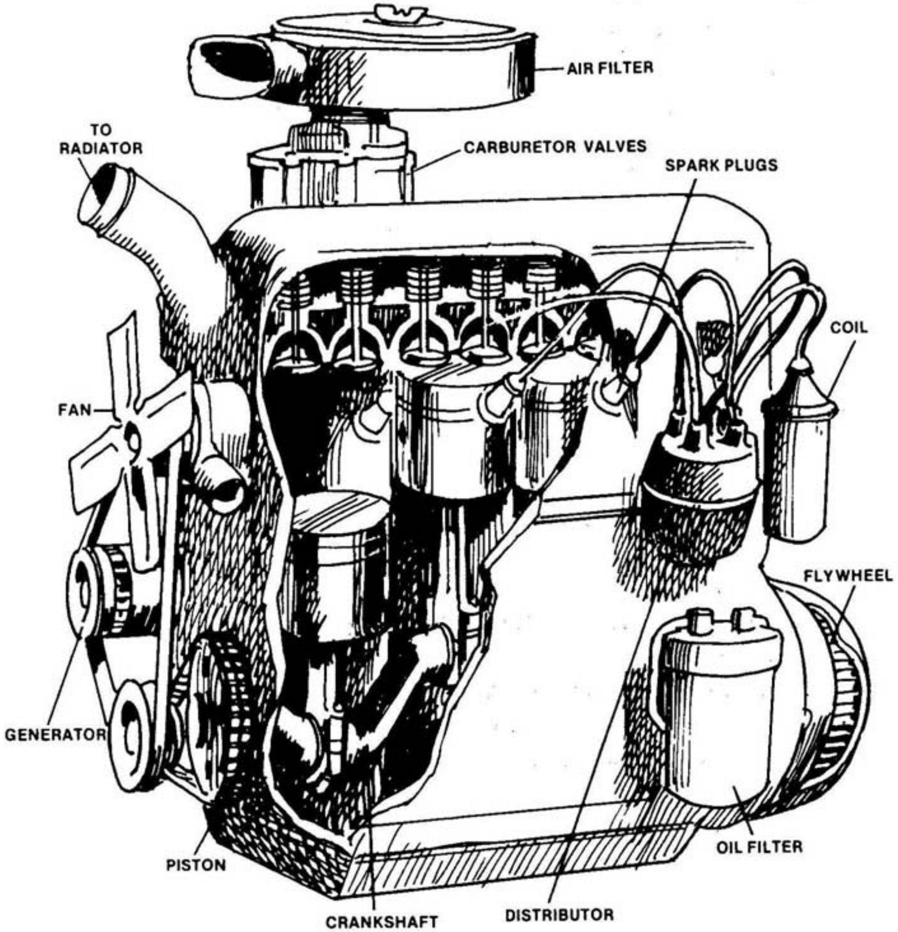

A 19th century belt-driven factory.

By the end of the century the preeminence of steam power was being threatened by two new power sources: electricity and internal combustion. Electric motors come within the field of electrical engineering and will not be discussed at any length in this book. It should be pointed out, however, that they provided greater safety in industrial operations since the shafts and belts used with steam engines were replaced by wires inside walls or under floors. The *internal combustion engine* will be examined in the following unit.

The twentieth century has seen the displacement of steam from many of its former uses in transportation and industry. We now take for granted the fact that cars are powered by internal combustion engines that burn gasoline. In the early days of the automobile there was experimentation with steam cars; some steam automobiles were even marketed successfully for a number of years. With the world's supply of petroleum now in question there is some renewed interest in steam as one alternate source of energy.

Steam still plays one vital role today in generating electricity. In an electric power plant a *turbine* drives the shaft of a *generator* which creates electricity by turning through a magnetic field. In a relatively small proportion of electric plants the turbine is activated by water power; in the majority it is steam that drives the turbine. A blast of steam strikes the blades of the turbine to make them revolve at a high rate of speed.

Even in electric generating plants that use nuclear energy it is steam that actually moves the turbines. The heat released by nuclear fission—the breaking apart of the particles in the center of an atom—is used to boil water. When the water is converted to steam at high pressure it drives the blades of a turbine, just as in a conventional power plant.



An internal combustion engine.

