CHAPTER 1
BASICS OF MECHANISMS

INTRODUCTION

Complex machines from internal combustion engines to helicopters and machine tools contain many mechanisms. However, it might not be as obvious that mechanisms can be found in consumer goods from toys and cameras to computer drives and printers. In fact, many common hand tools such as scissors, screwdrivers, wrenches, jacks, and hammers are actually true mechanisms. Moreover, the hands and feet, arms, legs, and jaws of humans qualify as functioning mechanisms as do the paws and legs, flippers, wings, and tails of animals.

There is a difference between a *machine* and a *mechanism*: All machines transform energy to do work, but only some mechanisms are capable of performing work. The term *machinery* means an assembly that includes both machines and mechanisms. Figure 1a illustrates a cross section of a machine—an internal combustion engine. The assembly of the piston, connecting rod, and crankshaft is a mechanism, termed a *slider-crank mechanism*. The basic schematic drawing of that mechanism, Fig. 1b, called a *skeleton outline*, shows only its fundamental structure without the technical details explaining how it is constructed.

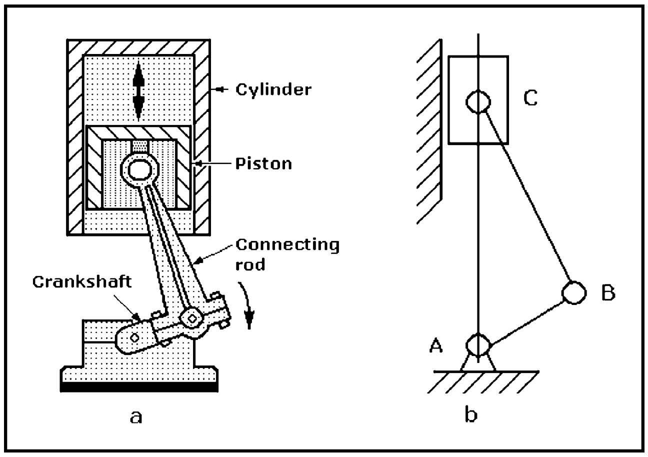

Fig. 1 Cross section of a cylinder of an internal combustion engine showing piston reciprocation (a), and the skeleton outline of the linkage mechanism that moves the piston (b).

PHYSICAL PRINCIPLES

Efficiency of Machines

Simple machines are evaluated on the basis of efficiency and mechanical advantage. While it is possible to obtain a larger force from a machine than the force exerted upon it, this refers only to force and not energy; according to the law of conservation of energy, *more work cannot be obtained from a machine than the energy supplied to it*. Because work = force × distance, for a machine to exert a larger force than its initiating force or operator, that larger force must be exerted through a correspondingly shorter distance. As a result of friction in all moving machinery, the energy produced by a machine is less than that applied to it. Consequently, by interpreting the law of conservation of energy, it follows that:

$$\text{Input energy} = \text{output energy} + \text{wasted energy}$$

This statement is true over any period of time, so it applies to any unit of time; because power is work or energy per unit of time, the following statement is also true:

$$\text{Input power} = \text{output power} + \text{wasted power}$$

The *efficiency of a machine is the ratio of its output to its input*, if both input and output are expressed in the same units of energy or power. This ratio is always less than unity, and it is usually expressed in percent by multiplying the ratio by 100.

$$\text{Percent efficiency} = \frac{\text{output energy}}{\text{input energy}} \times 100$$

or

$$\text{Percent efficiency} = \frac{\text{output power}}{\text{input power}} \times 100$$

A machine has high efficiency if most of the power supplied to it is passed on to its load and only a fraction of the power is wasted. The efficiency can be as high as 98 percent for a large electrical generator, but it is likely to be less than 50 percent for a screw jack. For example, if the input power supplied to a 20-hp motor with an efficiency of 70 percent is to be calculated, the foregoing equation is transposed.

$$\text{Input power} = \frac{\text{output power}}{\text{percent efficiency}} \times 100$$
$$= \frac{20\text{ hp}}{70} \times 100 = 28.6\text{ hp}$$

Mechanical Advantage

The *mechanical advantage* of a mechanism or system is the ratio of the load or weight *W*, typically in pounds or kilograms, divided by the effort or force *F* exerted by the initiating entity or operator, also in pounds or kilograms. If friction has been considered or is known from actual testing, the mechanical advantage, MA, of a machine is:

$$\text{MA} = \frac{\text{load}}{\text{effort}} = \frac{W}{F}$$

However, if it is assumed that the machine operates without friction, the ratio of W divided by F is called the *theoretical mechanical advantage*, TA.

$$\text{TA} = \frac{\text{load}}{\text{effort}} = \frac{W}{F}$$

Velocity Ratio

Machines and mechanisms are used to translate a small amount of movement or distance into a larger amount of movement or distance. This property is known as the *velocity ratio*. It is defined as the ratio of the distance moved by the effort per second divided by the distance moved by the load per second for a machine or mechanism. It is widely used in determining the mechanical advantage of gears or pulleys.

$$\text{VR} = \frac{\text{distance moved by effort/second}}{\text{distance moved by load/second}}$$

INCLINED PLANE

The *inclined* plane, shown in Fig. 2, has an incline length l (AB) = 8 ft and a height h (BC) = 3 ft. The inclined plane permits a smaller force to raise a given weight than if it were lifted directly from the ground. For example, if a weight W of 1000 lb is to be raised vertically through a height BC of 3 ft without using an inclined plane, a force F of 1000 lb must be exerted over that height. However, with an inclined plane, the weight is moved over the longer distance of 8 ft, but a force F of only $^3/_8$ of 1000 or 375 lb would be required because the weight is moved through a longer distance. To determine the mechanical advantage of the inclined plane, the following formula is used:

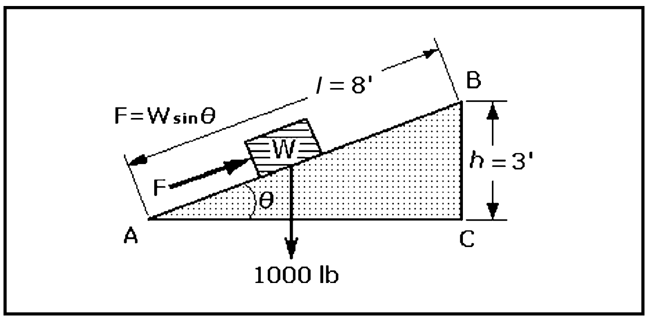

Fig. 2 Diagram for calculating mechanical advantage of an inclined plane.

$$F = W \sin \theta \qquad \sin \theta = \frac{\text{height } h}{\text{length } l}$$

where height h = 3 ft, length l = 8 ft, $\sin \theta = 0.375$, and weight W = 1000 lb.

$$F = 1000 \times 0.375$$

$$F = 375 \text{ lb}$$

$$\text{Mechanical advantage MA} = \frac{\text{load}}{\text{effort}} = \frac{W}{F} = \frac{1000}{375} = 2.7$$

PULLEY SYSTEMS

A single pulley simply changes the direction of a force so its mechanical advantage is unity. However, considerable mechanical advantage can be gained by using a combination of pulleys. In the typical pulley system, shown in Fig. 3a, each block contains two pulleys or sheaves within a frame or shell. The upper block is fixed and the lower block is attached to the load and moves with it. A cable fastened at the end of the upper block passes around four pulleys before being returned to the operator or other power source.

Figure 3b shows the pulleys separated for clarity. To raise the load through a height h, each of the sections of the cable A, B, C, and D must be moved to a distance equal to h. The operator or other power source must exert a force F through a distance $s = 4h$ so that the velocity ratio of s to h is 4. Therefore, the theoretical mechanical advantage of the system shown is 4, corresponding to the four cables supporting the load W. The theoretical mechanical advantage TA for any pulley system similar to that shown equals the number of parallel cables that support the load.

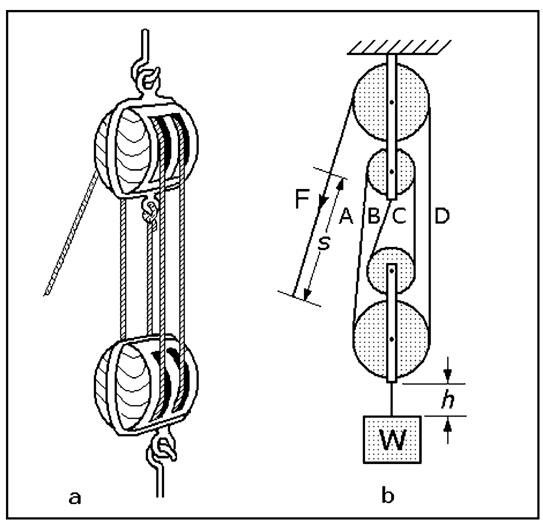

Fig. 3 Four cables supporting the load of this pulley combination give it a mechanical advantage of 4.

SCREW-TYPE JACK

Mechanisms are often required to move a large load with a small effort. For example, a car jack allows an ordinary human to lift a car which may weigh as much as 6000 lb, while the person only exerts a force equivalent to 20 or 30 lb.

The *screw jack*, shown in Fig. 4, is a practical application of the inclined plane because a screw is considered to be an inclined plane wrapped around cylinder. A force F must be exerted at the end of a length of horizontal bar l to turn the screw to raise the load (weight W) of 1000 lb. The 5-ft bar must be moved through a complete turn or a circle of length $s = 2\pi l$ to advance the load a distance h of 1.0 in. or 0.08 ft equal to the pitch p of the screw. The pitch of the screw is the distance advanced in a complete turn. Neglecting friction:

$$F = \frac{W \times h}{s}$$

where $s = 2\pi l = 2 \times 3.14 \times 5$, $h = p = 0.08$, and $W = 1000$ lb

$$F = \frac{1000 \times 0.08}{2 \times 3.14 \times 5} = \frac{80}{31.4} = 2.5 \text{ lb}$$

$$\text{Mechanical advantage MA} = \frac{\text{load}}{\text{effort}} = \frac{2\pi l}{p} = \frac{31.4}{0.08} = 393$$

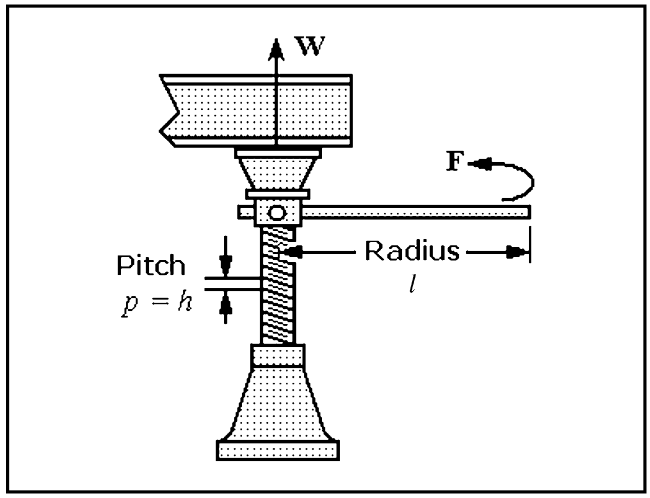

Fig. 4 Diagram for calculating the mechanical advantage of a screw jack.

LEVERS AND MECHANISMS

Levers

Levers are the simplest of mechanisms; there is evidence that Stone Age humans used levers to extend their reach or power; they made them from logs or branches to move heavy loads such as rocks. It has also been reported that primates and certain birds use twigs or sticks to extend their reach and act as tools to assist them in obtaining food.

A lever is a rigid beam that can rotate about a fixed point along its length called the *fulcrum*. Physical effort applied to one end of the beam will move a load at the other end. The act of moving the fulcrum of a long beam nearer to the load permits a large load to be lifted with minimal effort. This is another way to obtain *mechanical advantage*.

The three *classes of lever* are illustrated in Fig. 5. Each is capable of providing a different level of mechanical advantage. These levers are called *Class 1*, *Class 2*, and *Class 3*. The differences in the classes are determined by:

- Position along the length of the lever where the effort is applied
- Position along the length of the lever where the load is applied
- Position along the length of the lever where the fulcrum or pivot point is located

Class 1 lever, the most common, has its fulcrum located at or about the middle with effort exerted at one end and load positioned at the opposite end, both on the same side of the lever. Examples of Class 1 levers are playground seesaw, crowbar, scissors, claw hammer, and balancing scales.

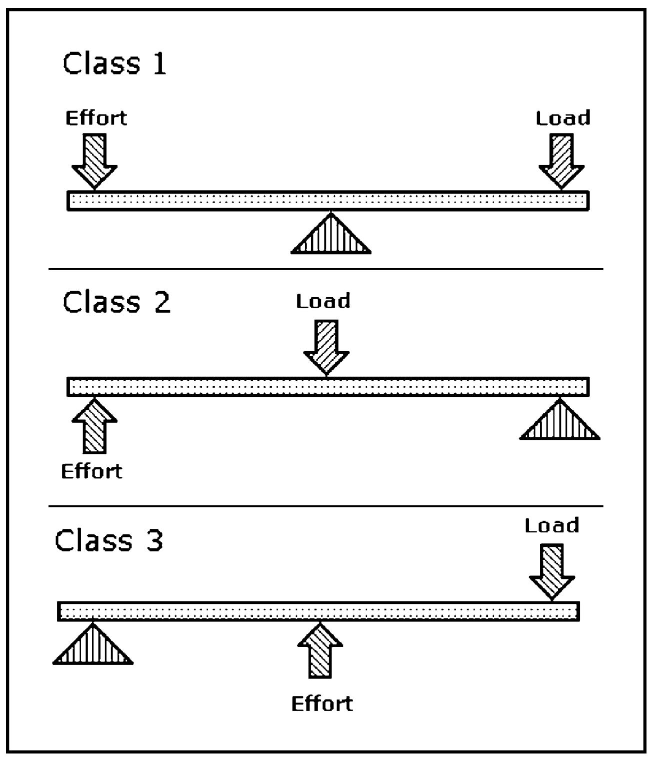

Fig. 5 Three levers classified by the locations of their fulcrums, loads, and efforts.

