Chapter 2

Playing with Gears

Solutions in this chapter:

- Counting Teeth
- Gearing Up and Down
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- Worming Your Way: The Worm Gear
- Limiting Strength with the Clutch Gear
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- Using Pulleys, Belts, and Chains
- Making a Difference: The Differential

Introduction

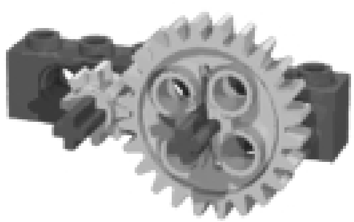
You might find yourself asking: Do I really *need* gears? Well, the answer is yes, you do. Gears are so important for machines that they are almost their symbol: Just the sight of a gear makes you think *machinery*. In this chapter, you will enter the amazing world of gears and discover the powerful qualities they offer, transforming one force into another almost magically. We'll guide you through some new concepts—velocity, force, torque, friction—as well as some simple math to lay the foundations that will give you the most from the machinery. The concepts are not as complex as you might think. For instance, the chapter will help you see the parallels between gears and simple levers.

We invite you once again to experiment with the real things. Prepare some gears, beams, and axles to replicate the simple setups of this chapter. No description or explanation can replace what you learn through hands-on experience.

Counting Teeth

A single gear wheel alone is not very useful—in fact, it is not useful at all, unless you have in mind a different usage from what it was conceived for! So, for a meaningful discussion, we need at least two gears. In Figure 2.1, you can see two very common LEGO gears: The left one is an 8t, while the right is a 24t. The most important property of a gear, as we'll explain shortly, is its *teeth*. Gears are classified by the number of teeth they have; the description of which is then shortened to form their name. For instance, a gear with 24 teeth becomes "a 24t gear."

Figure 2.1 An 8t and a 24t Gear



Let's go back to our example. We have two gears, an 8t and a 24t, each mounted on an axle. The two axles fit inside holes in a beam at a distance of two holes (one empty hole in between). Now, hold the beam in one hand, and with the other hand gently turn one of the axles. The first thing you should notice is that when you turn one axle, the other turns too. The gears are *transferring motion from one axle to the other.* This is their fundamental property, their very nature. The second important thing you should notice is that you are not required to apply much strength to make them turn. Their teeth match well and there is only a small amount of friction. This is one of the great characteristics of the LEGO TECHNIC system: Parts are designed to match properly at standard distances. A third item of note is that the two axles turn in opposite directions: one clockwise and the other counterclockwise.

A fourth, and more subtle, property you should have picked up on is that the two axles revolve at different speeds. When you turn the 8t, the 24t turns more slowly, while turning the 24t makes the 8t turn faster. Lets explore this in more detail.

Gearing Up and Down

Let's start turning the larger gear in our example. It has 24 teeth, each one meshing perfectly between two teeth of the 8t gear. While turning the 24t, every time a new tooth takes the place of the previous one in the contact area of the gears, the 8t gear turns exactly one tooth, too. The key point here is that you need to advance only 8 teeth of the 24 to make the small gear do a complete turn (360°). After 8 teeth more of your 24, the small gear has made a second revolution. With the last 8 teeth of your 24, the 8t gear makes its third turn. This is why there is a difference in speed: For every turn of the 24t, the 8t makes three turns! We express this relationship with a ratio that contains the number of teeth in both gears: 24 to 8. We can simplify it, dividing the two terms by the smaller of the two (8), so we get 3 to 1. This makes it very clear, in numerical terms, that one turn of the first corresponds to three turns of the second.

You have just found a way to get more speed! (To be technically precise, we should call it *angular velocity*, not *speed*, but you get the idea). Before you start imagining mammoth gear ratios for racecar robots, sorry to disappoint you—there is no free lunch in mechanics, you have to pay for this gained speed. You pay for it with a decrease in *torque*, or, to keep in simple terms, a decrease in strength.

So, our gearing is able to convert torque to velocity—the more velocity we want, the more torque we must sacrifice. The ratio is exactly the same, if you get three times your original angular velocity, you reduce the resulting torque to one third.

One of the nice properties of gears is that this conversion is symmetrical: You can convert torque into velocity or vice versa. And the math you need to manage and understand the process is as simple as doing one division. Along common conventions, we say that we *gear up* when our system increases velocity and reduces torque, and that we *gear down* when it reduces velocity and increases torque. We usually write the ratio 3:1 for the former and 1:3 for the latter.

Bricks & Chips…

What Is Torque?

