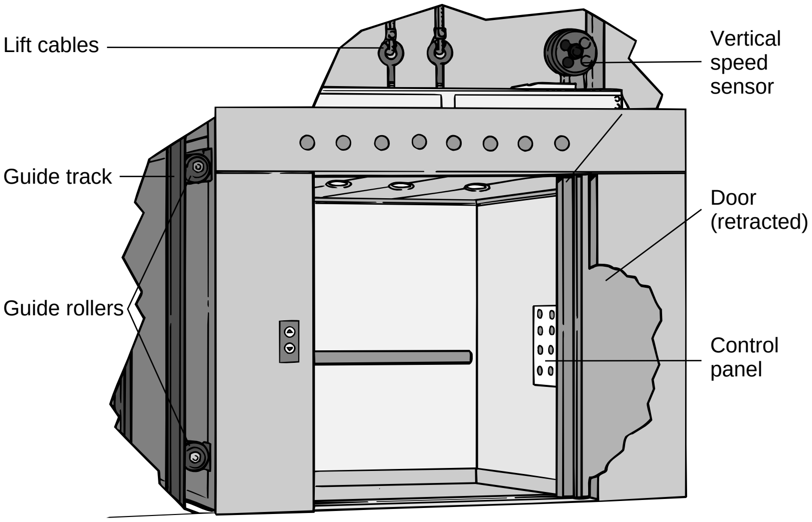

Section 4.4

Elevators

While the invention of steel made skyscrapers possible, the invention of elevators made them practical. Imagine life in a big city without elevators. Business at the top of World Trade Centers would be limited to a few world-class athletes.

At the heart of an elevator is a very simple lifting machine. There are only a few different types of elevators and the techniques they use to raise or lower their cars have changed very little since Elisha Otis invented the safety elevator in 1853. What has changed is the source of power for operating the elevators and the sophistication of their control equipment. Electricity has long since replaced steam as the power source and elevator operators have been replaced by computers.

Questions to Think About: *Why do many elevators have counterweights that descend as the car moves upward? Why does an elevator have a weight limit? How fast do elevators actually move? Why do you feel particularly heavy as the elevator you are in starts to move upward and light as that elevator starts to move downward?*

Experiments to Do: *Glass elevators are a popular form of functional art, providing exciting views for the passengers and giving you opportunities to see the mechanisms that make these elevators work. If you look into the shaft of a glass elevator, you will see its cables or hydraulic piston, its counterweights and its control machinery. Find a glass elevator and watch it work. Look for a shiny metal piston pushing the car upward from below or for metal cables lifting the car upward from above. Even if you can't find an elevator with visible parts, take a ride on an elevator. You may be able hear its motors activating, feel the cable lifting the car, or sense a jerkiness in the piston pushing the car upward. Close your eyes and try to feel the elevator start or stop. Can you tell which way you are moving when the elevator is traveling steadily up or down? Why do you experi-*

ence the same feeling when the car stops moving downward as when the car starts moving upward?

Pushing Up from Below: Hydraulic Elevators

The two main types of elevators are hydraulic elevators and cable-lifted elevators. A hydraulic elevator is lifted from below by a long metal shaft while a cable-lifted elevator is pulled up from above by a long metal cable. Let's begin by looking at hydraulic elevators. (For an earlier type of elevator, see ❐).

❐ The earliest reliable elevators were supported by jackscrews: screws used as lifting devices. A sturdy threaded shaft, the jackscrew, extended beneath the elevator platform and lifted the platform upward as it turned. The jackscrew provided mechanical advantage, so that only a modest torque was needed to turn the jackscrew and raise a heavy load on the platform. But sliding friction in the screw created heat and wear, limiting the speed at which the platform could rise and making jackscrew elevators impractical in modern skyscrapers.

The car of a hydraulic elevator is lifted from below by a hydraulic ram (Fig. 4.4.1). A *hydraulic ram* is a long *piston* that is driven into or out of a hollow cylinder by pressure in a hydraulic fluid. The hydraulic fluid, usually oil or water, exerts a force on any surface it touches, including the base of the piston. If the pressure in the hydraulic fluid is high enough, the force it exerts on the base of the piston will exceed the weight of the piston and elevator car and they will accelerate upward.