Class 2 lever has its fulcrum at one end; effort is exerted at the opposite end, and the opposing load is positioned at or near the middle. Examples of Class 2 levers are wheelbarrow, simple bottle openers, nutcracker, and foot pump for inflating air mattresses and inflatable boats.

Class 3 lever also has its fulcrum on one end; load is exerted at the opposite end, and the opposing effort is exerted on or about the middle. Examples of Class 3 levers are shovel and fishing rod where the hand is the fulcrum, tweezers, and human and animal arms and legs.

The application of a Class 1 lever is shown in Fig. 6. The lever is a bar of length AB with its fulcrum at X, dividing the length of the bar into parts: l_1 and l_2. To raise a load W through a height of h, a force F must be exerted downward through a distance s. The triangles AXC and BXD are similar and proportional; therefore, ignoring friction:

$$\frac{s}{h} = \frac{l_1}{l_2} \text{ and mechanical advantage MA } = \frac{l_1}{l_2}$$

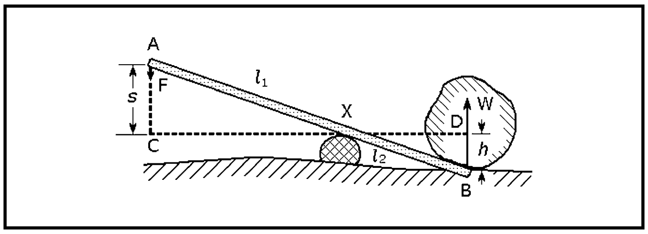

Fig. 6 Diagram for calculating the mechanical advantage of a simple lever for raising a weight.

Winches, Windlasses, and Capstans

Winches, windlasses, and capstans are machines that convert rotary motion into linear motion, usually with some mechanical advantage. These machines are essentially Class 1 levers: effort is applied to a lever or crank, the fulcrum is the center of the drum, and the load is applied to the rope, chain, or cable.

Manually operated windlasses and capstans, mechanically the same, were originally used on sailing ships to raise and lower anchors. Operated by one or more levers by one or more sailors, both had barrels or drums on which rope or chain was wound. In the past, windlasses were distinguished from capstans; windlasses had horizontal drums and capstans had vertical drums. The modern term *winch* is now the generic name for any manual or power-operated drum for hauling a load with cable, chain, or rope. The manually operated winch, shown in Fig. 7, is widely used today on sailboats for raising and trimming sails, and sometimes for weighing anchors.

Ignoring friction, the mechanical advantage of all of these machines is approximately the *length of the crank* divided by the *diameter of the drum*. In the winch example shown, when the left end of the line is held under tension and the handle or crank is turned clockwise, a force is applied to the line entering on the right; it is attached to the load to perform such useful work as raising or tensioning sails.

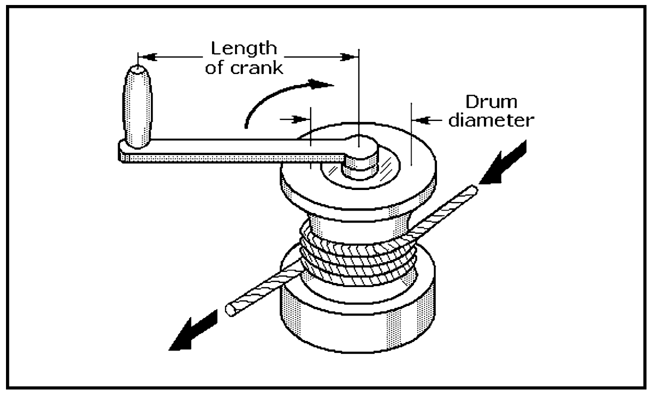

Fig. 7 Diagram for calculating the mechanical advantage of a manually operated winch for raising anchors or sails.

LINKAGES

A *linkage* is a mechanism formed by connecting two or more levers together. Linkages can be designed to change the direction of a force or make two or more objects move at the same time. Many different fasteners are used to connect linkages together yet allow them to move freely such as pins, end-threaded bolts with nuts, and loosely fitted rivets. There are two general classes of linkages: *simple planar linkages* and more complex *specialized linkages*; both are capable of performing tasks such as describing straight lines or curves and executing motions at differing speeds. The names of the linkage mechanisms given here are widely but not universally accepted in all textbooks and references.

Linkages can be classified according to their primary functions:

- *Function generation*: the relative motion between the links connected to the frame
- *Path generation*: the path of a tracer point
- *Motion generation*: the motion of the coupler link

Simple Planar Linkages

Four different simple planar linkages shown in Fig. 8 are identified by function:

- *Reverse-motion linkage*, Fig. 8a, can make objects or force move in opposite directions; this can be done by using the input link as a lever. If the fixed pivot is equidistant from the moving pivots, output link movement will equal input link movement, but it will act in the opposite direction. However, if the fixed pivot is not centered, output link movement will not equal input link movement. By selecting the position of the fixed pivot, the linkage can be designed to produce specific mechanical advantages. This linkage can also be rotated through 360°.
- *Push-pull linkage*, Fig. 8b, can make the objects or force move in the same direction; the output link moves in the same direction as the input link. Technically classed as a four-bar linkage, it can be rotated through 360° without changing its function.

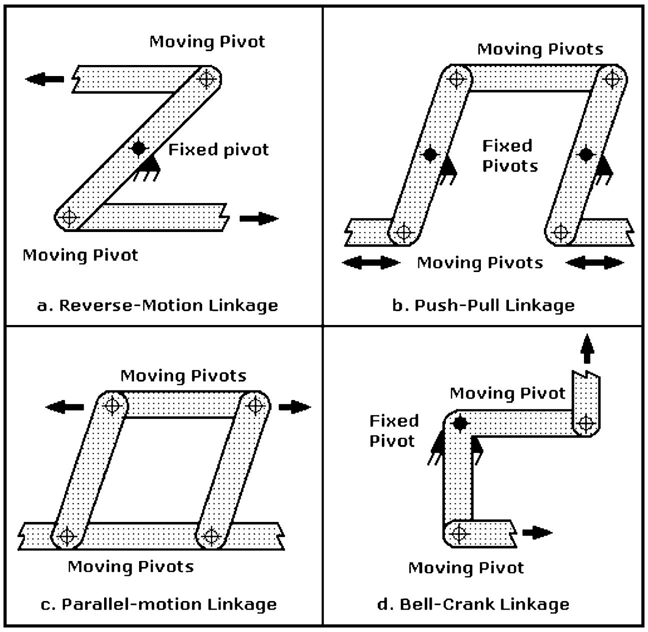

Fig. 8 Functions of four basic planar linkage mechanisms.

- *Parallel-motion linkage*, Fig. 8c, can make objects or forces move in the same direction, but at a set distance apart. The moving and fixed pivots on the opposing links in the parallelogram must be equidistant for this linkage to work correctly. Technically classed as a four-bar linkage, this linkage can also be rotated through 360° without changing its function. Pantographs that obtain power for electric trains from overhead cables are based on parallel-motion linkage. Drawing pantographs that permit original drawings to be manually copied without tracing or photocopying are also adaptations of this linkage; in its simplest form it can also keep tool trays in a horizontal position when the toolbox covers are opened.
- *Bell-crank linkage*, Fig. 8d, can change the direction of objects or force by 90°. This linkage rang doorbells before electric clappers were invented. More recently this mechanism has been adapted for bicycle brakes. This was done by pinning two bell cranks bent 90° in opposite directions together to form tongs. By squeezing the two handlebar levers linked to the input ends of each crank, the output ends will move together. Rubber blocks on the output ends of each crank press against the wheel rim, stopping the bicycle. If the pins which form a fixed pivot are at the midpoints of the cranks, link movement will be equal. However, if those distances vary, mechanical advantage can be gained.

Specialized Linkages

In addition to changing the motions of objects or forces, more complex linkages have been designed to perform many specialized functions: These include drawing or tracing straight lines; moving objects or tools faster in a retraction stroke than in an extension stroke; and converting rotating motion into linear motion and vice versa.

The simplest specialized linkages are four-bar linkages. These linkages have been versatile enough to be applied in many different applications. Four-bar linkages actually have only three moving links but they have one fixed link and four pin joints or pivots. A useful mechanism must have at least four links but closed-loop assemblies of three links are useful elements in structures. Because any linkage with at least one fixed link is a mechanism, both the parallel-motion and push-pull linkages mentioned earlier are technically machines.

Four-bar linkages share common properties: three rigid moving links with two of them hinged to fixed bases which form a *frame.* Link mechanisms are capable of producing rotating, oscillating, or reciprocating motion by the rotation of a crank. Linkages can be used to convert:

- Continuous rotation into another form of continuous rotation, with a constant or variable angular velocity ratio
- Continuous rotation into oscillation or continuous oscillation into rotation, with a constant or variable velocity ratio
- One form of oscillation into another form of oscillation, or one form of reciprocation into another form of reciprocation, with a constant or variable velocity ratio

There are four different ways in which four-bar linkages can perform inversions or complete revolutions about fixed pivot points. One pivoting link is considered to be the *input* or *driver* member and the other is considered to be the *output* or *driven member.* The remaining moving link is commonly called a *connecting link*. The fixed link, hinged by pins or pivots at each end, is called the *foundation link.*

Three inversions or linkage rotations of a four-bar chain are shown in Figs. 9, 10, and 11. They are made up of links AB, BC, CD, and AD. The forms of the three inversions are defined by the position of the shortest link with respect to the link selected as the foundation link. The ability of the driver or driven links to make complete rotations about their pivots determines their functions.

Drag-link mechanism, Fig. 9, demonstrates the first inversion. The shortest link AD between the two fixed pivots is the foundation link, and both driver link AB and driven link CD can make full revolutions.

Crank-rocker mechanism, Fig. 10, demonstrates the second inversion. The shortest link AB is adjacent to AD, the foundation link. Link AB can make a full 360° revolution while the opposite link CD can only oscillate and describe an arc.

Double-rocker mechanism, Fig. 11, demonstrates the third inversion. Link AD is the foundation link, and it is opposite the shortest link BC. Although link BC can make a full 360° revolution, both pivoting links AB and CD can only oscillate and describe arcs.

The fourth inversion is another *crank-rocker mechanism* that behaves in a manner similar to the mechanism shown in Fig. 10,

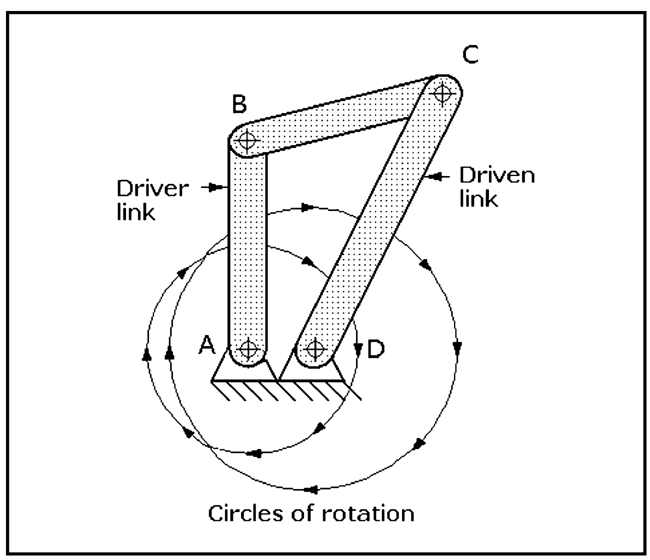

Fig. 9 Four-bar drag-link mechanism: Both the driver link AB and driven link CD can rotate through 360°. Link AD is the foundation link.

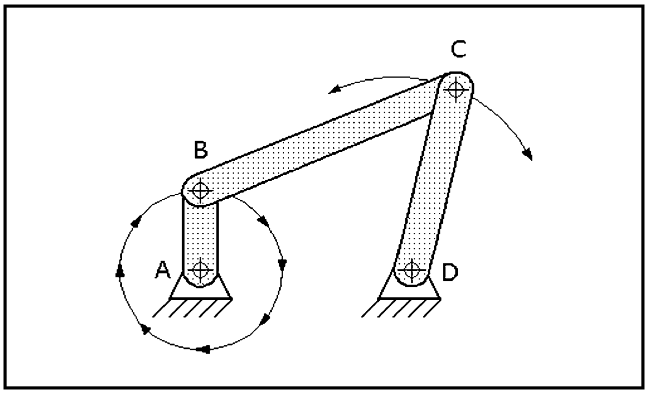

Fig. 10 Crank-rocker mechanism: Link AB can make a 360° revolution while link CD oscillates with C describing an arc. Link AD is the foundation link.