When you turn a nut on a bolt using a wrench, you are producing *torque*. When the nut offers some resistance, you've probably discovered that the more the distance from the nut you hold the wrench, the less the force you have to apply. Torque is in fact the product of two components: *force* and *distance*. You can increase torque by either increasing the applied force, or increasing the distance from the center of rotation. The units of measurement for torque are thus a unit for the force, and a unit for the distance. The International System of Units (SI) defines the newton-meter (Nm) and the newton-centimeter (Ncm).

If you have some familiarity with the properties of levers, you will recognize the similarities. In a lever, the resulting force depends on the distance between the application point and the fulcrum: the longer the distance, the higher the force. You can think of gears as levers whose fulcrum is their axle and whose application points are their teeth. Thus, applying the same force to a larger gear (that is to a longer lever) results in an increase in torque.

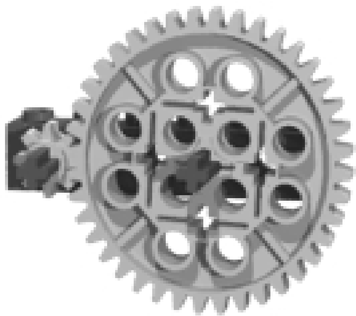
When should you gear up or down? Experience will tell you. Generally speaking, you will gear down many more times then you will gear up, because you'll be working with electric motors that have a relatively high velocity yet a fairly low torque. Most of the time, you reduce speed to get more torque and make your vehicles climb steep slopes, or to have your robotic arms lift some load. Other times you don't need the additional torque; you simply want to reduce speed to get more accurate positioning.

One last thing before you move on to the next topic. We said that there is no free lunch when it comes to mechanics. This is true for this conversion service as well: We have to pay something to get the conversion done. The price is paid in *friction*—something you should try and keep as low as possible—but it's unavoidable. Friction will always eat up some of your torque in the conversion process.

Riding That Train: The Geartrain

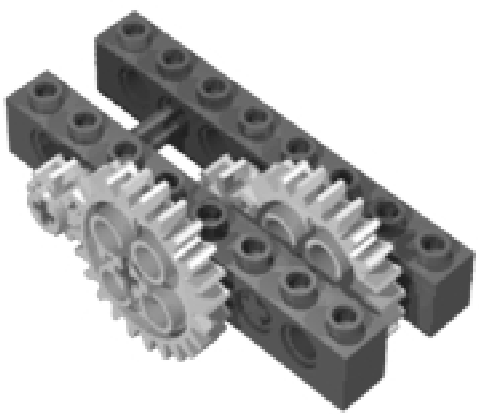
The largest LEGO gear is the 40t, while the smallest is the 8t (used in the previous discussion). Thus, the highest ratio we can obtain is 8:40, or 1:5 (Figure 2.2).

Figure 2.2 A 1:5 Gear Ratio



What if you need an even higher ratio? In such cases, you should use a *multistage reduction* (or multiplication) system, usually called a *geartrain*. Look at Figure 2.3. In this system, the result of a first 1:3 reduction stage is transferred to a second 1:3 reduction stage. So, the resulting velocity is one third of one third, which is one ninth, while the resulting torque is three times three, or nine. Therefore, the ratio is 1:9.

Figure 2.3 A Geartrain with a Resulting Ratio of 1:9



Geartrains give you incredible power, because you can trade as much velocity as you want for the same amount of torque. Two 1:5 stages result in a ratio of 1:25, while three of them result in 1:125 system! All this strength must be used with care, however, because your LEGO parts may get damaged if for any reason your robot is unable to convert it into some kind of work. In other words, if something gets jammed, the strength of a LEGO motor multiplied by 125 is enough to deform your beams, wring your axles, or break the teeth of your gears. We'll return to this topic later.

Designing & Planning…

Choosing the Proper Gearing Ratio

We suggest you perform some experiments to help you make the right decision in choosing a gearing ratio. Don't wait to finish your robot to discover that some geared mechanics doesn't work as expected! Start building a very rough prototype of your robot, or just of a particular subsystem, and experiment with different gear ratios until you're satisfied with the result. This prototype doesn't need to be very solid or refined, and doesn't even need to resemble the finished system you have in mind. It is important, however, that it accurately simulates the kind of work you're expecting from your robot, and the actual loads it will have to manage. For example, if your goal is to build a robot capable of climbing a slope with a 50 percent grade, put on your prototype all the weight you imagine your final model is going to carry: additional motors for other tasks, the RCX itself, extra parts, and so on. Don't test it without load, as you might discover it doesn't work.