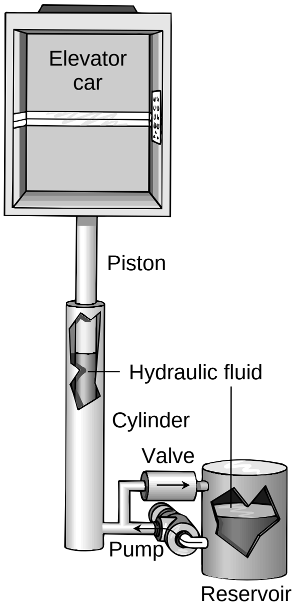

Fig. 4.4.1 - A hydraulic elevator supports the car with a hydraulic ram. The ram's piston rises as high-pressure hydraulic fluid is pushed into the hollow cylinder by a pump. The car is lowered by opening the valve and allowing the high-pressure hydraulic fluid to flow back into the storage reservoir.

But as the piston rises, the hydraulic fluid has more space to fill and its pressure drops. To keep the piston moving upward, something must continuously add high-pressure hydraulic fluid to the cylinder. That something is usually an electrically powered pump. This pump draws low-pressure hydraulic fluid from a reservoir and pumps it into the cylinder. The pump does work on the fluid and this work is what lifts the elevator car.

When the elevator car has reached the proper height, the pump stops and the piston rests on the high-pressure hydraulic fluid beneath it. As long as the amount of fluid in the cylinder doesn't change, the piston and car will stay where they are as the passengers get on and off.

To let the car descend, the elevator opens a valve and permits the high-pressure hydraulic fluid to return to the low-pressure reservoir. The fluid naturally accelerates toward the lower pressure and the cylinder begins to empty. The car descends. However, the fluid in the cylinder has considerable pressure potential energy and that energy must go somewhere. As it flows through the valve, the fluid accelerates and it rushes into the reservoir at high speed. But its kinetic energy soon becomes thermal energy as the fluid swirls around randomly. When the swirling has stopped, the fluid in the reservoir will be warmer than it was before the elevator made its trip up and down.

Because it lifts the car from below like a jackscrew, the hydraulic elevator is naturally very safe. Even if the cylinder springs a leak, the hydraulic fluid will probably not flow out of the cylinder fast enough for the car to descend at a dangerous speed. But unlike a jackscrew, a hydraulic ram encounters very little friction and wear, so its piston can move in or out of the cylinder rapidly. As a result, the car of a hydraulic elevator can be lifted as fast as the pump can deliver high-pressure hydraulic fluid. Of course, the pump has to do a great deal of work on that fluid in a short time, so it must be very powerful. Nonetheless, the speed of a hydraulic elevator is limited only by the power of the pump and the comfort of the passengers. Most passengers don't enjoy huge accelerations. While you could build a hydraulic elevator that would leap from one floor to another in the wink of an eye, it would require seat belts and airbags.

However, if speed is not important, even a very small pump can lift the elevator upward. With enough patience, you could actually lift a very heavy elevator with a hand-powered pump. That is just what you do when you lift an automobile with a hand-powered hydraulic jack or when you squeeze something together with a hand-powered hydraulic press. In these and many similar tools, hydraulic rams provide an interesting form of mechanical advantage.

To see how this mechanical advantage works, suppose that you have two hydraulic rams connected by a hose so that hydraulic fluid can flow freely from one cylinder to the other (Fig. 4.4.2). One hydraulic ram is much wider than the other. Since fluid accelerates toward lower pressure, the pressures in the two cylinders will tend to equalize. This pressure exerts an upward force on each piston equal to the pressure times the surface area of that piston. As a result, the upward force on the wide piston is enough to support the weight of an elevator car while the upward force on the narrow piston is only enough to support the weight of your hand. As things stand, neither the elevator nor your hand moves because each is supported by pressure in the hydraulic fluid.

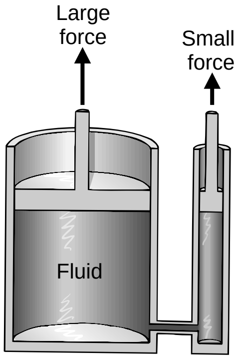

Fig. 4.4.2 - If fluid can flow freely between two hydraulic rams, then the pressures inside the two cylinders are equal. The force exerted on each piston is equal to that pressure times the surface area of the piston. The upward force on the wide piston is much greater than the upward force on the narrow piston.

Now imagine that you begin to push down a little harder on the narrow piston. The pressure inside that cylinder rises in order to exert an equal but oppositely directed force on your hand. Because of the pressure imbalance, fluid begins to flow out of the narrow cylinder and into the wide cylinder. With less fluid in the narrow cylinder, its piston descends and your hand moves downward. With more fluid in the wide cylinder, its piston rises and the elevator car move upward. You are raising a heavy elevator with a hand pump!