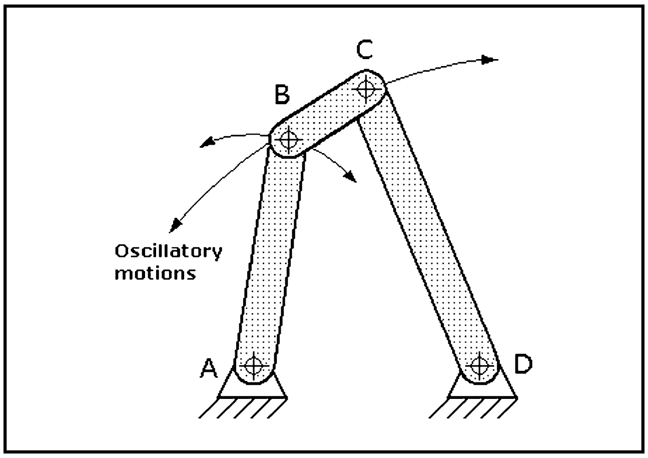

Fig. 11 Double-rocker mechanism: Short link BC can make a 360° revolution, but pivoting links AB and CD can only oscillate, describing arcs.

but the longest link, CD, is the foundation link. Because of this similarity between these two mechanisms, the fourth inversion is not illustrated here. A drag-link mechanism can produce either a nonuniform output from a uniform input rotation rate or a uniform output from a nonuniform input rotation rate.

Straight-Line Generators

Figures 12 to 15 illustrate examples of classical linkages capable of describing straight lines, a function useful in many different kinds of machines, particularly machine tools. The dimensions of the rigid links are important for the proper functioning of these mechanisms.

Watt's straight-line generator, illustrated in Fig. 12, can describe a short vertical straight line. Equal length links AB and CD are hinged at A and D, respectively. The midpoint E of connecting link BC traces a figure eight pattern over the full mechanism excursion, but a straight line is traced in part of the excursion because point E diverges to the left at the top of the stroke and to the right at the bottom of the stroke. This linkage was used by Scottish instrument maker, James Watt, in a steam-driven beam pump in about 1769, and it was a prominent mechanism in early steam-powered machines.

Scott Russell straight-line generator, shown in Fig. 13, can also describe a straight line. Link AB is hinged at point A and pinned to link CD at point B. Link CD is hinged to a roller at point C which restricts it to horizontal oscillating movement.

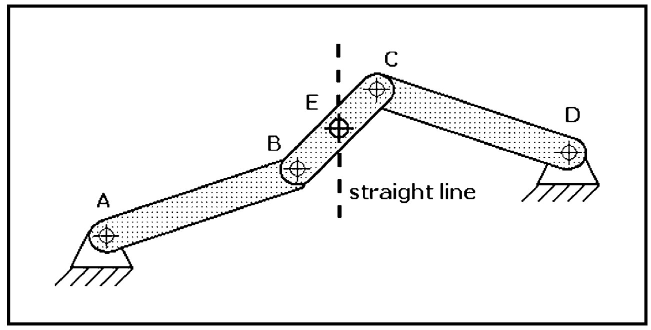

Fig. 12 Watt's straight-line generator: The center point E of link BC describes a straight line when driven by either links AB or CD.

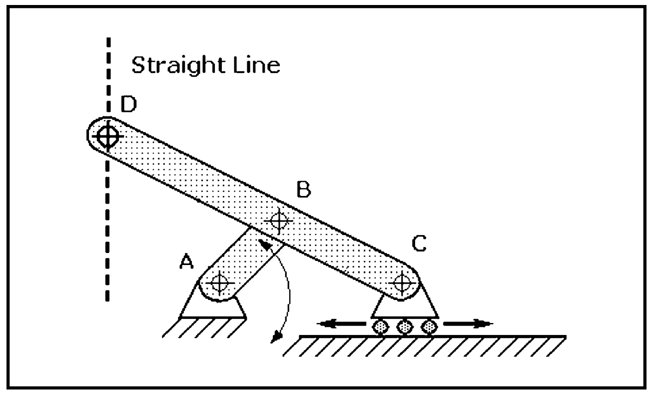

Fig. 13 Scott Russell straight-line generator: Point D of link DC describes a straight line as driver link AB oscillates, causing the slider at C to reciprocate left and right.

This configuration confines point D to a motion that traces a vertical straight line. Both points A and C lie in the same horizontal plane. This linkage works if the length of link AB is about 40 percent of the length of CD, and the distance between points D and B is about 60 percent of the length of CD.

Peaucellier's straight-line linkage, drawn as Fig. 14, can describe more precise straight lines over its range than either the Watt's or Scott Russell linkages. To make this linkage work correctly, the length of link BC must equal the distance between points A and B set by the spacing of the fixed pivots; in this figure, link BC is 15 units long while the lengths of links CD, DF, FE, and EC are equal at 20 units. As links AD and AE are moved,

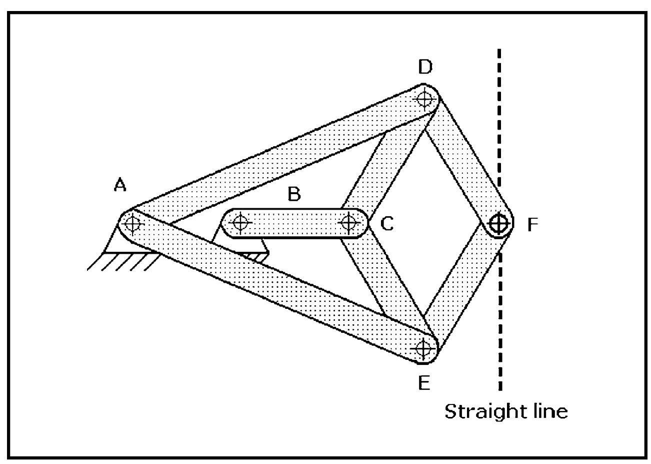

Fig. 14 Peaucellier's straight-line generator: Point F describes a straight line when either link AD or AE acts as the driver.

point F can describe arcs of any radius. However, the linkage can be restricted to tracing straight lines (infinite radiuses) by selecting link lengths for AD and AE. In this figure they are 45 units long. This linkage was invented in 1873 by the French engineer, Captain Charles-Nicolas Peaucellier.

Tchebicheff's straight-line generator, shown in Fig. 15, can also describe a horizontal line. Link CB with E as its midpoint traces a straight horizontal line for most of its transit as links AB and DC are moved to the left and right of center. To describe this straight line, the length of the foundation link AD must be twice the length of link CB. To make this mechanism work as a straight-line generator, CB is 10 units long, AD is 20 units long, and both AB and DC are 25 units long. With these dimensions, link CB will assume a vertical position when it is at the right and left extremes of its travel excursion. This linkage was invented by nineteenth-century Russian mathematician, Pafnuty Tchebicheff or Chebyshev.

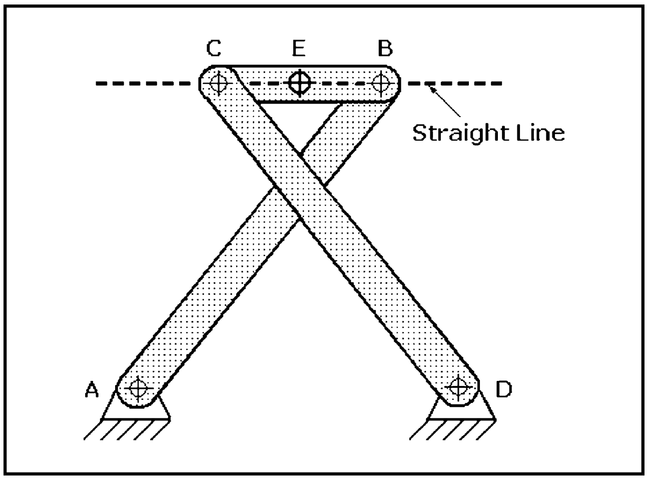

Fig. 15 Tchebicheff's straight-line generator: Point E of link CB describes a straight line when driven by either link AB or DC. Link CB moves into a vertical position at both extremes of its travel.

Rotary/Linear Linkages

Slider-crank mechanism (or a simple crank), shown as Fig. 16, converts rotary to linear motion and vice versa, depending on its application. Link AB is free to rotate 360° around the hinge while link BC oscillates back and forth because point C is hinged to a roller which restricts it to linear motion. Either the slider or the rotating link AB can be the driver.

This mechanism is more familiar as the piston, connecting rod, and crankshaft of an internal combustion engine, as illustrated in Fig. 1. The piston is the slider at C, the connecting rod is link BC, and the crankshaft is link AB. In a four-stroke engine, the piston is pulled down the cylinder by the crankshaft, admitting the air-fuel mixture; in the compression stroke the piston is driven back up the cylinder by the crankshaft to compress the air-fuel mixture. However, the roles change in the combustion stroke when the piston drives the crankshaft. Finally, in the exhaust stroke the roles change again as the crankshaft drives the piston back to expel the exhaust fumes.

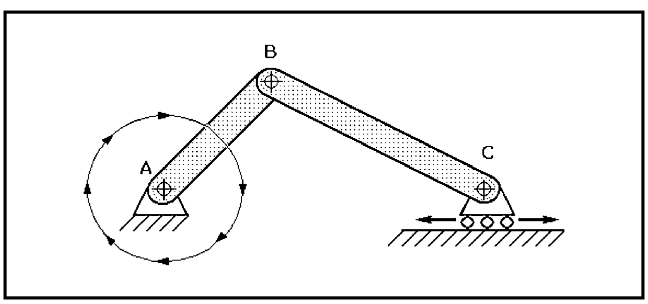

Fig. 16 Slider-crank mechanism: This simple crank converts the 360° rotation of driver link AB into linear motion of link BC, causing the slider at C to reciprocate.

Scotch-yoke mechanism, pictured in Fig. 17, functions in a manner similar to that of the simple crank mechanism except that its linear output motion is sinusoidal. As wheel A, the driver, rotates, the pin or roller bearing at its periphery exerts torque within the closed yoke B; this causes the attached sliding bar to reciprocate, tracing a sinusoidal waveform. Part a shows the sliding bar when the roller is at 270°, and part b shows the sliding bar when the roller is at 0°.

Rotary-to-linear mechanism, drawn in Fig. 18, converts a uniform rotary motion into an intermittent reciprocating motion. The three teeth of the input rotor contact the steps in the frame or yoke, exerting torque 3 times per revolution, moving the yoke with attached bar. Full linear travel of the yoke is accomplished in 30° of rotor rotation followed by a 30° delay before returning the yoke. The reciprocating cycle is completed 3 times per revolution of the input. The output is that of a step function.

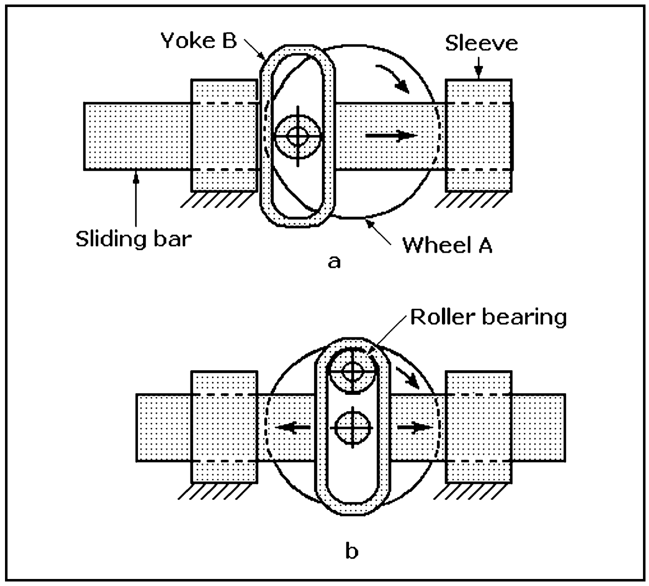

Fig. 17 Scotch-yoke mechanism translates the rotary motion of the wheel with a peripheral roller into reciprocating motion of the yoke with supporting bars as the roller exerts torque within the yoke. The yoke is shown in its left (270°) position in (a) and in its center (0°) position in (b).

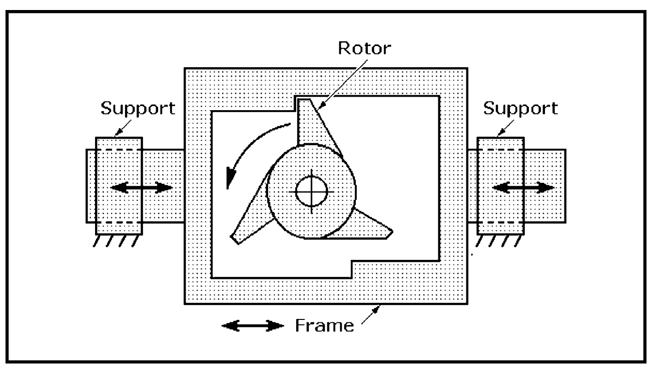

Fig. 18 Rotary-to-linear mechanism converts the uniform rotation of the 3-tooth rotor into a reciprocating motion of the frame and supporting bars. The reciprocating cycle is completed 3 times per rotor revolution.