NOTE

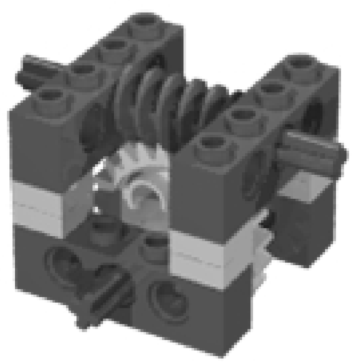
Remember that in adding multiple reduction stages, each additional stage introduces further *friction*, the bad guy that makes your world less than ideal. For this reason, if aiming for maximum efficiency, you should try and reach your final ratio with as few stages as possible.

Worming Your Way: The Worm Gear

In your MINDSTORMS box you've probably found another strange gear, a black one that resembles a sort of cylinder with a spiral wound around it. Is this thing really a gear? Yes, it is, but it is so peculiar we have to give it special mention.

In Figure 2.4, you can see a worm gear engaged with the more familiar 24t. In just building this simple assembly, you will discover many properties. Try and turn the axles by hand. Notice that while you can easily turn the axle connected to the worm gear, you can't turn the one attached to the 24t. We have discovered the first important property: The worm gear leads to an *asymmetrical system*; that is, you can use it to turn other gears, but it can't be turned *by* other gears. The reason for this asymmetry is, once again, friction. Is this a bad thing? Not necessarily. It can be used for other purposes.

Figure 2.4 A Worm Gear Engaged with a 24t



Another fact you have likely observed is that the two axles are perpendicular to each other. This change of orientation is unavoidable when using worm gears.

Turning to gear ratios, you're now an expert at doing the math, but you're probably wondering how to determine how many teeth this worm gear has! To figure this out, instead of discussing the theory behind it, we proceed with our experiment. Taking the assembly used in Figure 2.4, we turn the worm gear axle slowly by exactly one turn, at the same time watching the 24t gear. For every turn you make, the 24t rotates by exactly one tooth. This is the answer you were looking for: the worm gear is a 1t gear! So, in this assembly, we get a 1:24 ratio with a single stage. In fact, we could go up to 1:40 using a 40t instead of a 24t.

The asymmetry we talked about before makes the worm gear applicable only in reducing speed and increasing torque, because, as we explained, the friction of this particular device is too high to get it rotated by another gear. The same high friction also makes this solution very inefficient, as a lot of torque gets wasted in the process.

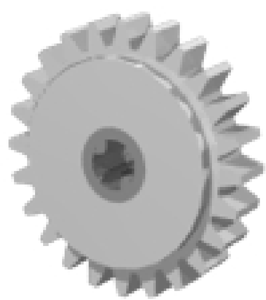
As we mentioned earlier, this outcome is not always a bad thing. There are common situations where this asymmetry is exactly what we want. For example, when designing a robotic arm to lift a small load. Suppose we use a 1:25 ratio made with standard gears: what happens when we stop the motor with the arm loaded? The symmetry of the system transforms the weight of the load (potential energy) into torque, the torque into velocity, and the motor spins back making the arm go down. In this case, and in many others, the worm gear is the proper solution, its friction making it impossible for the arm to turn the motor back.

We can summarize all this by saying that in situations where you desire precise and stable positioning under load, the worm gear is the right choice. And it's also the right choice when you need a high reduction ratio in a small space, since allows very compact assembly solutions.

Limiting Strength with the Clutch Gear

Another special device you should get familiar with is the thick 24t white gear, which has strange markings on its face (Figure 2.5). Its name is *clutch gear*, and in the next part of this section we'll discover just what it does.

Figure 2.5 The Clutch Gear



Our experiment this time requires very little work, just put the end of an axle inside the clutch gear and the other end into a standard 24t to use as a knob. Keep the latter in place with one hand and slowly turn the clutch gear with the other hand. It offers some resistance, but it turns. This is its purpose in life: to offer some resistance, then give in!

This clutch gear is an invaluable help to limit the strength you can get from a geared system, and this helps to preserve your motors, your parts, and to resolve some difficult situations. The mysterious "2.5·5 Ncm" writing stamped on it (as explained earlier, Ncm is a newton-centimeter, the unit of measurement for torque) indicates that this gear can transmit a maximum torque of about 2.5 to 5 Ncm. When exceeding this limit its internal clutch mechanism starts to slip.