As usual, you didn’t get something for nothing. Although you have lifted the elevator upward, it moves only a tiny distance. Pushing the narrow piston inward a long distance only squeezes a modest amount of fluid into the wide cylinder. The wide piston moves upward only a very short distance. You have produced a huge upward force on the elevator and lifted it a short distance by exerting a modest downward force on the narrow piston and moving it downward a very long distance. The work you do on the fluid is equal to the work the fluid does on the elevator car. Energy is conserved, as it must be.

The piston of the narrow cylinder will reach the bottom long before the elevator reaches the second floor. To make a more practical hand-powered elevator, you would need to add several one-way valves and a fluid reservoir to the narrow cylinder and convert it into a proper pump. That way you could slowly raise the elevator upward, with ever so many cycles of the pump: fill the narrow cylinder with fluid and then squeeze it into the wide cylinder, fill the narrow cylinder with fluid, and so on. To return the wide piston to its original position and lower the elevator, a bypass valve should allow the hydraulic fluid to flow back into the fluid reservoir.

While real hydraulic elevators don’t use hand-pumps of this sort, many tools do. Small hydraulic rams allow a normal person to exert Herculean forces on objects. Hand-operated hydraulic rams are used in small cranes, presses, punches, shears, and jacks. When a motorized pump is added, hydraulic rams become even more useful. They are ubiquitous in construction and industrial machines. Nearly every motion of most digging, lifting, and pushing machines is powered by its own hydraulic ram.

Although hydraulic elevators are wonderful in many situations, they do have at least two drawbacks. First, a hydraulic elevator is only as tall as its piston and cylinder. The piston has to reach all the way to the top floor and the equally tall cylinder must be hidden below the ground. Burying the cylinder is quite a procedure in a tall build. A deep hole must be drilled and the cylinder must be lowered into the hole with a crane. The difficulties involved in manufacturing the cylinder and piston and in assembling the completed hydraulic ram limit its height. However, some hydraulic elevators are over 30 stories tall.

The other deficiency of hydraulic elevators is that there is no mechanism for storing energy between trips. The energy expended in lifting people up 30 floors is not saved as those people descend. It becomes thermal energy in the hydraulic fluid as the hydraulic fluid returns to the reservoir. For a tall building with lots of up and down traffic, the elevator can turn a lot of electric energy into thermal energy in the hydraulic fluid.

Fig. 4.4.3 - The modern era of elevators began in 1853, when Elisha Otis first demonstrated his Safety Elevator. He stood in the elevator car, high above the ground, while an assistant cut the rope that supported it. A mechanism in the car immediately grabbed onto the side rails and prevented the car from falling.

CHECK YOUR UNDERSTANDING #1: Heavy Lifting

A typical hydraulic elevator is lifted by a piston 20 cm in diameter. Steel is very strong and a 10 cm steel rod could support the elevator. Why the thick piston?

Pulling Up from Above: Cable-Lifted Elevators

To eliminate the need for long hydraulic rams, most elevators are lifted from above by cables. Introducing cable-lifted elevators was not easy because people were wary of any system that would drop catastrophically if the rope broke. In 1853, the American inventor Elisha Graves Otis (1811–1861) demonstrated a “safety elevator” that would stop automatically if the rope broke (Fig. 4.4.3). In a further improvement, the ropes used to lift early elevators were replaced with metal cables, which were less prone to wear and aging and made cable failure a rare event. With safety no longer an issue, cable-lifted elevators soon became the dominant form of elevator. But before we look at how a cable-lifted elevator actually works, we’ll need to know how a rope lifts an object and how pulleys redirect forces exerted on a rope. Let’s take a moment to look at ropes and pulleys.

Suppose that the elevator in your building is broken. You decide to lift the empty elevator car by hand with a lightweight rope (Fig. 4.4.4). The elevator is on the ground floor and you are pulling the rope up from the fifth floor, where your apartment is located. The empty elevator weighs 500 N (112 pounds), which is about all you can lift. If your arms were long enough, you could pull the elevator up directly. The rope simply extends your reach so that you can exert an upward force on the elevator many meters below you.

Pulling on a rope produces tension throughout the rope. **Tension** means that each portion of the rope pulls on the two adjacent portions with a certain amount of force. To keep the empty elevator hanging motionless from the bottom of the rope, you must pull upward on the rope with 500 N of force. Each portion of rope then exerts 500 N of upward force on whatever is below it and 500 N of downward force on whatever is above it. The bottom of the rope exerts 500 N of upward force on the elevator. Overall, your upward force of 500 N is conveyed meter by meter along the rope until it’s exerted on the elevator far below. In effect, you are exerting an upward force of 500 N on the elevator and it’s pulling back. As promised, the rope simply extends your reach.