Geneva wheel mechanism, illustrated in Fig. 19, is an example of intermittent gearing that converts continuous rotary motion into intermittent rotary motion. Geneva wheel C makes a quarter turn for every turn of lever AB attached to driving wheel A. When pin B on lever AB turns clockwise, it enters one of the four slots of geneva wheel C; the pin moves downward in the slot, applying enough torque to the geneva wheel to turn it counterclockwise $^1/_4$ revolution before it leaves the slot. As wheel A continues to rotate clockwise, it engages the next three slots in a sequence to complete one geneva wheel rotation. If one of the slots is obstructed, the pin can only move through part of the revolution, in either direction, before it strikes the closed slot, stopping the rotation of the geneva wheel. This mechanism has been used in mechanical windup watches, clocks, and music boxes to prevent overwinding.

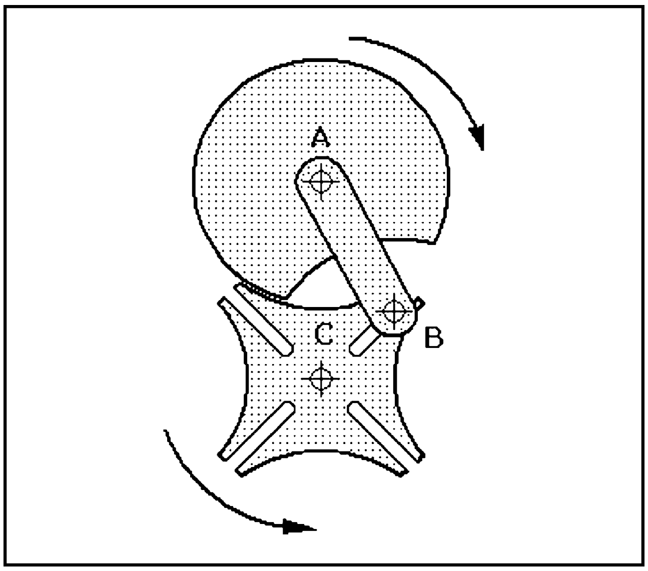

Fig. 19 Geneva wheel escapement mechanism: Pin B at the end of lever AB (attached to wheel A) engages a slot in geneva wheel C as wheel A rotates clockwise. Pin B moves down the slot, providing torque to drive the geneva wheel counterclockwise $^1/_4$ revolution before it exits the first slot; it then engages the next three slots to drive the geneva wheel through one complete counterclockwise revolution.

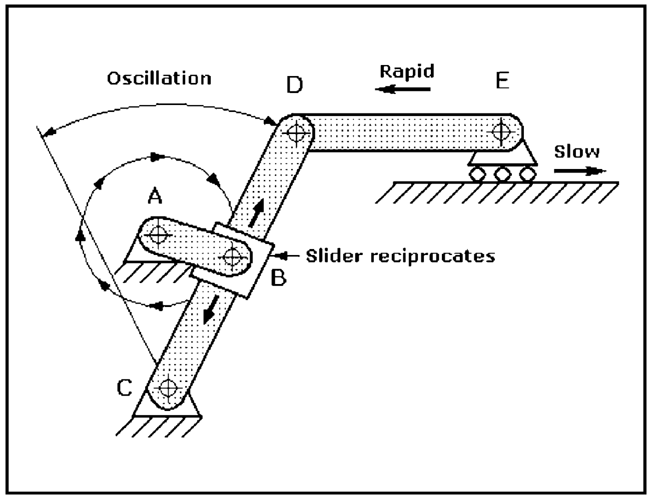

Fig. 20 Swing-arm quick-return mechanism: As drive link AB rotates 360° around A, it causes the slider at B to reciprocate up and down along link CD, causing CD to oscillate though an arc. This motion drives link DE in a reciprocating motion that moves the rolling slider at E slowly to the right before returning it rapidly to the left.

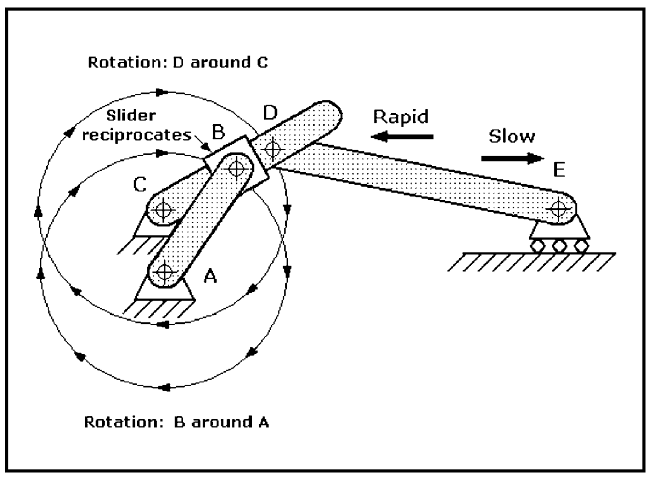

Fig. 21 Whitworth's quick-return mechanism: As drive link AB rotates 360° around A, it causes the slider at B to reciprocate back and forth along link CD, which, in turn causes CD to rotate 360° around C. This, motion causes link DE to reciprocate, first moving rolling slider at E slowly to the right before returning it rapidly to the left.

Swing-arm quick-return mechanism, drawn as Fig. 20, converts rotary motion into nonuniform reciprocating motion. As drive link AB rotates 360° around pin A, it causes the slider at B to reciprocate up and down along link CD. This, in turn, causes CD to oscillate left and right, describing an arc. Link DE, pinned to D with a rolling slider pinned at E, moves slowly to the right before being returned rapidly to the left.

Whitworth quick-return mechanism, shown as Fig. 21, converts rotary motion to nonuniform reciprocating motion. Drive link AB rotates 360° about pin A causing the slider at B to reciprocate back and forth along link CD; this, in turn, causes link CD to rotate 360° around point C. Link DE is pinned to link CD at D and a rolling slider at E. The slider at E is moved slowly to the right before being returned rapidly to the left. This mechanism, invented in the nineteenth century by English engineer, Joseph Whitworth, has been adapted for shapers, machine tools with moving arms that cut metal from stationary workpieces. A hardened cutting tool attached at the end of the arm (equivalent to point E) advances slowly on the cutting stroke but retracts rapidly on the backstroke. This response saves time and improves productivity in shaping metal.

Simple ratchet mechanism, drawn as Fig. 22, can only be turned in a counterclockwise direction. The ratchet wheel has many wedge-shaped teeth that can be moved incrementally to turn an oscillating drive lever. As driving lever AB first moves clockwise to initiate counterclockwise movement of the wheel, it drags pawl C pinned at B over one or more teeth while pawl D prevents the wheel from turning clockwise. Then, as lever AB reverses to drive the ratchet wheel counterclockwise, pawl D is released, allowing the wheel to turn it in that direction. The amount of backward incremental motion of lever AB is directly proportional to pitch of the teeth: smaller teeth will reduce the degree of rotation while larger teeth will increase them. The contact surfaces of the teeth on the wheel are typically inclined, as shown, so they will not be disengaged if the mechanism is subjected to vibration or shock under load. Some ratchet mechanisms include a spring to hold pawl D against the teeth to assure no clockwise wheel rotation as lever AB is reset.

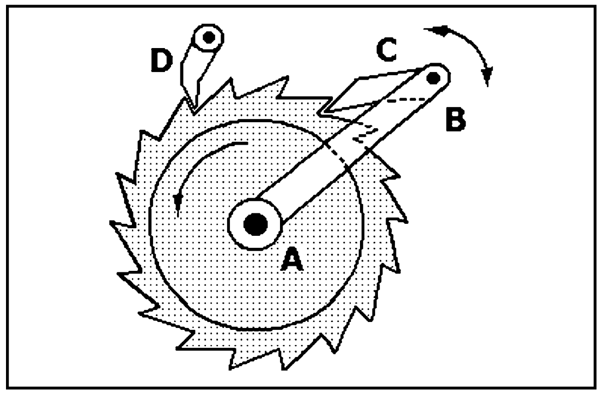

Fig. 22 This ratchet wheel can be turned only in a counterclockwise direction. As driving lever AB moves clockwise, it drags pawl C, pinned at B over one or more teeth while pawl D prevents the wheel from turning clockwise. Then as lever AB reverses to drive the ratchet wheel counterclockwise, pawl D is released allowing the wheel to turn it in that direction.

GEARS AND GEARING

A *gear* is a wheel with evenly sized and spaced teeth machined or formed around its perimeter. Gears are used in rotating machinery not only to transmit motion from one point to another, but also for the mechanical advantage they offer. Two or more gears transmitting motion from one shaft to another is called a *gear train,* and *gearing* is a system of wheels or cylinders with meshing teeth. Gearing is chiefly used to transmit rotating motion but can also be adapted to translate reciprocating motion into rotating motion and vice versa.

Gears are versatile mechanical components capable of performing many different kinds of power transmission or motion control. Examples of these are

- Changing rotational speed
- Changing rotational direction
- Changing the angular orientation of rotational motion
- Multiplication or division of torque or magnitude of rotation
- Converting rotational to linear motion, and its reverse
- Offsetting or changing the location of rotating motion

The teeth of a gear can be considered as levers when they mesh with the teeth of an adjoining gear. However, gears can be rotated continuously instead of rocking back and forth through short distances as is typical of levers. A gear is defined by the number of its teeth and its diameter. The gear that is connected to the source of power is called the *driver*, and the one that receives power from the driver is the *driven gear*. It always rotates in a direction opposing that of the driving gear; if both gears have the same number of teeth, they will rotate at the same speed. However, if the number of teeth differs, the gear with the smaller *r* number of teeth will rotate faster. The size and shape of all gear teeth that are to mesh properly for working contact must be equal.

Figure 23 shows two gears, one with 15 teeth connected at the end of shaft A, and the other with 30 teeth connected at the end of shaft B. The 15 teeth of smaller driving gear A will mesh with 15 teeth of the larger gear B, but while gear A makes one revolution gear B will make only $\frac{1}{2}$ revolution.

The number of teeth on a gear determines its diameter. When two gears with different diameters and numbers of teeth are meshed together, the number of teeth on each gear determines gear ratio, velocity ratio, distance ratio, and mechanical advantage. In Fig. 23, gear A with 15 teeth is the driving gear and gear B with 30 teeth is the driven gear. The gear ratio GR is determined as:

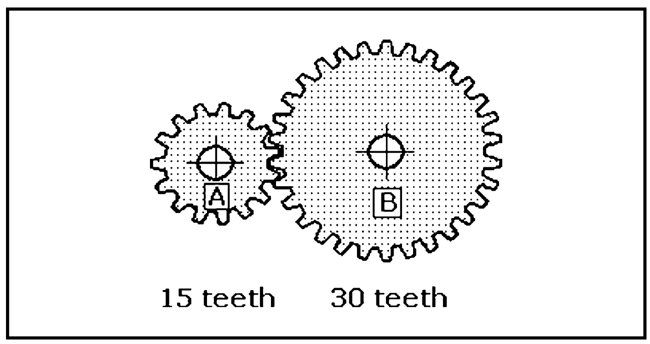

Fig. 23 Gear B has twice as many teeth as gear A, and it turns at half the speed of gear A because gear speed is inversely proportional to the number of teeth on each gear wheel.

$$GR = \frac{\text{number of teeth on driven gear B}}{\text{number of teeth on driving gear A}}$$

$$= \frac{30}{15} = \frac{2}{1} \text{ (also written as 2:1)}$$

The number of teeth in both gears determines the rotary distance traveled by each gear and their angular speed or velocity ratio. The angular speeds of gears are inversely proportional to the numbers of their teeth. Because the smaller driving gear A in Fig. 23 will revolve twice as fast as the larger driven gear B, velocity ratio VR is:

$$VR = \frac{\text{velocity of driving gear A}}{\text{velocity of driven gear B}} = \frac{2}{1} \text{ (also written as 2:1)}$$

In this example load is represented by driven gear B with 30 teeth and the effort is represented by driving gear A with 15 teeth. The distance moved by the load is twice that of the effort. Using the general formula for mechanical advantage MA:

$$\text{MA} = \frac{\text{load}}{\text{effort}} = \frac{30}{15} = 2$$

Simple Gear Trains

A gear train made up of multiple gears can have several drivers and several driven gears. If the train contains an odd number of gears, the output gear will rotate in the same direction as the input gear, but if the train contains an even number of gears, the output gear will rotate opposite that of the input gear. The number of teeth on the intermediate gears does not affect the overall velocity ratio, which is governed purely by the number of teeth on the first and last gear.

In simple gear trains, high or low gear ratios can only be obtained by combining large and small gears. In the simplest basic gearing involving two gears, the driven shaft and gear revolves in a direction opposite that of the driving shaft and gear. If it is desired that the two gears and shafts rotate in the same direction, a third *idler gear* must be inserted between the driving gear and the driven gear. The idler revolves in a direction opposite that of the driving gear.

A simple gear train containing an idler is shown in Fig. 24. Driven idler gear B with 20 teeth will revolve 4 times as fast counterclockwise as driving gear A with 80 teeth turning clockwise. However, gear C, also with 80 teeth, will only revolve one turn clockwise for every four revolutions of idler gear B, making the velocities of both gears A and C equal except that gear C turns in the same direction as gear A. In general, the velocity ratio of the first and last gears in a train of simple gears is not changed by the number of gears inserted between them.