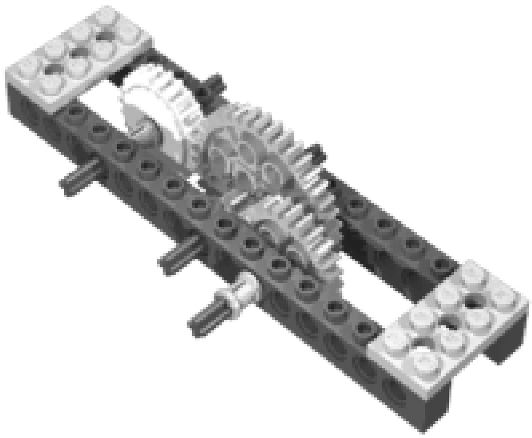
What's this feature useful for? You have seen before that through some reduction stages you can multiply your torque by high factors, thus getting a system strong enough to actually damage itself if something goes wrong. This clutch gear helps you avoid this, limiting the final strength to a reasonable value.

There are other cases in which you don't gear down very much and the torque is not enough to ruin your LEGO parts, but if the mechanics jam, the motor stalls—this is a very bad thing, because your motor draws a lot of current and risks permanent damage. The clutch gear prevents this damage, automatically disengaging the motor when the torque becomes too high.

In some situations, the clutch gear can even reduce the number of sensors needed in your robot. Suppose you build a motorized mechanism with a bounded range of action, meaning that you simply want your subsystem (arms, levers, actuators—anything) to be in one of two possible states: open or closed, right or left, engaged or disengaged, with no intermediate position. You need to turn on the motor for a short time to switch over the mechanism from one state to the other, but unfortunately it's not easy to calculate the precise time a motor needs to be on to perform a specific action (even worse, when the load changes, the required time changes, too). If the time is too short, the system will result in an intermediate state, and if it's too long, you might do damage to your motor. You can use a sensor to detect when the desired state has been reached; however, if you put a clutch gear somewhere in the geartrain, you can now run the motor for the approximate time needed to reach the limit in the worst load situation, because the clutch gear slips and prevents any harm to your robot and to your motor if the latter stays on for a time longer than required.

There's one last topic about the clutch gear we have to discuss: where to put it in our geartrain. You know that it is a 24t and can transmit a maximum torque of 5 Ncm, so you can apply here the same gear math you have learned so far. If you place it before a 40t gear, the ratio will be 24:40, which is about 1:1.67. The maximum torque driven to the axle of the 40t will be 1.67 multiplied by 5 Ncm, resulting in 8.35 Ncm. In a more complex geartrain like that in Figure 2.6, the ratio is 3:5 then 1:3, coming to a final 1:5; thus the maximum resulting torque is 25 Ncm. A system with an output torque of 25 Ncm will be able to produce a force five times stronger than one of 5 Ncm. In other words, it will be able to lift a weight five times heavier.

Figure 2.6 Placing the Clutch Gear in a Geartrain



From these examples, you can deduce that the maximum torque produced by a system that incorporates a clutch gear results from the maximum torque of the clutch gear multiplied by the ratio of the following stages. When gearing down, the more output torque you want, the closer you have to place your clutch gear to the source of power (the motor) in your geartrain. On the contrary, when you are reducing velocity, not to get torque but to get more accuracy in positioning, and you really want a soft touch, place the clutch gear as the very last component in your geartrain. This will minimize the final supplied torque.

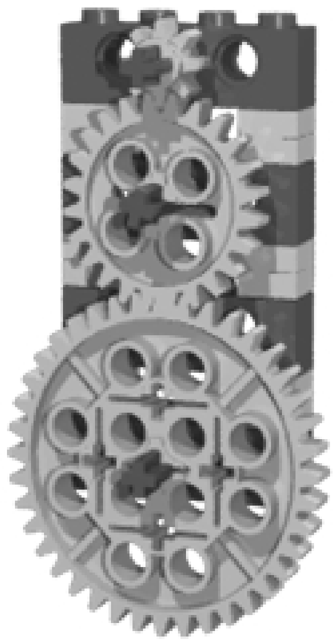
This might sound a bit complex, but we again suggest you learn by doing, rather than by simply reading. Prototyping is a very good practice. Set up some very simple assemblies to experiment with the clutch gear in different positions, and discover what happens in each case.

Placing and Fitting Gears

The LEGO gear set includes many different types of gear wheels. Up to now, we played with the straight 8t, 24t, and 40t, but the time has come to explore other kinds of gears, and to discuss their use according to size and shape.

The 8t, 24t, and 40t have a radius of 0.5 studs, 1.5 studs, and 2.5 studs, respectively (measured from center to half the tooth length). The distance between the gears' axles when placing them is the sum of their radii, so it's easy to see that those three gears make very good combinations at distances corresponding to whole numbers. 8t to 24t is 2 studs, 8t to 40t is 3 studs, and 24t to 40t equates to four studs. The pairs that match at an even distance are very easy to connect one above the other in our standard grid, because we know it goes by increments of two studs for every layer (Figure 2.7).