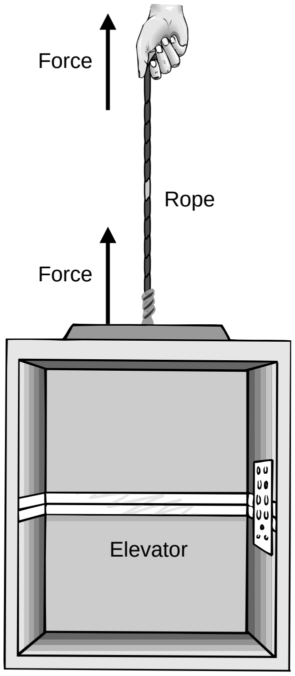

Fig. 4.4.4 - If you pull on a very light, stationary rope, you produce a uniform tension throughout the rope that is equal to the force you exert on it. Each portion of rope, for example the two end portions or the shaded portion near the middle, experiences an upward force from whatever is above and a downward force from whatever is below.

Since the elevator weighs 500 N and you are exerting an upward force of 500 N on it, the net force on the elevator is zero and it doesn’t accelerate. Because the elevator is initially stationary, it remains stationary. If you now exert a little more upward force on the rope, the elevator will experience a net upward force and will accelerate toward the fifth floor. Once the elevator has begun to move upward, you can reduce your force back to 500 N and the elevator will continue to move upward at constant velocity. You are now doing work on the elevator because you are pulling upward on it via the rope and it’s moving upward.

Lifting the empty elevator to the fifth floor doesn’t require an enormous amount of force, but that force must come from the middle of the elevator shaft. It would be nice to stand somewhere else as you pulled on the rope, so you suspend a *pulley* in the elevator shaft (Fig. 4.4.5). With the rope draped over the pulley, you can create tension in the rope from a different location. In fact, you can even pull downward on the rope. While each portion of rope continues to pull inward on its neighbors, the directions of these forces gradually change as the rope bends around the pulley. The pulley redirects the forces on the rope so that a downward force on one end of the rope can exert an upward force on the other end. This redirection makes it much easier to lift the elevator. A pulley even permits the weight of water to lift an elevator (see ❐).

CHECK YOUR UNDERSTANDING #2: Pulling on a Pulley

A rope is draped over a pulley near the ceiling and you and a friend are each pulling downward on opposite ends. If each of you exerts 100 N of force on an end, what is the tension in the rope?

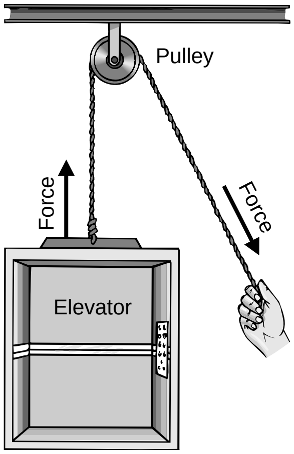

Fig. 4.4.5 - With the rope drawn over a pulley, you can lift the elevator by pulling from almost anywhere. You exert the same force and the tension in the rope is the same, but the pulley redirects the force to make the job more convenient.

Multiple Pulleys

However the elevator is not always empty. Last week the bathtub cracked and you and your friends pushed it off the fire escape. That was easy enough, although it ruined the flower garden next door. But the new bathtub weighs 1300 N (292 pounds), so how are you going to get it up to your apartment? It has to ride up in the elevator. You could rig up the same single pulley and get all of your friends to pull on the rope. But a better idea is to use a multiple-pulley, sometimes called a block-and-tackle. When you pull on a rope, you produce a tension all along that rope. If you could use that same tension several times, you could get mechanical advantage. Here is how a multiple-pulley works.

In a multiple-pulley, the cord goes back and forth between a fixed set of pulleys and a moving set of pulleys (Fig. 4.4.6). The far end is tied to one of the pulley sets. It's important that the cord pass easily over the pulleys. Now when you create tension in the cord, that same tension appears on every segment of cord between the two sets of pulleys. If you exert 500 N of force on the cord, each cord segment will have 500 N of tension. As a result, the two sets of pulleys will be pulled together with 500 N of force for each segment of cord connecting them. If there are 4 cord segments attached between the top of the elevator and the fifth floor, then the total lifting force on the elevator and bathtub will be 2000 N. Since the bathtub and elevator only weigh 1800 N, they will experience a net upward force and will accelerate upward.