The Internal Combustion Engine

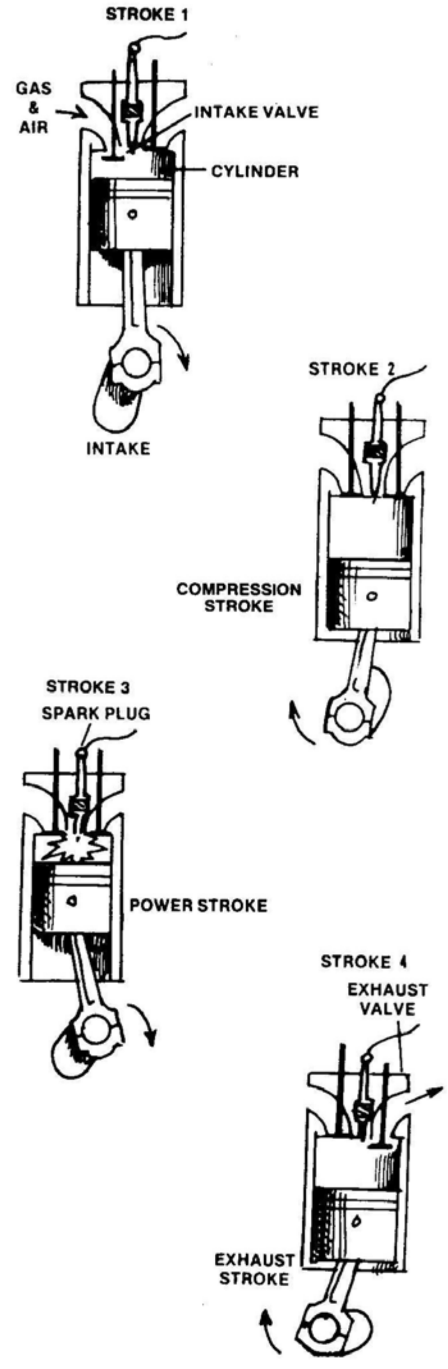
Combustion is a word for fire or burning; an internal combustion engine is one in which a fire inside the engine itself makes the engine work. Despite its polluting emissions, this is one of the most significant inventions of all time, especially because of its primary uses as a portable power source. The steam engine uses a fire in a boiler rather than inside the engine; for this reason steam engines are sometimes called external combustion engines.

Experiments with internal combustion go back to the seventeenth century. The first fuel tried was gunpowder, with a predictably explosive result. Other experiments were made with different kinds of gases including hydrogen which is explosively combustible. It was not until the second half of the nineteenth century that the development of petroleum products made possible today's internal combustion engine. Kerosene for lamps and stoves was the product first sought from petroleum while gasoline seemed nothing more than a dangerous by-product. But after other fuels had been tried it was gasoline that emerged as the most practical for internal combustion.

The first genuinely marketable internal combustion engine was the work of a German inventor, Nikolaus August Otto. The Otto device was a *four-stroke engine* in which each piston made four movements (two up and two down) for each combustion in the cylinder using gasoline vaporized and mixed with air in a *carburetor*. It utilized a cycle in which the combustible mixture is drawn into the cylinder of an internal combustion engine on a suction stroke (1), is compressed and ignited by a *spark plug* on a compression stroke (2), burns and performs work on an expansion stroke (3), expels combustion products on an exhaust stroke (4).