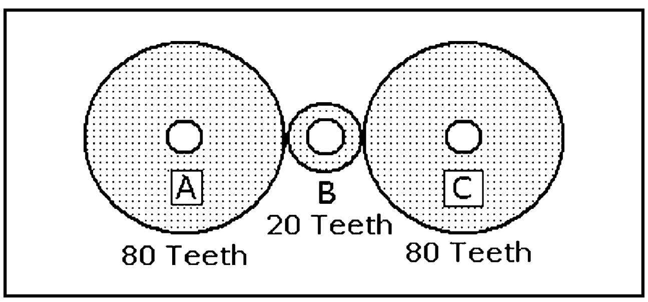

Fig. 24 Gear train: When gear A turns once clockwise, gear B turns four times counter clockwise, and gear wheel C turns once clockwise. Gear B reverses the direction of gear C so that both gears A and C turn in the same direction with no change in the speed of gear C.

Compound Gear Trains

More complex compound gear trains can achieve high and low gear ratios in a restricted space by coupling large and small gears on the same axle. In this way gear ratios of adjacent gears can be multiplied through the gear train. Figure 25 shows a set of compound gears with the two gears B and D mounted on the middle shaft. Both rotate at the same speed because they are fastened together. If gear A (80 teeth) rotates at 100 rpm clockwise, gear B (20 teeth) turns at 400 rpm counterclockwise because of its velocity ratio of 1 to 4. Because gear D (60 teeth) also turns at 400 rpm and its velocity ratio is 1 to 3 with respect to gear C

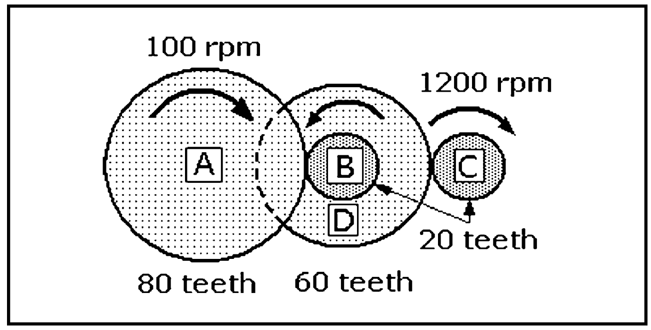

Fig. 25 Compound gears: Two gears B and D are mounted on a central shaft and they turn at the same speed. If gear A rotates at 100 rpm clockwise, gears B and D turn counterclockwise at 400 rpm, and gear C, driven by gear D, turns clockwise at 1200 rpm.

(20 teeth), gear C will turn at 1200 rpm clockwise. The velocity ratio of a compound gear train can be calculated by multiplying the velocity ratios for all pairs of meshing gears. For example, if the driving gear has 45 teeth and the driven gear has 15 teeth, the velocity ratio is $^{15}/_{45} = {}^{1}/_{3}$.

Gear Classification

All gears can be classified as either external gears or internal or annual gears:

- *External gears* have teeth on the outside surface of the disk or wheel.
- *Internal* or *annual gears* have teeth on the inside surface of a ring or cylinder.

Spur gears are cylindrical external gears with teeth that are cut straight across the edge of the disk or wheel parallel to the axis of rotation. The spur gears shown in Fig. 26a are the simplest gears. They normally translate rotating motion between two parallel shafts. An *internal* or *annual* gear, as shown in Fig. 26b, is a variation of the spur gear except that its teeth are cut on the inside of a ring or flanged wheel rather than on the outside. Internal gears usually drive or are driven by a pinion. The disadvantage of a simple spur gear is its tendency to produce thrust that can misalign other meshing gears along their respective shafts, thus reducing the face widths of the meshing gears and reducing their mating surfaces.

Rack gears, as the one shown in Fig. 26c, have teeth that lie in the same plane rather than being distributed around a wheel. This gear configuration provides straight-line rather than rotary motion. A rack gear functions like a gear with an infinite radius.

Pinions are small gears with a relatively small number of teeth which can be mated with rack gears.

Rack and pinion gears, shown in Fig. 26c, convert rotary motion to linear motion; when mated together they can transform the rotation of a pinion into reciprocating motion, or vice versa. In some systems, the pinion rotates in a fixed position and engages the rack which is free to move; the combination is found in the steering mechanisms of vehicles. Alternatively, the rack is fixed while the pinion rotates as it moves up and down the rack: Funicular railways are based on this drive mechanism; the driving pinion on the rail car engages the rack positioned between the two rails and propels the car up the incline.

Bevel gears, as shown in Fig. 26d, have straight teeth cut into conical circumferences which mate on axes that intersect, typically at right angles between the input and output shafts. This class of gears includes the most common straight and spiral bevel gears as well as miter and hypoid gears.

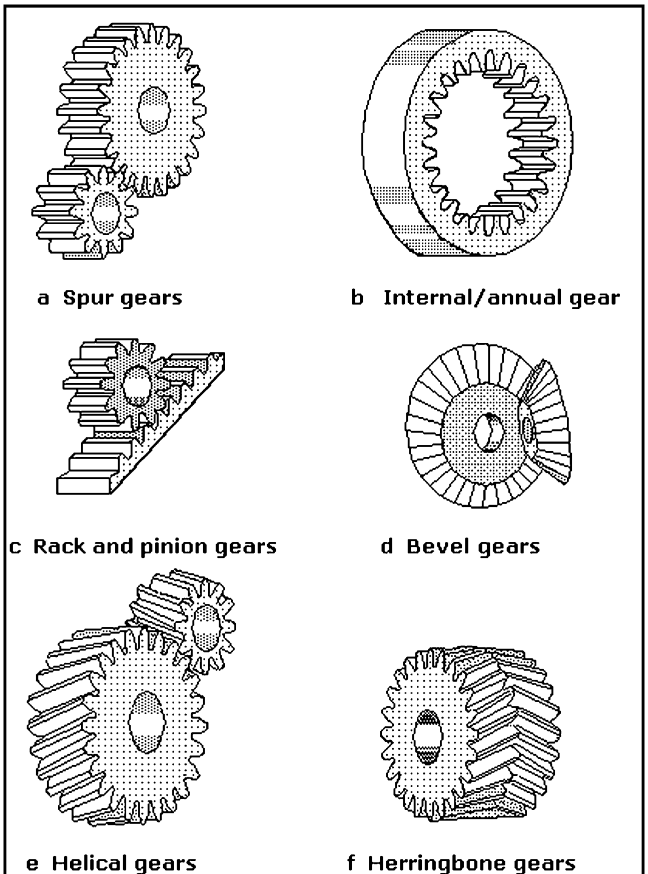

Fig. 26 Gear types: Eight common types of gears and gear pairs are shown here.

Straight bevel gears are the simplest bevel gears. Their straight teeth produce instantaneous line contact when they mate. These gears provide moderate torque transmission, but they are not as smooth running or quiet as spiral bevel gears because the straight teeth engage with full-line contact. They permit medium load capacity.

Spiral bevel gears have curved oblique teeth. The spiral angle of curvature with respect to the gear axis permits substantial tooth overlap. Consequently, the teeth engage gradually and at least two teeth are in contact at the same time. These gears have lower tooth loading than straight bevel gears and they can turn up to 8 times faster. They permit high load capacity.

Miter gears are mating bevel gears with equal numbers of teeth used between rotating input and output shafts with axes that are 90° apart.

Hypoid gears are helical bevel gears used when the axes of the two shafts are perpendicular but do not intersect. They are commonly used to connect driveshafts to rear axles of automobiles, and are often incorrectly called *spiral gearing*.

Helical gears are external cylindrical gears with their teeth cut at an angle rather than parallel to the axis. A simple helical gear, as shown in Fig. 26e, has teeth that are offset by an angle with respect to the axis of the shaft so that they spiral around the shaft in a helical manner. Their offset teeth make them capable of smoother and quieter action than spur gears, and they are capable of driving heavy loads because the teeth mesh at an acute angle rather than at 90°. When helical gear axes are parallel they are called parallel helical gears, and when they are at right angles they are called helical gears. Herringbone and worm gears are based on helical gear geometry.

Herringbone or double helical gears, as shown in Fig. 26f, are helical gears with V-shaped right-hand and left-hand helix angles side by side across the face of the gear. This geometry neutralizes axial thrust from helical teeth.

Worm gears, also called *screw gears*, are other variations of helical gearing. A worm gear has a long, thin cylindrical form with one or more continuous helical teeth that mesh with a helical gear. The teeth of the worm gear slide across the teeth of the driven gear rather than exerting a direct rolling pressure as do the teeth of helical gears. Worm gears are widely used to transmit rotation, at significantly lower speeds, from one shaft to another at a 90° angle.

Face gears have straight tooth surfaces, but their axes lie in planes perpendicular to shaft axes. They are designed to mate with instantaneous point contact. These gears are used in right-angle drives, but they have low load capacities.

Practical Gear Configurations

Isometric drawing Fig. 27 shows a *special planetary gear configuration.* The external driver spur gear (lower right) drives the outer ring spur gear (center) which, in turn, drives three internal planet spur gears; they transfer torque to the driven gear (lower left). Simultaneously, the central planet spur gear produces a summing motion in the pinion gear (upper right) which engages a rack with a roller follower contacting a radial disk cam (middle right).

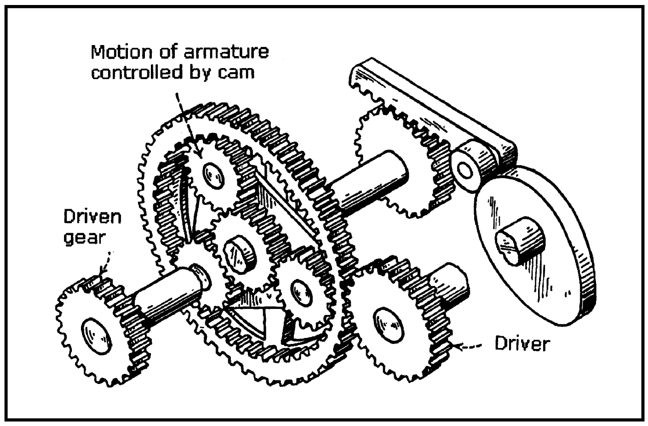

Fig. 27 A special planetary-gear mechanism: The principal of relative motion of mating gears illustrated here can be applied to spur gears in a planetary system. The motion of the central planet gear produces the motion of a summing gear.

Isometric drawing Fig. 28 shows a *unidirectional drive.* The output shaft B rotates in the same direction at all times, regardless of the rotation of the input shaft A. The angular velocity of output shaft B is directly proportional to the angular velocity of input shaft A. The spur gear C on shaft A has a face width that is twice as wide as the faces on spur gears F and D, which are mounted on output shaft B. Spur gear C meshes with idler E and with spur gear D. Idler E meshes with the spur gears C and F. Output shaft B carries two free-wheel disks, G and H, which are oriented unidirectionally.

When input shaft A rotates clockwise (bold arrow), spur gear D rotates counterclockwise and it idles around free-wheel disk H. Simultaneously, idler E, which is also rotating counterclockwise, causes spur gear F to turn clockwise and engage the rollers on free-wheel disk G. Thus, shaft B is made to rotate clockwise. On the other hand, if the input shaft A turns counterclockwise

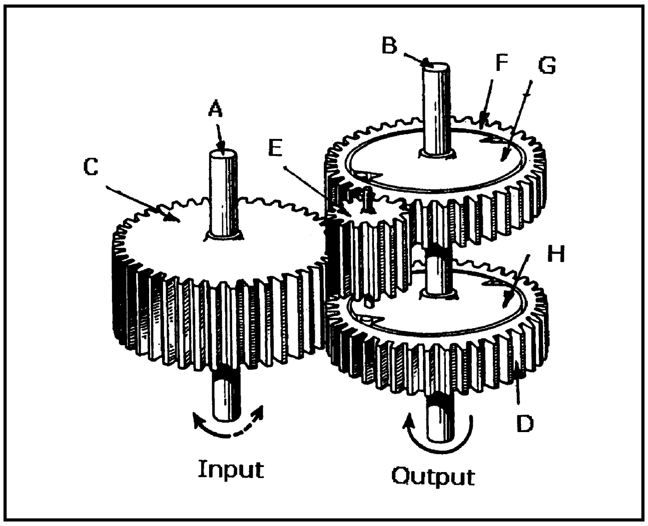

Fig. 28 The output shaft of this unidirectional drive always rotates in the same direction regardless of the direction of rotation of the input shaft.

(dotted arrow), spur gear F will idle while spur gear D engages free-wheel disk H, which drives shaft B so that it continues to rotate clockwise.

Gear Tooth Geometry

The geometry of gear teeth, as shown in Fig. 29, is determined by pitch, depth, and pressure angle.