Figure 2.7 Vertical Matching of Gears



Another very common straight gear is the 16t gear (Figure 2.8). Its radius is 1, and it combines well with a copy of itself at a distance of two. Getting it to cooperate with other members of its family, however, is a bit more tricky, because whenever matched with any of the other gears it leads to a distance of some studs *and a half*, and here is where the special beams we discussed in the previous chapter (1 x 1, 1 hole, and 1 x 2, 2 holes) may help you (Figure 2.9).

Figure 2.8 The 16t Gear

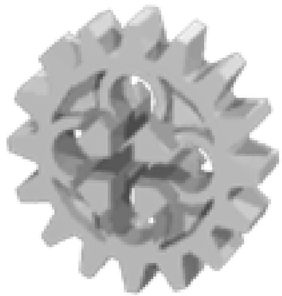
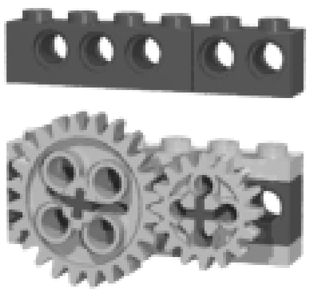


Figure 2.9 How to Match the 16t Gear to a 24t Gear



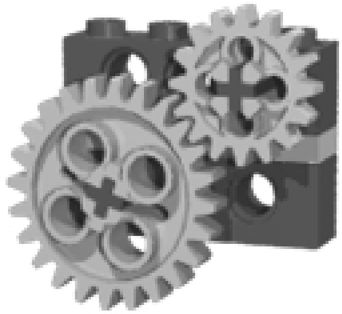
Bricks & Chips…

Idler Gears

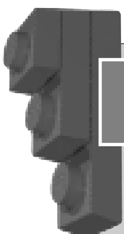
Figure 2.7 offers us the opportunity to talk about *idler gears*. What's the ratio of the geartrain in the figure? Starting from the 8t, the first stage performs an 8:24 reduction, while the second is a 24:40. Multiplying the two fractions, you get 8:40, or 1:5, the same result you'd get meshing the 8t directly to the 40t. The intermediate 24t is an idler gear, which doesn't affect the gear ratio. Idler gears are quite common in machines, usually to help connect distant axles. Are idler gears totally lacking in effects on the system? No, they have one very important effect: They change the direction of the output!

As we've already said, you're not restricted to using the standard grid. You can try out different solutions that don't require any special parts, like the one showed in Figure 2.10.

Figure 2.10 A Diagonal Matching



When using a pair of 16t gears, the resulting ratio is 1:1. You don't get any effect on the angular velocity or torque (except in converting a fraction of them into friction), but indeed there are reasons to use them as a pair—for instance, when you want to transfer motion from one axle to another with no other effects. This is, in fact, another task that gears are commonly useful for. There's even a class of gears specifically designed to transfer motion from one axle to another axle perpendicular to it, called *bevel gears*.



Designing & Planning…

Backlash

Diagonal matching is often less precise than horizontal and vertical types, because it results in a slightly larger distance between gear teeth. This extra distance increases the *backlash*, the amount of oscillation a gear can endure without affecting its meshing gear. Backlash is amplified when gearing up, and reduced when gearing down. It generally has a bad effect on a system, reducing the precision with which you can control the output axle, and for this reason, it should be kept to a minimum.

The most common member of this class is the 12t bevel gear, which can be used *only* for this task (Figure 2.11), meaning it does not combine at all with any other LEGO gear we have examined so far. Nevertheless, it performs a very useful function, allowing you to transmit the motion toward a new direction, while using a minimum of space. There's also a new 20t bevel conical gear with the same design of the common 12t (Figure 2.12). Both of these bevel gears are half a stud in thickness, while the other gears are 1 stud.

Figure 2.11 Bevel Gears on Perpendicular Axles

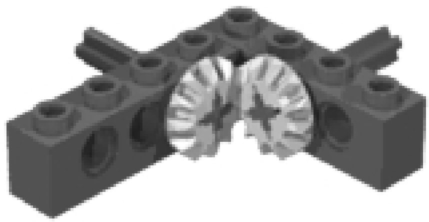


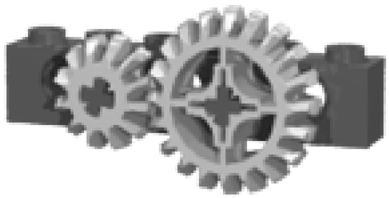
Figure 2.12 The 20t Bevel Gear

The 24t gear also exists in the form of a *crown gear*, a special gear with front teeth that can be used like an ordinary 24t, which can combine with another straight gear to transmit motion in an orthogonal direction (that is, composed of right angles), possibly achieving at the same time a ratio different from 1:1 (Figure 2.13).