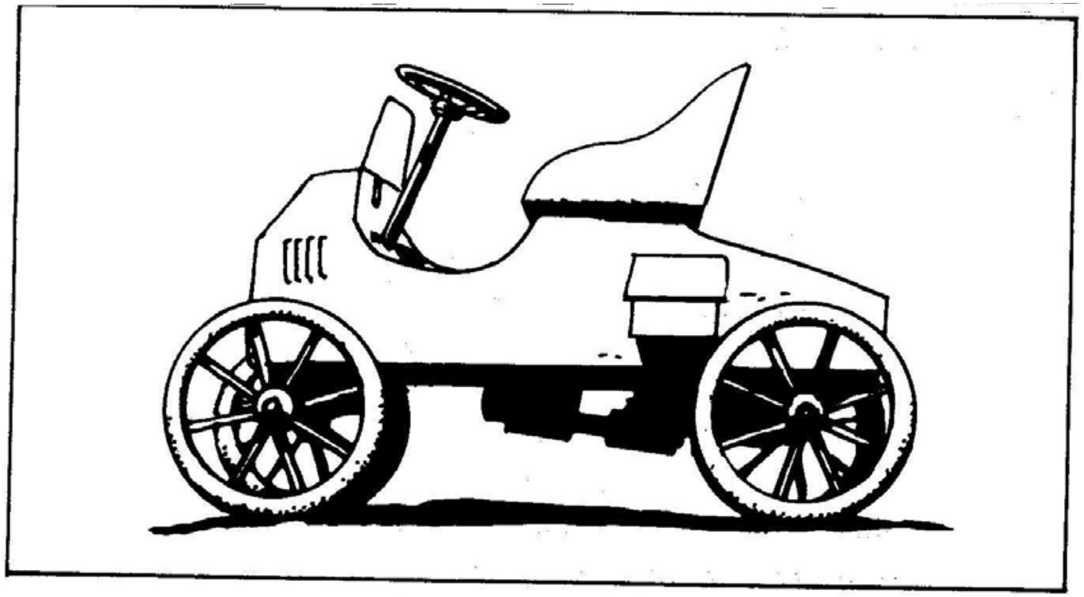
Since only the third stroke produces work, the piston needs help over the other strokes. This is given by a *flywheel* attached to the crankshaft. The flywheel in effect stores energy from the power stroke; this energy then carries the piston through the three strokes until the next power stroke caused by the combustion is repeated.

Another necessary component of the four-stroke engine is a *camshaft* which controls the cams that open or close valves to let gases in and out of the cylinder. The camshaft makes one revolution for every two of the crankshaft since the valves open only on every other stroke.



The cycle of a four-stroke engine.

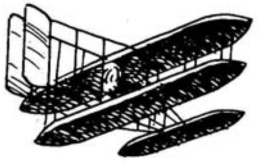
The engine designed by Otto was an immediate success. When he died in 1891, 30,000 of his engines had been sold, but they were suitable only for stationary use. Another German, Gottlieb Daimler, pioneered in adapting the Otto engine so that it could be used to power vehicles. By 1900 automobiles appeared with increasing frequency, first on the streets of Europe and then in the United States. This series of inventions has changed daily life for most people as much as any other in our history. It has made possible great industries, provided convenient transportation for millions of people and established new patterns of living.



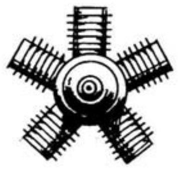
An early automobile.

The automobile emerged and developed because of the ingenuity of many different inventors. As an addition to the basic four-stroke engine, increasingly efficient carburetors were designed. The first improved carburetors replaced coal gas with petroleum products like benzine and gasoline. Another development was the use of several cylinders rather than the one in the first Otto engines. At various times automobile engines have had from two to sixteen cylinders; the standard numbers today are four, six, and eight. Other problems solved to achieve the efficiency of modern automobiles include *ignition systems* that cause combustion several hundred times a minute and cooling systems for cylinders rapidly heated by this combustion. Methods that employ both air and water to cool the engine have been engineered though most modern cars are water-cooled.

Automobiles had just gained wide acceptance when inventors began to experiment with the internal combustion engine as a source of power for flying machines. Flight is one of our oldest dreams but the reality of powered flight transcending the bonds of wind, air currents, and gravity belongs entirely to the twentieth century. The first successful flight in a powered aircraft was made by two Americans, Wilbur and Orville Wright, in December of 1903 at Kitty Hawk, North Carolina. They put a gasoline engine into a *glider* and this fragile contrivance flew for twelve seconds. In time for World War I (1914-1918) airplanes had been developed for use as weapons. The decades of the 1920s and 1930s saw the beginning of commercial aviation. When World War II (1939-1945) exploded air power was a major factor for victory and defeat.

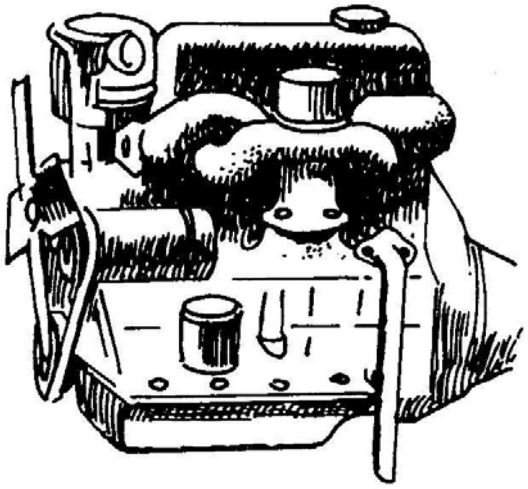

The Wright brothers plane.