While it takes less force on the cord to lift the bathtub and elevator with a multiple pulley than with a single pulley, you don't get something for nothing. To lift the elevator 1 m, you must shorten each segment of cord by 1 m. Since there are 4 segments, you will have to pull 4 m of cord through the system of pulleys. You are obtaining mechanical advantage, using a modest force exerted over a long distance to obtain a larger force exerted over a shorter distance. The amount of work required to lift the bathtub and elevator to your apartment is the same, whether you use a single or multiple pulley. The multiple pulley merely allows you to do this work more gradually, with a smaller force exerted over a longer distance.

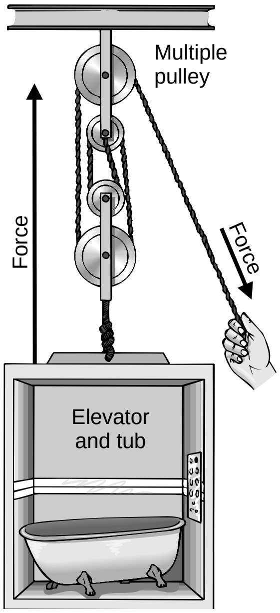

Fig. 4.4.6 - A multiple-pulley being used to lift an elevator and bathtub. The tension in the rope pulls upward on the elevator four times because there are four rope segments between the elevator and the support above it. The upward force on the elevator is thus four times the tension in the rope.

CHECK YOUR UNDERSTANDING #3: Pulling Yourself Up

If you stood inside the elevator shown in Fig. 4.4.6 and pulled on the free end of the rope, could you lift yourself up?

Cable-Lifted Elevators and Counterweights

True cable-lifted elevators (Fig. 4.4.7) resemble the hand-powered one we have just discussed, except that machines pull the cables. In early cable-lifted elevators, the cables were pulled by steam-powered hydraulic rams. Steam was used to pump fluid into or out of the ram and the ram's movement was used to pull the cables. Usually, the ram was used to separate the two halves of a multiple-pulley. The cable coming out of this multiple pulley ran over a pulley at the top of the elevator shaft and down to the elevator car itself. As the two halves of the multiple pulleys were drawn apart, they drew in more cable and lifted the elevator car. As fluid was released from the hydraulic ram, the multiple pulley released cable and the elevator car descended.

Fig. 4.4.7 - The car of this elevator is pulled upward from above by 4 cables and rides on rails to its left and right. The riders control the car through the electric cable hanging below the car.

The first improvement that appeared in cable-lifted elevators was the counterweight (Fig. 4.4.8). Lifting the elevator car by itself requires a considerable amount of work because the car's gravitational potential energy increases as it rises. It would be nice to get back this stored energy when the car descends. Unfortunately, it's hard to turn gravitational potential energy back into high-pressure steam. However, it's possible to use that energy to lift a counterweight.

The counterweight in an elevator descends when the car rises and rises when the car descends. Because the two objects have similar masses, the total amount of mass that is rising or falling as the elevator moves is almost zero. The overall gravitational potential energy of the elevator is not changing very much; it's simply moving around between the various parts of the machine. The counterweight balances the car so that it takes very little power to move the system. The elevator and counterweight resemble a balanced seesaw, which requires only a tiny push to make it move.

The counterweight on most elevators hangs from its own cable attached to the elevator car. That cable travels from the car, over pulleys at the top of the elevator shaft, and down to the counterweight. The counterweight is usually equal to the mass of the empty elevator car plus about 40% of the elevator's rated load. Thus, when the elevator is 40% filled, the counterweight will exactly balance the car and very little work will be done in raising or lowering the car.

Most modern elevators are driven by electric motors. The advantages of electric motors are their variable speeds of rotation, high torque, and reliability. While we will save our discussion of electric motors for a later chapter, we will note here that electric motors can be made to operate efficiently at many rotational speeds, torques, and overall power-levels. The output power of an electric motor is frequently rated in horsepower and the motors used in elevators may be as large as several hundred horsepower.

Because early electric motors could not deliver so much mechanical power, the first electric elevators used *winches* to lift their elevator cars. The cable from the elevator car was actually wound up on a drum at the top of the elevator shaft. The counterweight was attached to a cable that was also wound on the drum. The two cables were arranged so that the counterweight cable unwound as the car cable wound up. An electric motor used gears to turn the drum.