To conclude our discussion of gears, we'll briefly introduce some recent types not included in the MINDSTORMS kit, but that you might find inside other LEGO sets. The two *double bevel* ones in Figure 2.14 are a 12t and a 20t, respectively 0.75 and 1.25 studs in radius. If you create a pair that includes one per kind of the two, they are an easy match at a distance of 2 studs.

Figure 2.13 The Crown Gear on Perpendicular Axles

Figure 2.14 Double Bevel Gears



Things get a bit more complicated when you want to couple two of the same kind, as the resulting distance is 1.5 or 2.5. And even more complicated when combined with other gears, causing resulting distances that include a quarter or three quarters of a stud. These gears are designed to work well in perpendicular setups as well (Figure 2.15).

Figure 2.15 Double Bevel Gear on Perpendicular Axles

Using Pulleys, Belts, and Chains

The MINDSTORMS kit includes some *pulleys* and *belts*, two classes of components designed to work together and perform functions similar to that of gears—

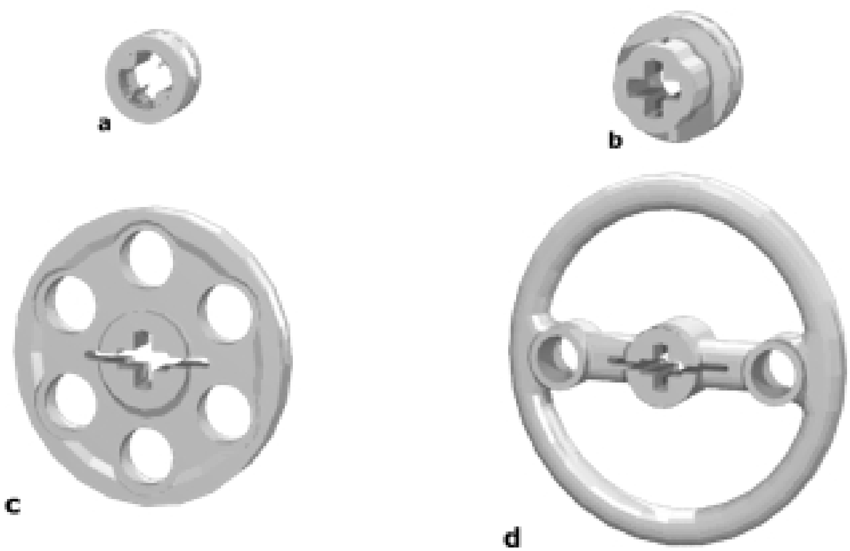
similar, that is, but not identical. They have indeed some peculiarities which we shall explore in the following paragraphs.

Chains, on the other hand, are not part of the basic MINDSTORMS kit. You will need to buy them separately. Though not essential, they allow you to create mechanical connections that share some properties with both geartrains and pulley-belt systems.

Pulleys and Belts

Pulleys are like wheels with a groove (called a *race*) along their diameter. The LEGO TECHNIC system currently includes four kinds of pulleys, shown in Figure 2.16.

Figure 2.16 Pulleys



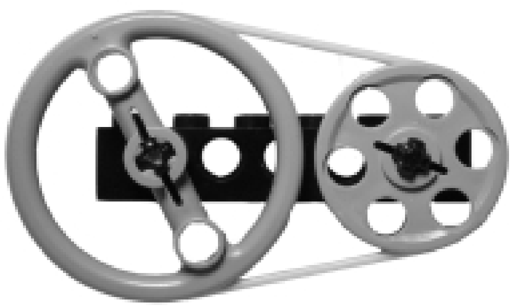
The smallest one (a) is actually the half-size bush, normally used to hold axles in place to prevent them from sliding back and forth. Since it does have a race, it can be properly termed a pulley. Its diameter is one LEGO unit, with a thickness of half a unit.

The small pulley (b) is 1 unit in thickness and about 1.5 units in width. It is asymmetrical, however, since the race is not in the exact center. One side of the axle hole fits a rubber ring that's designed to attach this pulley to the micro-motor. The medium pulley (c) is again half a unit thick and 3 units in diameter. Finally, the large pulley (d) is 1 unit thick and about 4.5 units in diameter.