Before the development of modern jet engines, to be explored in the next unit, airplanes were powered by gasoline internal combustion engines; these were light and powerful, both necessary conditions for flight. They used a *radial engine* with cylinders arranged around a central point like the spokes of a wheel. One cylinder was joined to the crank by a master connecting rod; the other cylinders were joined by hinged rods to the master connecting rod rather than to the crank. The crankshaft connected to a propeller which, as previously described, makes a helical motion that almost literally "screws" the plane through the air.

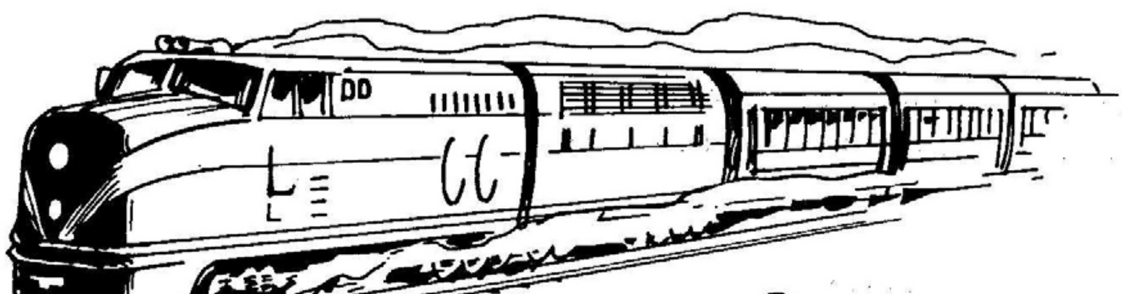

A radial engine.

Another type of internal combustion engine is the *diesel engine*, named for its German inventor, Rudolf Diesel. In a diesel engine air is compressed to a very small proportion of its original volume; this causes the air to become so hot that combustion takes place when fuel is injected into the cylinder. Diesel engines have several advantages: they do not require a spark, they operate with cheaper fuel than other internal combustion engines, and they have a higher thermal efficiency thereby developing more power in ratio to the amount of fuel used.

Diesel engines have gained wide acceptance for many heavy-duty vehicles, including ships, trucks, heavy equipment, and some types of passenger cars. Diesel locomotives have almost completely replaced steam engines on railroads. As an example of the complexity of modern machinery, diesel engines are used to provide power to run electric generators whose electricity is then used by the electric motors that perform the actual work on diesel locomotives!


A diesel engine.

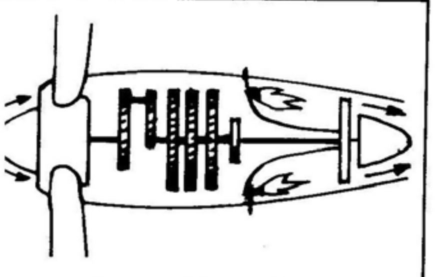
A diesel locomotive.




A diesel truck.

Gas Turbines and Other Types of Engines

The idea of an internal combustion engine to drive a turbine, rather than pistons, evolved on paper as long ago as 1791 but it needed modern technology to make such an engine possible. The problem was that the blades of a turbine could not withstand the great heat resulting from the combustion in such an engine. Now new alloys or mixtures of metals, as well as some ceramics and crystals that do not fail or disintegrate at high degrees of heat, have been developed.



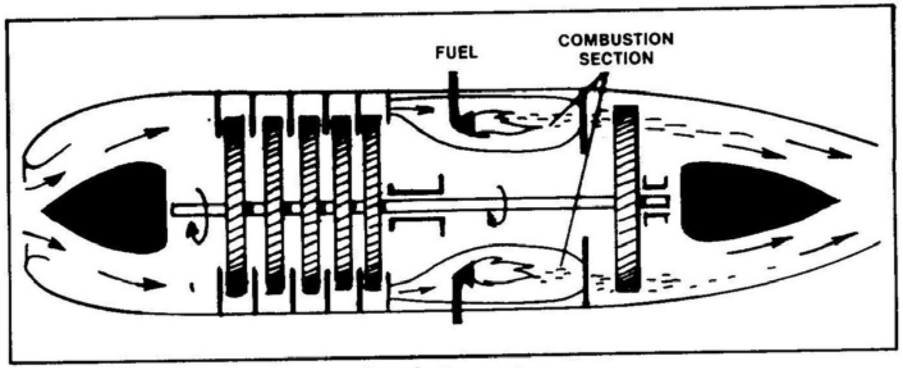
A gas turbine engine.