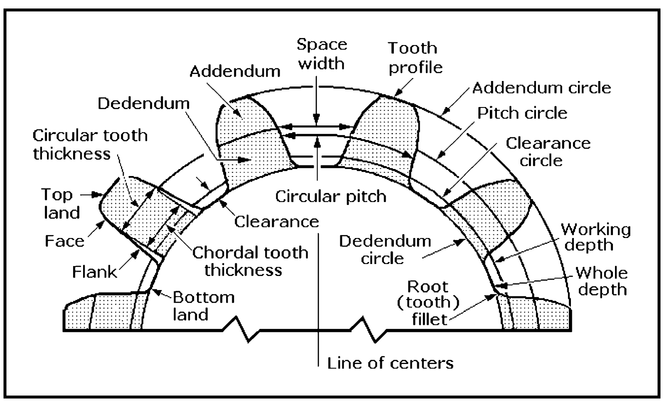

Fig. 29 Gear-tooth geometry.

Gear Terminology

addendum: The radial distance between the *top land* and the *pitch circle.* This distance is measured in inches or millimeters.

addendum circle: The circle defining the outer diameter of the gear.

circular pitch: The distance along the pitch circle from a point on one tooth to a corresponding point on an adjacent tooth. It is also the sum of the *tooth thickness* and the *space width*. This distance is measured in inches or millimeters.

clearance: The radial distance between the *bottom land* and the *clearance circle*. This distance is measured in inches or millimeters.

contact ratio: The ratio of the number of teeth in contact to the number of teeth not in contact.

dedendum: The radial distance between the *pitch circle* and the *dedendum circle.* This distance is measured in inches or millimeters.

dedendum circle: The theoretical circle through the *bottom lands* of a gear.

depth: A number standardized in terms of pitch. Full-depth teeth have a *working depth* of $2/P$. If the teeth have equal *addenda* (as in standard interchangeable gears), the addendum is $1/P$. Full-depth gear teeth have a larger contact ratio than stub teeth, and their working depth is about 20 percent more than stub gear teeth. Gears with a small number of teeth might require *undercutting* to prevent one interfering with another during engagement.

diametral pitch (*P*): The ratio of the number of teeth to the *pitch diameter*. A measure of the coarseness of a gear, it is the index of tooth size when U.S. units are used, expressed as teeth per inch.

pitch: A standard pitch is typically a whole number when measured as a *diametral pitch (P). Coarse pitch gears* have teeth larger than a diametral pitch of 20 (typically 0.5 to 19.99). *Fine-pitch gears* usually have teeth of diametral pitch greater than 20. The usual maximum fineness is 120 diametral pitch, but involute-tooth gears can be made with diametral pitches as fine as 200, and cycloidal tooth gears can be made with diametral pitches to 350.

pitch circle: A theoretical circle upon which all calculations are based.

pitch diameter: The diameter of the *pitch circle*, the imaginary circle that rolls without slipping with the pitch circle of the mating gear, measured in inches or millimeters.

pressure angle: The angle between the *tooth profile* and a line perpendicular to the *pitch circle*, usually at the point where the pitch circle and the tooth profile intersect. Standard angles are 20° and 25°. It affects the force that tends to separate mating gears. A high pressure angle decreases the *contact ratio*, but it permits the teeth to have higher capacity and it allows gears to have fewer teeth without *undercutting*.

Gear Dynamics Terminology

backlash: The amount by which the width of a tooth space exceeds the thickness of the engaging tooth measured on the pitch circle. It is the shortest distance between the noncontacting surfaces of adjacent teeth.

gear efficiency: The ratio of output power to input power taking into consideration power losses in the gears and bearings and from windage and the churning of the gear lubricant.

gear power: A gear's load and speed capacity. It is determined by gear dimensions and type. Helical and helical-type gears have capacities to approximately 30,000 hp, spiral bevel gears to about 5000 hp, and worm gears to about 750 hp.

gear ratio: The number of teeth in the larger gear of a pair divided by the number of teeth in the *pinion* gear (the smaller gear of a pair). It is also the ratio of the speed of the pinion to the speed of the gear. In reduction gears, the ratio of input speed to output speed.

gear speed: A value determined by a specific pitchline velocity. It can be increased by improving the accuracy of the gear teeth and the balance of all rotating parts.

undercutting: The recessing in the bases of gear tooth flanks to improve clearance.

PULLEYS AND BELTS

Pulleys and belts transfer rotating motion from one shaft to another. Essentially, pulleys are gears without teeth that depend on the frictional forces of connecting belts, chains, ropes, or cables to transfer torque. If both pulleys have the same diameter, they will rotate at the same speed. However, if one pulley is larger than the other, mechanical advantage and velocity ratio are gained. As with gears, the velocities of pulleys are inversely proportional to their diameters. A large drive pulley driving a smaller driven pulley by means of a belt or chain is shown in Fig. 30. The smaller pulley rotates faster than the larger pulley in the same direction as shown in Fig. 30a. If the belt is crossed, as shown in Fig. 30b, the smaller pulley also rotates faster than the larger pulley, but its rotation is in the opposite direction.

A familiar example of belt and pulley drive can be seen in automotive cooling fan drives. A smooth pulley connected to the engine crankshaft transfers torque to a second smooth pulley coupled to the cooling fan with a reinforced rubber endless belt. Before reliable direct-drive industrial electric motors were developed, a wide variety of industrial machines equipped with smooth pulleys of various diameters were driven by endless leather belts from an overhead driveshaft. Speed changes were achieved by switching the belt to pulleys of different diameters on the same machine. The machines included lathes and milling machines, circular saws in sawmills, looms in textile plants, and grinding wheels in grain mills. The source of power could have been a water wheel, windmill, or a steam engine.

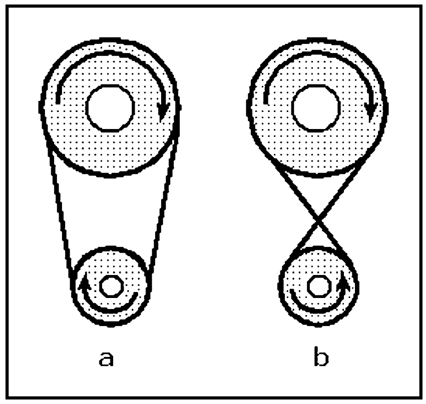

Fig. 30 Belts on pulleys: With a continuous belt both pulleys rotate in the same direction (a), but with a crossed belt both pulleys rotate in opposite directions (b).

SPROCKETS AND CHAINS

Sprockets and chains offer another method for transferring rotating motion from one shaft to another where the friction of a drive belt would be insufficient to transfer power. The speed relationships between sprockets of different diameters coupled by chains are the same as those between pulleys of different diameters coupled by belts, as shown in Fig. 30. Therefore, if the chains are crossed, the sprockets will rotate in different directions. Bicycles have sprocket and chain drives. The teeth on the sprockets mesh with the links on the chains. Powered winches on large ships act as sprockets because they have teeth that mate with the links of heavy chain for raising anchors. Another example can be seen in tracked equipment including bulldozers, cranes, and military tanks. The flexible treads have teeth that mate with teeth on driving sprockets that propel these machines.

CAM MECHANISMS

A *cam* is a mechanical component capable of transmitting motion to a follower by direct contact. In a cam mechanism, the cam is the driver and the driven member is called the *follower*. The follower can remain stationary, translate, oscillate, or rotate. The general form of a plane cam mechanism is illustrated in the kinematic diagram Fig. 31. It consists of two shaped members A and B with smooth, round, or elongated contact surfaces connected to a third body C. Either body A or body B can be the driver, while the other body is the follower. These shaped bodies can be replaced by an equivalent mechanism. Points 1 and 2 are pin-jointed at the centers of curvature of the contacting surfaces. If any change is made in the relative positions of bodies A and B, points 1 and 2 are shifted, and the links of the equivalent mechanisms have different lengths.

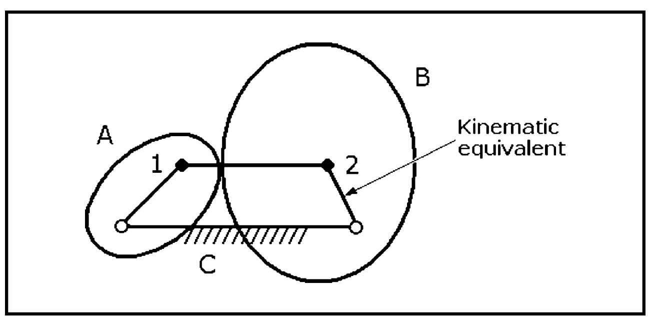

Fig. 31 Basic cam mechanism and its kinematic equivalent. Points 1 and 2 are centers of curvature of the contact point.

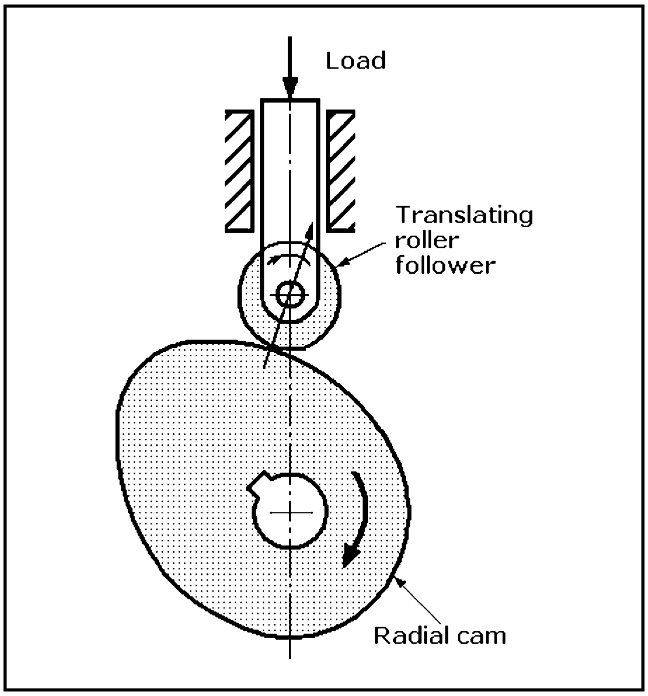

Fig. 32 Radial open cam with a translating roller follower. The roller is kept in contact with the cam by the mass of the load.

A widely used open radial-cam mechanism is shown in Fig. 32. The roller follower is the most common follower used in these mechanisms because it can transfer power efficiently between the cam and follower by reducing friction and minimizing wear between them. The arrangement shown here is called a *gravity constraint cam*; it is simple and effective and can be used with rotating disk or end cams if the weight of the follower system is enough to keep it in constant contact with the cam profile. However, in most practical cam mechanisms, the cam and follower are constrained at all operating speeds by preloaded compression springs. Cams can be designed by three methods:

- Shaping the cam body to some known curve, such as a spiral, parabola, or circular arc
- Designing the cam mathematically to determine follower motion and then plotting the tabulated data to form the cam
- Drawing the cam profile freehand using various drafting curves

The third method is acceptable only if the cam motion is intended for low speeds that will permit the use of a smooth, "bumpless" curve. In situations where higher loads, mass, speed, or elasticity of the members are encountered, a detailed study must be made of both the dynamic aspects of the cam curve and the accuracy of cam fabrication.

Many different kinds of machines include cams, particularly those that operate automatically such as printing presses, textile looms, gear-cutters, and screw machines. Cams open and close the valves in internal combustion engines, index cutting tools on machine tools, and operate switches and relays in electrical control equipment. Cams can be made in an infinite variety of shapes from metal or hard plastic. Some of the most important cams will be considered here. The possible applications of mechanical cams are still unlimited despite the introduction of *electronic cams* that mimic mechanical cam functions with appropriate computer software.

Classification of Cam Mechanisms

Cam mechanisms can be classified by their input/output motions, the configuration and arrangement of the follower, and the shape of the cam. Cams can also be classified by the kinds of motions made by the follower and the characteristics of the cam profile. The possible kinds of input/output motions of cam mechanisms with the most common disk cams are shown in Figs. 33a to e; they are examples of rotating disk cams with translating followers. By contrast, Fig. 33f shows a follower arm with a roller that swings or oscillates in a circular arc with respect to the follower hinge as the cam rotates. The follower configurations in Figs. 33a to d are named according to their characteristics: a *knife-edge;* b, e, and f *roller;* c *flat-faced;* and d *spherical-faced.* The face of the flat follower can also be oblique with respect to the cam. The follower is an element that moves either up and down or side to side as it follows the contour of the cam.

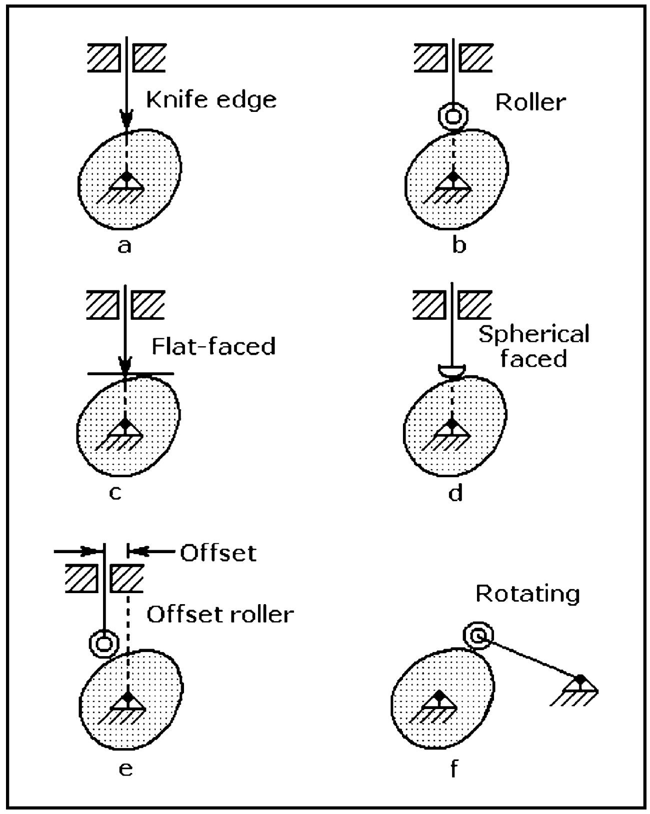

Fig. 33 Cam configurations: Six different configurations of radial open cams and their followers.