LEGO belts are rings of rubbery material that look similar to rubber bands. They come in three versions in the MINDSTORMS kit, with different colors corresponding to different lengths: white, blue, and yellow (in other sets, you can find a fourth size in red). Don't confuse them with the actual rubber bands, the black ones you found in the kit: Rubber bands have much greater elasticity, and for this reason are much less suitable to the transfer of motion between two pulleys. This is, in fact, the purpose of belts: to connect a pair of pulleys. LEGO belts are designed to perfectly match the race of LEGO pulleys.

Let's examine a system made of a pair of pulleys connected through a belt (Figure 2.17). The belt transfers motion from one pulley to the other, making them similar to a pair of gears. How do you compute the ratio of the system? You don't have any teeth to count... The rule with pulleys is that the reduction ratio is determined by finding the ratio between their diameters (this rules applies to gears too, but the fact that their circumference is covered with evenly spaced teeth provides a convenient way to avoid measurement). You actually should consider the diameter of the pulley *inside* its race, because the sides of the race are designed specifically to prevent the belt from slipping from the pulley and don't count as part of the diameter the belt acts over.

Figure 2.17 Pulleys Connected with a Belt



You must also consider that pulleys are not very suitable to transmitting high torque, because the belts tend to slip. The amount of slippage is not easy to estimate, as it depends on many factors, including the torque and speed, the tension of the belt, the friction between the belt and the pulley, and the elasticity of the belt.

For those reasons, we preferred an experimental approach and measured some actual ratios among the different combination of pulleys under controlled conditions. You can find our results in Table 2.1.

Table 2.1 Ratios Among Pulleys

	Half Bush	Small Pulley	Medium Pulley	Large Pulley
Half bush	1:1	1:2	1:4	1:6
Small pulley	2:1	1:1	1:2.5	1:4.1
Medium pulley	4:1	2.5:1	1:1	1:1.8
Large pulley	6:1	4.1:1	1.8:1	1:1

Designing & Planning…

Finding the Ratio between Two Pulleys

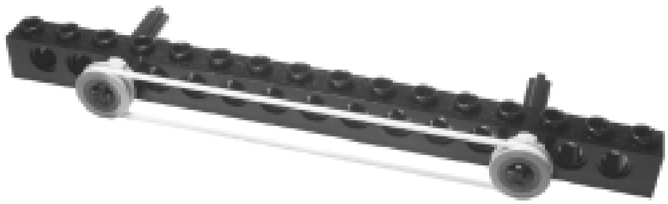
How did we find out the actual ratio between two pulleys? By simply connecting them with a belt and comparing the number of rotations when one of the two gets turned and drags the other. But turning pulleys by hand would have been quite a boring and time-consuming task, and could cause some counts to be missed. What better device for this job than our RCX, equipped with a motor and two rotation sensors? So, we built this very simple machine: a motor connected to a pulley, whose axle is attached to the first rotation sensor, and a second pulley, placed at a very short distance, with its axle attached to the second rotation sensor. We used some care to minimize the friction and maintain the same tension in the belt for all the pairs of pulleys.

When running the motor, the RCX counted the rotations for us. We stopped the motor after a few seconds, read the rotation sensor counts, and divided the two to get the ratio you see in Table 2.1.

These values may change significantly in a real-world application, when the system is under load. Because of this, it's best to think of the figures as simply an indication of a possible ratio for systems where very low torque is applied. Generally speaking, you should use pulleys in your first stages of a reduction system, where the velocity is high and the torque still low. You could even view the slippage problem as a positive feature in many cases, acting as a torque-limiting mechanism like the one we discussed in the clutch gear, with the same benefits and applications.

Another advantage of pulleys over gear wheels is that their distance is not as critical. Indeed, they help a great deal when you need to transfer motion to a distant axle (Figure 2.18). And at high speeds they are much less noisy than gears—a facet that occasionally comes in handy.