In a basic *gas turbine engine* air is taken in and compressed until it becomes extremely hot. The compressed air is then mixed with fuel, usually kerosene, which ignites. The expanding gases caused by the combustion cause the turbine to turn. The turbine then turns a shaft which performs the actual work. In a *turboprop engine* for aircraft that shaft turns a propeller.

Experiments to adapt gas turbines for other forms of transportation have not been entirely successful. A major drawback, especially in view of today's energy crisis, is the necessity for large amounts of fuel; the combustion is continuous in gas turbines rather than intermittent as in piston engines.

The first successful *turbojet engine* was designed by Frank Whittle, an English officer in the Royal Air Force. Jets were in use as military aircraft before the end of World War II but they did not come into commercial use until the 1950s. They have enormously increased the speed, range, and size of modern airplanes. Some types of turbojets can propel a plane at speeds faster than sound. The use of engines at supersonic speeds is one of the more controversial subjects of our time.

In a turbojet engine air is taken in by a *blower* that operates on a shaft from a turbine; the waste gases are expelled from the rear of the engine at an extremely high rate of speed. The plane is driven forward by a practical illustration of Newton's Third Law of Motion: for every action there is an equal and opposite reaction; therefore the thrust of the gases backward pushes the plane forward.

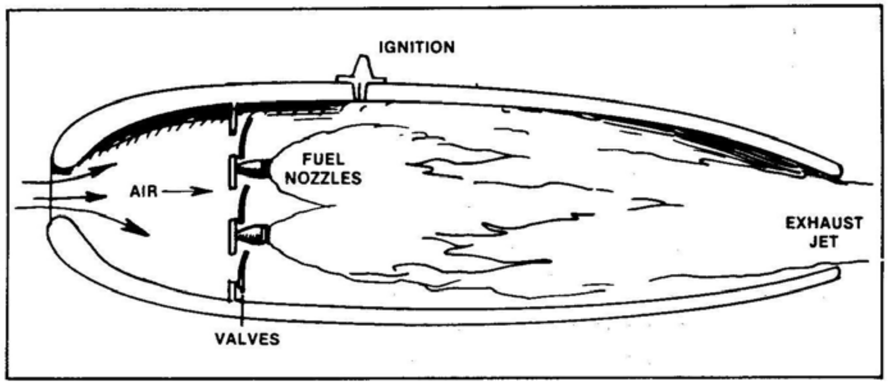


A turbojet engine.

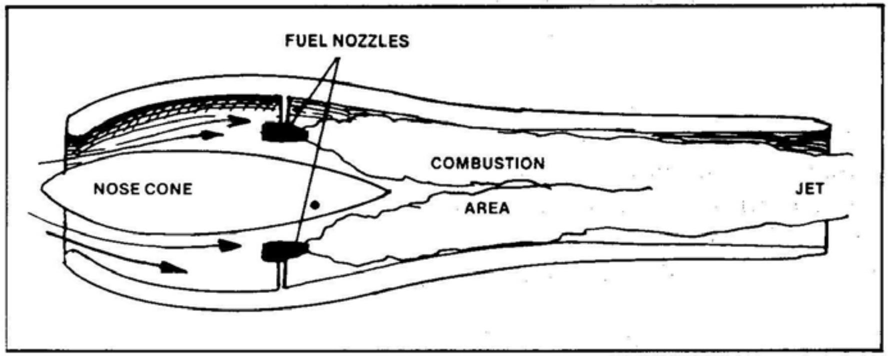
The type of turbojet in common commercial use is the *fanjet.* The intake blower is in effect a highly sophisticated version of the everyday electric fan. Two other types, used for military aircraft, are the *pulsejet* and the *ramjet.* The pulsejet, used by the German V-1 bombs to attack London during World War II, has lateral intake valves that produce a pulsing or vibrating movement; air pressure opens the valves, the explosions of fuel close them and push against them to provide forward propulsion; no turbine is necessary in this type of engine. In the ramjet, air is rammed or forced into the intake at such pressure that no blower or turbine is necessary, only a means of injecting the fuel.