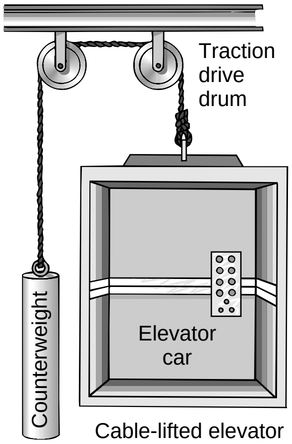

Fig. 4.4.8 - A cable-lifted elevator usually supports the car and a counterweight from opposite ends of its cable. A motor turns a traction drive that either raises or lowers the car. The counterweight moves in the other direction, assisting the motor in lifting the car or storing energy as the car descends.

This winch mechanism had a number of disadvantages. It raised or lowered the car relatively slowly because the gearing limited the rate at which the drum could be turned. The overall height of the elevator was limited because the drum had to be able to hold all of the cable when the elevator was at the top of its travel. The diameter of the drum was constrained by the need to keep torques low and only about 100 m of cable could be accommodated.

Instead of winding and unwinding cable from a drum, most modern elevators use traction to draw a cable over a drum. The cable rises from the elevator car, travels over the traction drive drum and then descends into the elevator shaft where it's attached to the counterweight. An electric motor turns the traction drive drum. When high speed is not important, the drum can be turned by a small motor through the use of gears. However, in tall buildings, the drum is usually turned directly by a large motor. Elevators of this type can run at speeds as high as 10 m/s (22 mph) in buildings of any height.

The mechanical power required from the drive motor depends on how well balanced the car and counterweight are. If the elevator car is loaded to 40% of capacity so that the two weights are balanced, the motor will have little difficulty in moving the car up or down. If the car is particularly empty or particularly full, the motor will have to provide considerable mechanical power when lifting the heavy side of the system and various brakes will have to absorb energy released by the elevator when the heavy side descends. The motor’s maximum mechanical power, together with the strength of the cables, limits how much weight the elevator can lift.

In many freight elevators, the car is lifted by a multiple pulley so that a single segment of cable doesn’t have to support the entire load. Even when a single pulley is used, several separate cables support the car, both for safety and to reduce cable stretching. Cable stretching is a serious problem in tall elevators. Tension always tends to pull things apart, so a cable becomes longer. Like most objects, a cable behaves as a spring when it’s subject to tension. Its length increases by an amount proportional to the tension it experiences. As people enter the elevator car and its total weight increases, the tension on its support cable increases and that cable stretches slightly. Modern elevators are equipped with automatic leveling systems that turn the traction drum to make up for the stretching of the cables. The passengers are unaware of this careful adjustment taking place as they step on or off the elevator. Nonetheless, you may be able to feel the cable stretch if you bounce up and down on a cable-lifted elevator.

❐ The development of safe elevators had an enormous effect on people’s interest in tall buildings. Suddenly the upper floors became more desirable than the lower floors. Speed became very important. A “water balance” elevator was tried in the New York Western Union Building in 1873. The elevator car was drawn upward by the weight of an enormous bucket of water. To descend, the bucket of water was emptied. Controlled only by braking and without any automatic safety system, this elevator was too scary to be popular.

CHECK YOUR UNDERSTANDING #4: A Light Load

If an elevator car is nearly empty and weighs much less than the counterweight, how much work must the motor do to lift that elevator car upward?

Balance

Elevator cars must remain level no matter where the passengers choose to stand. The only way to keep the car level is to make it run along a vertical track. To see why the track is necessary, consider the case of an empty car (Fig. 4.4.9). The lifting force on the car is exerted at the middle of the elevator car, at either its top or its bottom. The center of mass of the empty car is also at the middle of the elevator car so the lifting force exerts no torque on the car about its center of mass. The car remains level.

Now consider what happens when passengers enter the car and begin to walk around inside. The center of mass of the car moves with the people inside. Now the lifting force exerts a torque on the car about its new center of mass and