There are two basic types of follower: *in-line* and *offset*. The centerline of the in-line follower passes through the centerline of the camshaft. Figures 33a to d show five followers that move in a plane perpendicular to the axis of rotation of the camshaft. By contrast, the centerline of the offset follower, as illustrated in Fig. 33e, does not pass through the centerline of the camshaft. The amount of offset is the horizontal distance between the two centerlines. Follower offset reduces the side thrust introduced by the roller follower. Figure 33f illustrates a translating or swing-arm rotating follower that must be constrained to maintain contact with the cam profile.

The most common rotating disk or plate cams can be made in a variety of shapes including offset round, egg-shaped, oval, and cardioid or heart-shaped. Most cams are mounted on a rotating shaft. The cam and follower must be constrained at all operating speeds to keep them in close contact throughout its cycle if a cam mechanism is to function correctly. Followers are typically spring-loaded to maintain constant contact with the shaped surface of the cam, but gravity constraint is still an option.

If it is anticipated that a cam mechanism will be subjected to severe shock and vibration, a *grooved disk cam,* as shown in Fig. 34, can be used. The cam contour is milled into the face of a disk so that the roller of the cam follower will be confined and continuously constrained within the side walls of the groove throughout the cam cycle. The groove confines the follower roller during the entire cam rotation. Alternatively, the groove can be milled on the outer circumference of a cylinder or barrel to form a *cylindrical* or *barrel cam,* as shown in Fig. 35. The follower of this cam can translate or oscillate. A similar groove can also be milled around the conical exterior surface of a *grooved conical cam.*

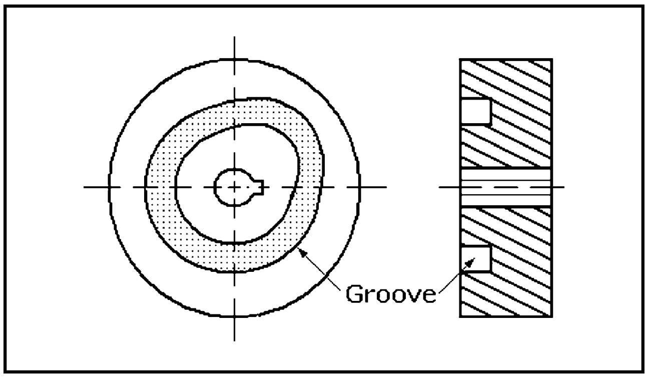

Fig. 34 Grooved cam made by milling a contoured cam groove into a metal or plastic disk. A roller follower is held within the grooved contour by its depth, eliminating the need for spring-loading.

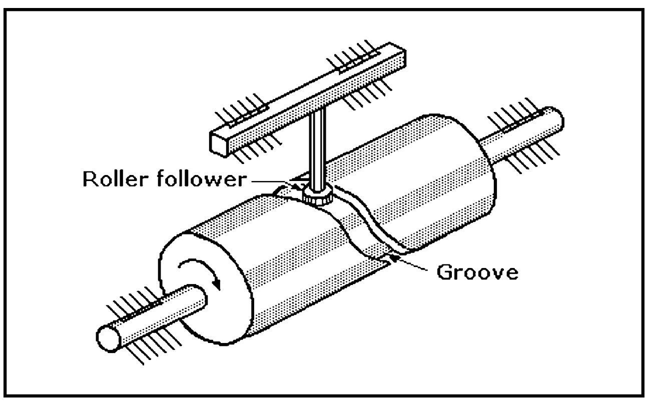

Fig. 35 Cylindrical or barrel cam: A roller follower tracks the groove precisely because of the deep contoured groove milled around the circumference of the rotating cylinder.

By contrast, the barrel-shaped *end cam,* shown in Fig. 36, has a contour milled on one end. This cam is usually rotated, and its follower can also either translate or oscillate, but the follower system must be carefully controlled to exercise the required constraint because the follower roller is not confined by a groove. Another distinct form of cam is the *translating cam,* as shown in Fig. 37. It is typically mounted on a bed or carrier that moves back and forth in a linear reciprocal motion under a stationary vertical translating follower, usually with a roller. However, the cam can also be mounted so that it remains stationary while a follower system moves in a linear reciprocal motion over the limited range of the cam.

The unusual dual-rotary cam configuration shown in Fig. 38 is a *constant-diameter cam*; it consists of two identical disk cams

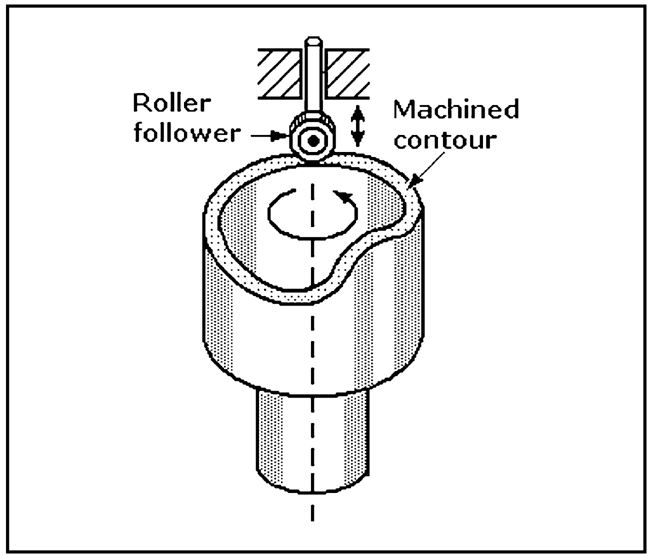

Fig. 36 End cam: A roller follower tracks a cam contour machined at the end of this rotating cylindrical cam.

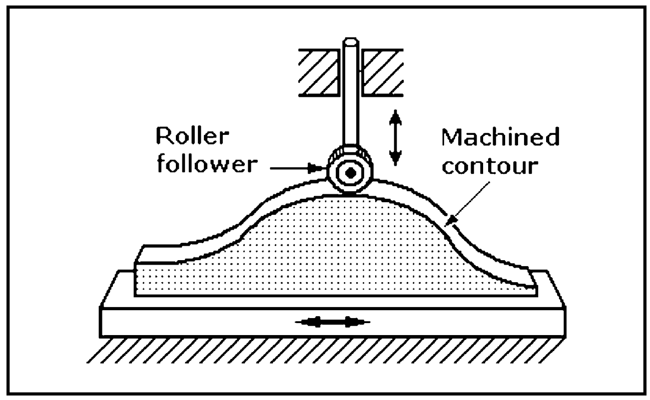

Fig. 37 Translating cam: A roller follower either tracks the reciprocating motion of the cam profile or is driven back and forth over a stationary cam profile.

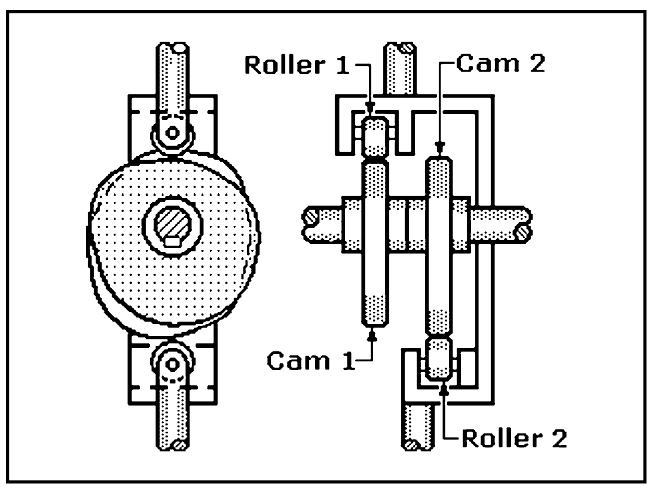

Fig. 38 Constant-diameter cam: Two identical cams, 1 and 2, are separated on the same shaft and offset at an angle that provides a virtual constant diameter. Cam 1 with roller follower 1 is the functioning cam, and cam 2 with roller follower 2 constrains cam 1 to smooth its motion.

with followers mounted a fixed distance apart on a common shaft, but the cams are offset so that if superimposed their contours form a virtual circle of constant diameter. Cam 1 is the functional cam while cam 2 acts as a constraint, effectively canceling out the irregular motion that occurs with a single rotary cam and follower.

The motions of the followers of all of these cam mechanisms can be altered to obtain a different sequence by changing the contour of the cam profile. The timing of the sequence of disk and cylinder cams can be changed by altering the rotational speed of their camshafts. The timing of the sequence of the translation cam can be changed by altering the rate of reciprocal motion of the bed on which it is mounted on its follower system. The rotation of the follower roller does not influence the motion of any of the cam mechanisms.

Cam Terminology

Figure 39 illustrates the nomenclature for a radial open disk cam with a *roller follower* on a plate cam.

base circle: The circle with the shortest radius from the cam center to any part of the cam profile.

cam profile: The outer surface of a disk cam as it was machined.

follower travel: For a *roller follower* of a disk cam it is the vertical distance of follower travel measured at the center point of the roller as it travels from the *base circle* to the *cam profile.*

motion events: When a cam rotates through one cycle, the follower goes through rises, dwells, and returns. A *rise* is the motion of the follower away from the cam center; a *dwell* occurs when the follower is resting; and a *return* is the motion of the follower toward the cam center.

pitch curve: For a *roller follower* of a disk cam it is the path generated by the center point of the roller as the follower is rotated around a stationary plate cam.

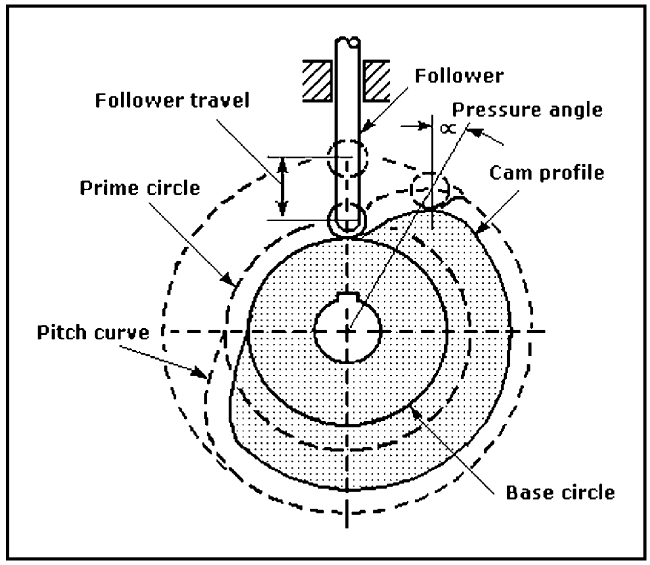

Fig. 39 Cam nomenclature: This diagram identifies the industry-accepted technical terms for cam features.

pressure angle: For a *roller follower* of a disk cam it is the angle at any point between the normal to the pitch curve and the instantaneous direction of follower motion. This angle is important in cam design because it indicates the steepness of the cam profile.

prime circle (reference circle): For a *roller follower* of a disk cam it is the circle with the shortest radius from the cam center to the pitch curve.

stroke or throw: The longest distance or widest angle through which the follower moves or rotates.

working curve: The working surface of a cam that contacts the follower. For a *roller follower* of a plate cam it is the path traced by the center of the roller around the cam profile.

CLUTCH MECHANISMS

A *clutch* is defined as a coupling that connects and disconnects the driving and driven parts of a machine; an example is an engine and a transmission. Clutches typically contain a driving shaft and a driven shaft, and they are classed as either externally or internally controlled. *Externally controlled clutches* can be controlled either by friction surfaces or components that engage or mesh positively. *Internally controlled clutches* are controlled by internal mechanisms or devices; they are further classified as *overload, overriding*, and *centrifugal*. There are many different schemes for a driving shaft to engage a driven shaft.

Externally Controlled Friction Clutches

Friction-Plate Clutch. This clutch, shown in Fig. 40, has a control arm, which when actuated, advances a sliding plate on the driving shaft to engage a mating rotating friction plate on the same shaft; this motion engages associated gearing that drives the driven shaft. When reversed, the control arm disengages the sliding plate. The friction surface can be on either plate, but is typically only on one.

Cone Clutch. A clutch operating on the same principle as the friction-plate clutch except that the control arm advances a cone on the driving shaft to engage a mating rotating friction cone on the same shaft; this motion also engages any associated gearing that drives the driven shaft. The friction surface can be on either cone but is typically only on the sliding cone.

Expanding Shoe Clutch. This clutch is similar to the friction-plate clutch except that the control arm engages linkage that forces several friction shoes radially outward so they engage the inner surface of a drum on or geared to the driven shaft.