A word about the energy crisis: the world's supply of petroleum was created millions of years ago and it cannot be replaced or renewed in our time. Estimates vary on how long the supply will last but according to some experts it may not be much more than thirty years at the present rate of consumption. Automobiles, diesels, and jets use enormous amounts of fuel derived from petroleum as do households and power plants that produce electricity. Petroleum is also the basis for *petrochemical products* including many of today's plastics, fertilizers, and insecticides.

Therefore there is a mounting interest in engines that do not use petroleum as fuel. Some power plants are already converting from oil to coal, but while coal is in much greater supply than petroleum it is another nonrenewable energy source which will eventually be exhausted. Experiments are under way to harness such energy sources as the wind, the tides, and the sun. *Nuclear fu-*



A pulsejet.

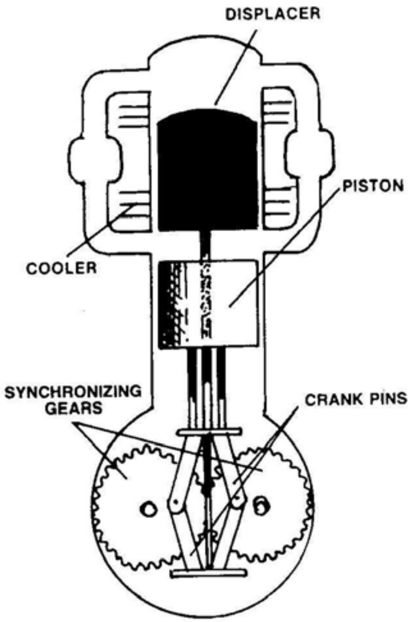


A ramjet.

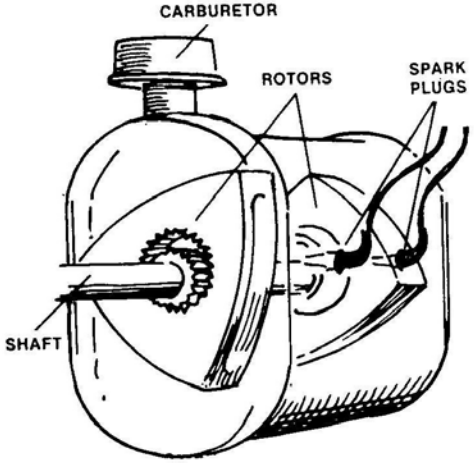
sion—the release of energy when atoms join together—is being explored as a safer alternative to *nuclear fission* with its hazardous byproducts of radioactive wastes that pose a serious threat to the environment and to human life. The difficulty with fusion is that it requires an enormously high degree of heat to start the reaction; to date it has not been possible to generate that much heat even under laboratory conditions.

There is much interest today in *hot-air* and *rotary engines*. The hot-air engine has a long history: a Scotsman, Robert Stirling, built one in 1827 so the hot-air engine is often called the Stirling engine. Then John Ericsson, a Swede who became a citizen of the United States (he is best remembered as the designer of the ironclad ship *Monitor* during the Civil War), built and marketed thousands of hot-air engines. The Stirling engine has two cylinders, one of which compresses air; when the air is heated it expands and pushes down a piston in the other cylinder. Engineers today are working to improve the basic Stirling engine and this offers a promise of greater fuel efficiency.

A rotary engine should more properly be called a rotating internal combustion engine. Instead of the reciprocating motion of pistons, a rotary motion is produced directly. The best-known rotary engine is the Wankel engine, named for its German inventor, Felix Wankel. The combustion in the Wankel engine turns a *rotor* that is triangular, though the outer edges are curved outward or convex. It produces almost no vibration because it has fewer parts; for this reason it is cheaper to manufacture but its fuel efficiency is still in question. Automobiles with Wankel engines use gasoline as fuel since that is what is available; if other fuels become commercially feasible the Wankel engine may be more economical than it is at present. Other inventors have produced other types of rotating combustion engines which offer interesting possibilities in experimental models.



The Stirling engine.



The Wankel engine.

Industrial Engineering and Automation

One distinction between a mechanical engineer and an *industrial engineer* is that the former deals with individual machines while the latter deals with machines in combination as part of a system. Industrial engineering is concerned with problems such as manufacturing processes and plant layout.