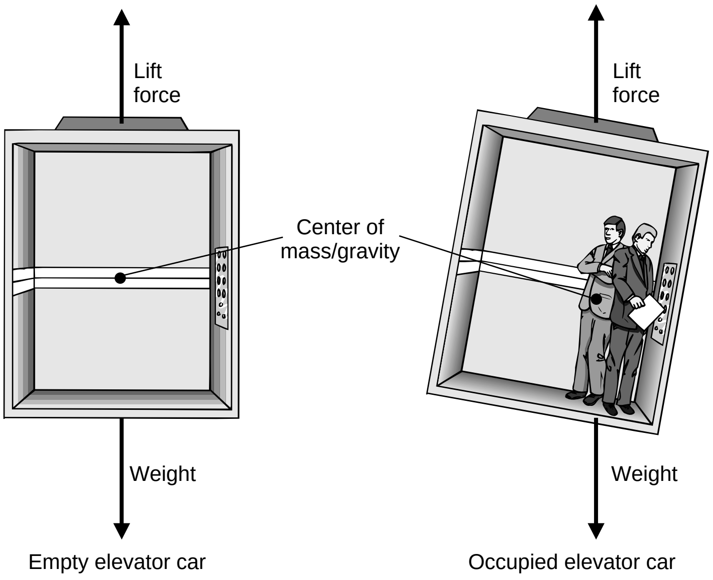

Fig. 4.4.9 - An empty elevator car (left) experiences no torque about its center of mass so it remains level. The occupied car (right) has a different center of mass. The lift force exerts a torque on this car about its center of mass and it begins rotating. For the car to remain level as the passengers move around, the car must run in a track that can exert leveling torques on the car.

it tends to rotate. The best way to prevent the car from tilting is to confine the car on a track. The rails of the track exert the torques needed to keep the car level.

CHECK YOUR UNDERSTANDING #5: Not on the Level

If the track supporting an elevator car were suddenly removed so that it could tilt, would its center of gravity move up or down?

Safety

All cable-lifted elevators have safety devices to keep them from falling if their cables break. Most modern elevators have more than one lifting cable, but they still require mechanisms to ensure that there are no accidents (see ❐).

❐ The only time a safety elevator plummeted to the bottom of its shaft was in 1945, when a military airplane struck the Empire State Building. The plane lodged in the elevator shaft near the 79th floor, cutting all of the cables to the elevator car on the 38th floor. The car dropped to the basement, but its descent was cushioned by the increasing air pressure beneath it and by a mountain of severed cables and an emergency bumper at the bottom of the shaft. The only occupant of the car, a 20-year-old elevator operator, survived without serious injury.

The original safety device that Otis developed for his first elevators had jaws that would grab onto the rails of the elevator track if there were a loss of tension in the supporting cable. If the cable broke and its tension vanished, springs would force the jaws into the track.

Modern elevators use mechanisms that monitor the vertical speed of the elevator. If the speed exceeds a certain permissible value, brakes on the car grab the tracks. This speed control prevents a nearly empty elevator from moving upward too quickly just as it prevents a full elevator from falling. One such speed-sensing device is the *centrifugal governor*, a mechanism that senses how quickly a shaft is turning (Fig. 4.4.10). When it's used with an elevator, the shaft is turned by a pulley on a special cable attached to the elevator car. The faster the elevator moves, the faster the shaft turns. The centrifugal governor swings several masses around in a circle. Since the masses travel in uniform circular motion, they need some centripetal force to accelerate them toward the center of the circle. In the centrifugal governor, this centripetal force is exerted by several rods that are held apart by a spring.

As long as the shaft is turning slowly, the spring can keep the rods from moving together. But when the shaft is turning quickly, the centripetal force becomes very large and the rods compress the spring. As the rods move, they push on a lever. In the case of the elevator, this lever activates brakes that slow the elevator down.

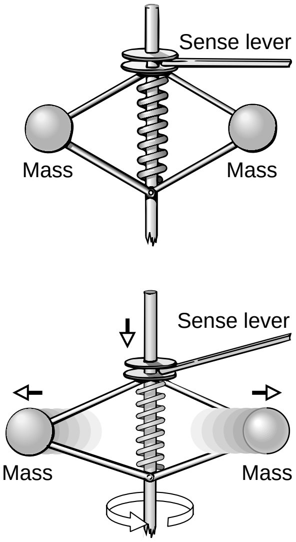

Fig. 4.4.10 - A centrifugal governor uses the principle that a central force is required to accelerate masses around in a circle. As long as the shaft is stopped or spinning slowly (top), the spring can keep the upper and lower rods apart. But once the shaft spins too quickly, the masses swing outward (bottom) and the sense lever is shifted.

CHECK YOUR UNDERSTANDING #6: Going for a Spin

How does the spinning centrifugal governor sense that the elevator is moving too fast in *either* direction?

Starting and Stopping

Simply moving the elevator car up or down is not enough. To be useful, an elevator must be able to stop at the proper level, exchange passengers or freight, and then start to move to a new level. To be pleasant to ride, the elevator must start and stop slowly enough that it doesn't knock the passengers off their feet. To meet these added requirements on the motion of the elevator car, variable speed electric motors are used.