Externally Controlled Positive Clutches

Jaw Clutch. This clutch is similar to the plate clutch except that the control arm advances a sliding jaw on the driving shaft to make positive engagement with a mating jaw on the driven shaft.

Other examples of externally controlled positive clutches are the *planetary transmission clutch* consisting essentially of a sun gear keyed to a driveshaft, two planet gears, and an outer driven

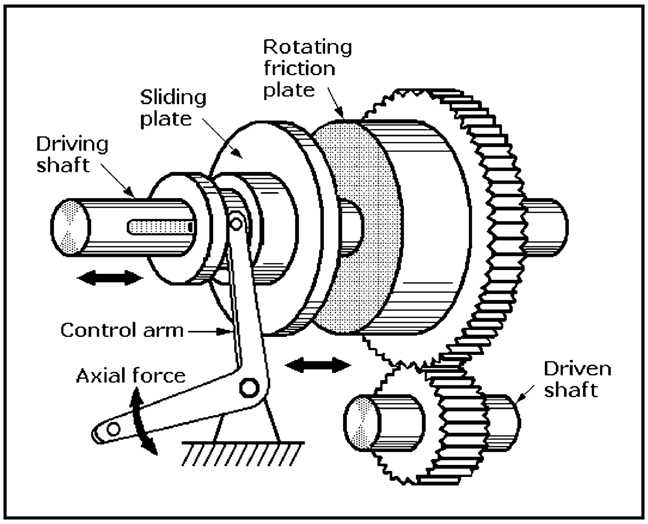

Fig. 40 Friction plate clutch: When the left sliding plate on the driving shaft is clamped by the control arm against the right friction plate idling on the driving shaft, friction transfers the power of the driving shaft to the friction plate. Gear teeth on the friction plate mesh with a gear mounted on the driven shaft to complete the transfer of power to the driven mechanism. Clutch torque depends on the axial force exerted by the control arm.

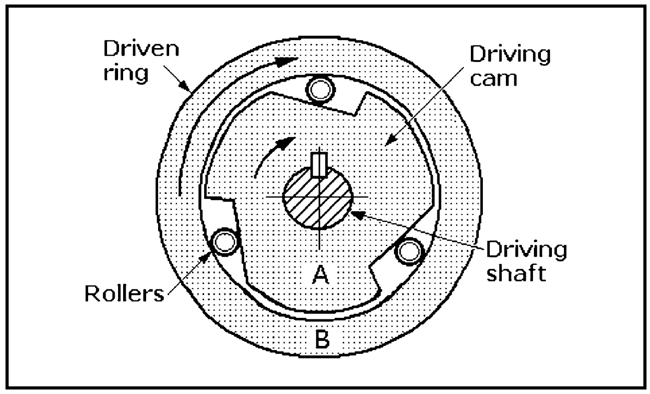

Fig. 41 Overrunning clutch: As driving cam A revolves clockwise, the rollers in the wedge-shaped gaps between cam A and outer ring B are forced by friction into those wedges and are held there; this locks ring B to cam A and drives it clockwise. However, if ring B is turned counterclockwise, or is made to revolve clockwise faster than cam A, the rollers are freed by friction, the clutch slips, and no torque is transmitted.

ring gear. The *pawl and ratchet clutch* consists essentially of a pawl-controlled driving ratchet keyed to a driven gear.

Internally Controlled Clutches

Internally controlled clutches can be controlled by springs, torque, or centrifugal force. The *spring and ball radial-detent clutch,* for example, disengages when torque becomes excessive, allowing the driving gear to continue rotating while the driveshaft stops rotating. The *wrapped-spring clutch* consists of two separate rotating hubs joined by a coil spring. When driven in the right direction, the spring tightens around the hubs increasing the friction grip. However, if driven in the opposite direction the spring relaxes, allowing the clutch to slip.

The *expanding-shoe centrifugal clutch* is similar to the externally controlled *expanding shoe clutch* except that the friction shoes are pulled in by springs until the driving shaft attains a preset speed. At that speed centrifugal force drives the shoes radially outward so that they contact the drum. As the driveshaft rotates faster, pressure between the shoes and drum increases, thus increasing clutch torque.

The *overrunning or overriding clutch*, as shown in Fig. 41, is a specialized form of a cam mechanism, also called a *cam and roller clutch.* The inner driving cam A has wedge-shaped notches on its outer rim that hold rollers between the outer surface of A and the inner cylindrical surfaces of outer driven ring B. When driving cam A is turning clockwise, frictional forces wedge the rollers tightly into the notches to lock outer driven ring B in position so it also turns in a clockwise direction. However, if driven ring B is reversed or runs faster clockwise than driving cam A (when it is either moving or immobile) the rollers are set free, the clutch will slip and no torque is transmitted. Some versions of this clutch include springs between the cam faces and the rollers to ensure faster clutching action if driven ring B attempts to drive driving cam A by overcoming residual friction. A version of this clutch is the basic free-wheel mechanism that drives the rear axle of a bicycle.

Some low-cost, light-duty overrunning clutches for one-direction-only torque transmission intersperse cardioid-shaped pellets called *sprags* with cylindrical rollers. This design permits cylindrical internal drivers to replace cammed drivers. The sprags bind in the concentric space between the inner driver and the outer driven ring if the ring attempts to drive the driver. The torque rating of the clutch depends on the number of sprags installed. For acceptable performance a minimum of three sprags, equally spaced around the circumference of the races, is usually necessary.

GLOSSARY OF COMMON MECHANICAL TERMS

acceleration: The time rate of change of velocity of a body. It is always produced by force acting on a body. Acceleration is measured as feet per second per second (ft/s^2) or meters per second per second (m/s^2).

component forces: The individual forces that are the equivalent of the resultant.

concurrent forces: Forces whose lines of action or directions pass through a common point or meet at a common point.

crank: A side link that revolves relative to the frame.

crank-rocker mechanism: A four-bar linkage characterized by the ability of the shorter side link to revolve through 360° while the opposing link rocks or oscillates.

couple: Two equal and opposite parallel forces that act at diametrically opposite points on a body to cause it to rotate around a point or an axis through its center.

displacement: Distance measured from a fixed reference point in a specified direction; it is a vector quantity; units are measured in inches, feet, miles, centimeters, meters, and kilometers.

double-crank mechanism: A four-bar linkage characterized by the ability of both of its side links to oscillate while the shortest link (opposite the foundation link) can revolve through 360°.

dynamics: The study of the forces that act on bodies not in equilibrium, both balanced and unbalanced; it accounts for the masses and accelerations of the parts as well as the external forces acting on the mechanisms. It is a combination of *kinetics* and *kinematics*.

efficiency of machines: The ratio of a machine's output divided by its input is typically expressed as a percent. There are energy or power losses in all moving machinery caused primarily by friction. This causes inefficiency, so a machine's output is always less than its input; both output and input must be expressed in the same units of power or energy. This ratio, always a fraction, is multiplied by 100 to obtain a percent. It can also be determined by dividing the machine's mechanical advantage by its velocity ratio and multiplying that ratio by 100 to get a percent.

energy: A physical quantity present in three-dimensional space in which forces can act on a body or particle to bring about physical change; it is the capacity for doing work. Energy can take many forms, including mechanical, electrical, electromagnetic, chemical, thermal, solar, and nuclear. Energy and work are related and measured in the same units: foot-pounds, ergs, or joules; it cannot be destroyed, but it can be wasted.

- *Kinetic energy* is the kind of energy a body has when it is in motion. Examples are a rolling soccer ball, a speeding automobile, or a flying airplane.
- *Potential energy* is the kind of energy that a body has because of its position or state. Examples are a concrete block poised at the edge of a building, a shipping container suspended above ground by a crane, or a roadside bomb.

equilibrium: In mechanics, a condition of balance or static equilibrium between opposing forces. An example is when there are equal forces at both ends of a seesaw resting on a *fulcrum*.

force: Strength or energy acting on a body to push or pull it; it is required to produce acceleration. Except for gravitation, one body cannot exert a force on another body unless the two are in contact. The Earth exerts a force of attraction on bodies, whether they are in contact or not. Force is measured in poundals (lb-ft/s^2) or newtons (kg-m/s^2).

fulcrum: A pivot point or edge about which objects are free to rotate.

kinematic chain: A combination of links and pairs without a fixed link.

kinematics: The study of the motions of bodies without considering how the variables of force and mass influence the motion. It is described as the geometry of motion.

kinetics: The study of the effects of external forces including gravity upon the motions of physical bodies.

lever: A simple machine that uses opposing torque around a fulcrum to perform work.

linear motion: Motion in a straight line. An example is when a car is driving on a straight road.

link: A rigid body with pins or fasteners at its ends to connect it to other rigid bodies so it can transmit a force or motion. All machines contain at least one link, either in a fixed position relative to the Earth or capable of moving the machine and the link during the motion; this link is the *frame* or *fixed link* of the machine.

linkages: Mechanical assemblies consisting of two or more levers connected to produce a desired motion. They can also be mechanisms consisting of rigid bodies and lower *pairs*.

machine: An assembly of mechanisms or parts or mechanisms capable of transmitting force, motion, and energy from a power source; the objective of a machine is to overcome some form of resistance to accomplish a desired result. There are two functions of machines: (1) the transmission of relative motion and (2) the transmission of force; both require that the machine be strong and rigid. While both machines and mechanisms are combinations of rigid bodies capable of definite relative motions, machines transform energy, but mechanisms do not. A *simple machine* is an elementary mechanism. Examples are the lever, wheel and axle, pulley, inclined plane, wedge, and screw.

machinery: A term generally meaning various combinations of machines and mechanisms.

mass: The quantity of matter in a body indicating its inertia. Mass also initiates gravitational attraction. It is measured in ounces, pounds, tons, grams, and kilograms.

mechanical advantage: The ratio of the load (or force W) divided by the effort (or force F) exerted by an operator. If friction is considered in determining mechanical advantage, or it has been determined by the actual testing, the ratio W/F is the mechanical advantage MA. However, if the machine is assumed to operate without friction, the ratio W/F is the theoretical mechanical advantage TA. Mechanical advantage and velocity ratio are related.

mechanics: A branch of physics concerned with the motions of objects and their response to forces. Descriptions of mechanics begin with definitions of such quantities as acceleration, displacement, force, mass, time, and velocity.

mechanism: In mechanics, it refers to two or more rigid or resistant bodies connected together by joints so they exhibit definite relative motions with respect to one another. Mechanisms are divided into two classes:

- *Planar*: Two-dimensional mechanisms whose relative motions are in one plane or parallel planes.
- *Spatial*: Three-dimensional mechanisms whose relative motions are not all in the same or parallel planes.

moment of force or torque: The product of the force acting to produce a turning effect and the perpendicular distance of its line of action from the point or axis of rotation. The perpendicular distance is called the *moment* arm or the *lever arm torque*. It is measured in pound-inches (lb-in.), pound-feet (lb-ft), or newton-meters (N-m).

moment of inertia: A physical quantity giving a measure of the *rotational inertia* of a body about a specified axis of rotation; it depends on the mass, size, and shape of the body.

nonconcurrent forces: Forces whose lines of action do not meet at a common point.

noncoplanar forces: Forces that do not act in the same plane.

oscillating motion: Repetitive forward and backward circular motion such as that of a clock pendulum.

pair: A joint between the surfaces of two rigid bodies that keeps them in contact and relatively movable. It might be as simple as a pin, bolt, or hinge between two links or as complex as a universal joint between two links. There are two kinds of pairs in mechanisms classified by the type of contact between the two bodies of the pair: *lower pairs* and *higher pairs*.

- Lower pairs are *surface-contact pairs* classed either as *revolute* or *prismatic.* Examples: a hinged door is a revolute pair and a sash window is a prismatic pair.
- Higher pairs include *point, line, or curve pairs.* Examples: paired rollers, cams and followers, and meshing gear teeth.

power: The time rate of doing work. It is measured in foot-pounds per second (ft-lb/s), foot-pounds per minute (ft-lb/min), horsepower, watts, kilowatts, newton-meters/s, ergs/s, and joules/s.

reciprocating motion: Repetitive back and forth linear motion as that of a piston in an internal combustion engine.

resultant: In a system of forces, it is the single force equivalent of the entire system. When the resultant of a system of forces is zero, the system is in equilibrium.

rotary motion: Circular motion as in the turning of a bicycle wheel.

skeleton outline: A simplified geometrical line drawing showing the fundamentals of a simple machine devoid of the actual details of its construction. It gives all of the geometrical information needed for determining the relative motions of the main links. The relative motions of these links might be complete circles, semicircles, or arcs, or even straight lines.

statics: The study of bodies in equilibrium, either at rest or in uniform motion.

torque: An alternative name for *moment of force*.

velocity: The time rate of change with respect to distance. It is measured in feet per second (ft/s), feet per minute (ft/min), meters per second (m/s), or meters per minute (m/min).

velocity ratio: A ratio of the distance movement of the effort divided by the distance of movement of the load per second for a machine. This ratio has no units.

weight: The force on a body due to the gravitational attraction of the Earth; weight W = mass $n \times$ acceleration g due to the Earth's gravity; mass of a body is constant but g, and therefore W vary slightly over the Earth's surface.

work: The product of force and distance: the distance an object moves in the direction of force. Work is not done if the force exerted on a body fails to move that body. Work, like energy, is measured in units of ergs, joules, or foot-pounds.