Industrial engineers must make the most efficient use of plant and equipment to achieve the highest possible degree of productivity. Originally this was conceived entirely in the mechanical terms of what machines could do and how they should be arranged. Now it is known that the effectiveness of the workers in the system must also be considered. The industrial engineer is therefore often involved in labor relations.

Industrial engineering in practice if not in name was born at the beginning of the machine age. People like Newcomen, Watt, and Pickard had to be involved not only in the invention of machines but in their application and installation. Throughout the eighteenth and nineteenth centuries the use of machines for all kinds of manufacturing (beginning in most countries with textiles) multiplied many times. We have mentioned the belt drives common in factories where steam engines powered other machines. These dangerous belts are an example of the problems with which industrial engineers dealt and the solutions they evolved.

A major advance in twentieth century manufacturing was the development of *mass production* techniques. Mass production refers to manufacturing processes in which an *assembly line*, usually a conveyor belt, moves the product to stations where each worker performs a limited number of operations until the product is assembled. In the automobile assembly plant such systems have reached a highly-developed form. A complex system of conveyer belts and chain drives moves car parts to workers who perform the thousands of necessary assembling tasks.

Mass production increases efficiency and productivity to a point beyond which the monotony of repeating an operation over and over slows down the workers. Many ways have been tried to increase productivity on assembly lines: some of them are as superficial as piping music into the plant or painting the industrial apparatus in bright colors; others entail giving workers more variety in their tasks and more responsibility for the product. Some automobile companies have experimented with giving individual workers complete responsibility for assembling an entire car; this obviously requires an extraordinarily high degree of skill.

These human factors are important considerations for industrial engineers who must try to balance an efficient system of manufacturing with the complex needs of workers.

Another factor for the industrial engineer to consider is whether each manufacturing process can be automated in whole or in part. *Automation* is a word coined in the 1940s to describe processes by which machines do tasks previously performed by people. The word was new but the idea was not. We know of the advance in the development of steam engines that produced automatic valves. Long before that, during the Middle Ages, windmills had been made to turn by taking advantage of changes in the wind by means of devices that worked automatically. A major development in textile manufacturing was the loom developed in 1801 by Joseph-Marie Jacquard, a French inventor. Intricate patterns woven into the cloth were controlled by steel cards with holes which were forerunners of the modern computer punch card.

We now use the term automation for specific techniques combined to operate automatically in a complete system. These techniques are possible because of electronic devices, most of which have come into use in the last thirty years. They include *program, action, sensing* or *feedback, decision*, and *control elements* as components of a complete system.

The program elements determine what the system does and the step-by-step manner in which it works to produce the desired result. A program is a step-by-step sequence that breaks a task into its individual parts. Some steps in an industrial automation program direct other parts of the system when and how to carry out their jobs.

The action elements are those which do the actual work. They may carry or convey materials to specific places at specific times or they may perform operations on the materials. The term *mechanical handling device* is also used for the action elements.

Perhaps the most important part of an automated system is sensing or feedback. Sensing devices automatically check on parts of the manufacturing process such as the degree of heat or the thickness of a sheet of steel or paper. This is called feedback because the instruments return or feed back this information to the central system control.

The decision element is used to compare what *is* going on in the system with what *should* be going on; it receives information from the sensing devices and makes decisions necessary to maintain the system correctly. If some action is necessary the decision element can give instructions or commands to the system.

The control element consists of devices to carry out the commands of the decision element. They may be many kinds of devices: valves that open or close, switches that control the flow of electricity, or regulators that change the voltage in various machines; they make the necessary corrections or adjustments to keep the system in conformity with its program.

Automation was first applied to industry in continuous-process manufacturing such as refining petroleum, making petrochemicals, and refining steel. A later development was computer-controlled automation of assembly line manufacturing, especially those in which quality control was an important factor.

An industrial engineer working with automated systems is part of a team. Many components of the system, such as computers, are electronic devices so electronic engineers and technicians are also involved. Many of the industries in which automation has proved particularly suitable—chemicals, papermaking, metals processing—involve chemical processes, so there may be chemical engineers at work too. An industrial engineer with expertise in all these fields may become a systems engineer for automation projects thereby coordinating the activities of all the members of the team.