Whether the elevator is handled by an operator or is run automatically, the torque exerted on the traction drive drum is carefully controlled in order to avoid sudden accelerations. Whenever the elevator you are in accelerates upward, as it does when it starts moving upward or stops moving downward, you feel particularly heavy. Your apparent weight increases because of the upward acceleration. If the upward acceleration is too great, you may be thrown to the tion. If the upward acceleration is too great, you may be thrown to the floor of car. Whenever the elevator accelerates downward, as its does when it starts moving downward or stops moving upward, you feel particularly light. Your apparent weight decreases because of the downward acceleration. If the downward acceleration is too great, you may leave the floor of the elevator and bump against its ceiling. Only after the elevator reaches constant velocity, either up or down, does your apparent weight return to your true weight.

A well-designed elevator accelerates and decelerates smoothly and gradually. This need for smooth deceleration means that the operator or the automatic mechanism must anticipate stops and begin to decelerate before reaching the stopping point. Operating an antique elevator, with no machinery to help anticipate the stop, required great skill. In manually operated elevators, the operator's ability to stop at the correct height limited the maximum vertical speed that could be used effectively. Modern elevators anticipate stops automatically and gradually reduce the speed of travel so as to come to a stop at exactly the right height. These elevators can move up or down extremely quickly and still stop properly.

CHECK YOUR UNDERSTANDING #7: Fast Track to the Basement

What would it feel like to be in an elevator car if the cable broke on the top floor of a skyscraper and no safety mechanism turned on the brakes?

Jackscrew Elevators

One of the oldest and simplest lifting devices is the *jackscrew*—a screw used as a lifting mechanism. Jackscrews are used frequently in industry, construction, and maintenance to support or move heavy objects. Jackscrews are also used to level buildings and support sagging beams, and the repair jack that you have in your automobile is probably a jackscrew or a mechanism that incorporates a jackscrew. It's not surprising then that early elevators were based on the jackscrew. The elevator sat on top of a jackscrew and was raised or lowered by turning the screw into or out of a threaded hole. While jackscrews are no longer used in passenger elevators, they're still worth a few moments discussion.

A jackscrew elevator consisted of a lifting platform that was pushed upward from below by a jackscrew (Fig. 4.4.11). What made jackscrews so appealing for early elevators was that they were unlikely to fail catastrophically and that they exhibited mechanical advantage. The worry about catastrophic failure was very real before 1853—the cars in elevators built prior to that time were prone to dropping suddenly when the rope lifting them broke. Since the consequences of such a fall were awful, knowing that a thick metal jackscrew was pushing the car upward from beneath was very comforting to the passengers.

But what makes jackscrews so useful in lifting devices of all sorts is mechanical advantage. A modest torque exerted on the threaded cylinder in a jackscrew can lift a very heavy object. As we noted in Chapter 1, lifting a piano to the second floor requires a certain amount of work, regardless of how you get it there. In that chapter we used a ramp and here we use a jackscrew. Actually, the jackscrew is just a rotating ramp, so the principle is exactly the same. The jackscrew allows the elevator operator to do the work required to lift the piano a little at a time. A modest torque exerted over many, many turns of the screw does the same amount of work as lifting the piano straight up to the second floor.

However, while a jackscrew provides a great deal of lifting force, it must be turned very rapidly in order to raise its platform at any reasonable rate. But a jackscrew encounters sliding friction and becomes extremely hot if it's turned too

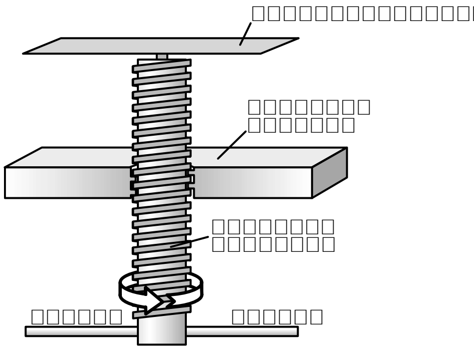

Fig. 4.4.11 - A jack screw uses the motion of a threaded cylinder—a screw—through a threaded hole to raise or lower a heavy object. A modest torque exerted on the handles will rotate the screw and produce a very large lifting force on the lifting platform.

quickly. It may also wear out. Friction and wear severely limit the vertical speed of a jackscrew elevator and an elevator that climbs upward at only 2 meters-per-minute will lose many of its passengers to the staircase. Furthermore, the jackscrew itself must be as tall as the building it serves and buildings have become very tall. So jackscrew-based elevators quickly gave way to hydraulic and cable-lift elevators.

CHECK YOUR UNDERSTANDING #8:

Many two-wheeled car trailers have a jackscrew mounted behind the trailer hitch to support the front of the trailer when it's not attached to a car. Even when the front of the trailer is so heavy that you can't lift it, the jackscrew lifts it almost effortlessly. How is that possible?