Figure 2.18 Pulleys Allow Transmission across Long Distances

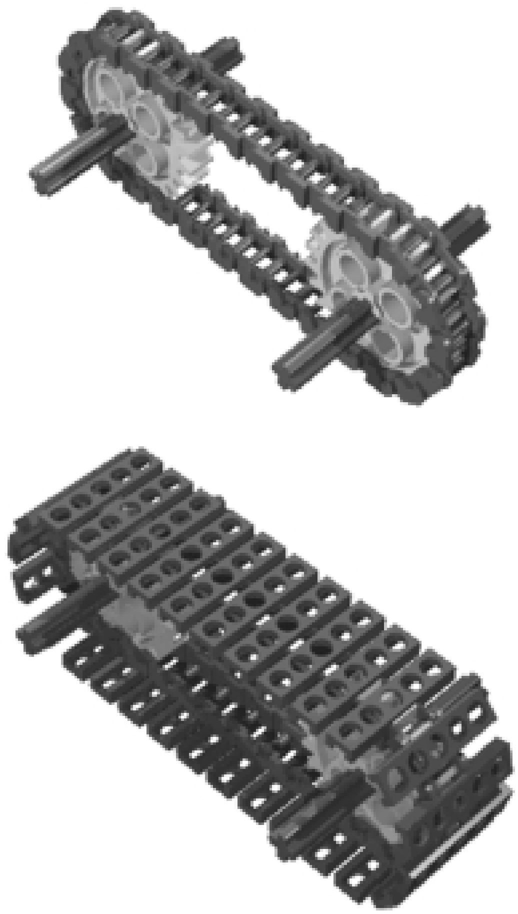


Chains

LEGO *chains* come in two flavors: *chain links* and *tread links* (as shown in Figure 2.19, top and bottom, respectively). The two share the same hooking system and are freely mixable to create a chain of the required length.

Chains are used to connect gear wheels as the same way belts connect with pulleys. They share similar properties as well: Both systems couple parallel axles without reversing the rotation direction, and both give you the chance to connect distant axles. The big difference between the two is that chain links don't allow any slippage, so they transfer *all* the torque. (The maximum torque a chain can transfer depends on the resistance of its individual links, which in the case of LEGO chains is not very high.) On the other hand, they introduce further friction into the system, and for this reason are much less efficient then direct gear matches. You will find chains useful when you have to transfer motion to a distant axle in low velocity situations. The ratio of two gears connected by a chain is the same as their corresponding direct connection. For example, a 16t connected to a 40t results in a 2:5 ratio.

Figure 2.19 Chain Links

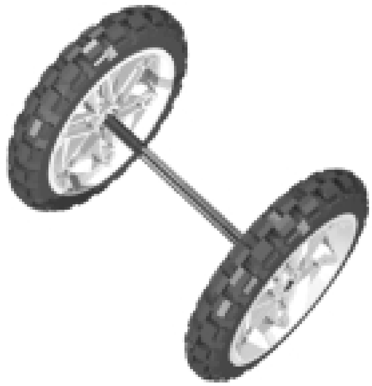


Making a Difference: The Differential

There's a very special device we want to introduce you to at this time: the *differential gear*. You probably know that there's at least one differential gear in every car. What you might not know is why the differential gear is so important.

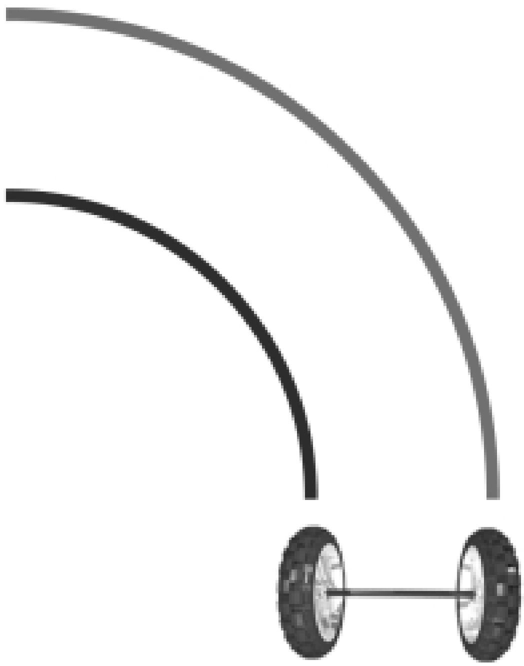
Let's do an experiment together. Take the two largest wheels that you find in the MINDSTORMS kit and connect their hubs with the longest axle (Figure 2.20). Now put the wheels on your table and push them gently: They run smoothly and advance some feet, going straight. *Very straight*. Keep the axle in the middle with your fingers and try to make the wheels change direction while pushing them. It's not so easy, is it?

Figure 2.20 Two Connected Wheels Go Straight



The reason is that when two parallel wheels turn, their paths must have different lengths, the outer one having a longer distance to cover (Figure 2.21). In our example, in which the wheels are rigidly connected, at any turn they cover the same distance, so there's no way to make them turn unless you let one slip a bit.

Figure 2.21 During Turns the Wheels Cover Different Distances



The next phase of our experiment requires that you now build the assembly shown in Figure 2.22. You see a differential gear with its three 12t bevel gears, two 6-stud axles, and two beams and plates designed to provide you with a way to handle this small system. Placing the wheels again on your table, you will notice that while pushing them, you can now easily turn smoothly in any direction. Please observe carefully the *body* of the differential gear and the central bevel gear: when the wheels go straight, the body itself rotates while the bevel gear is stationary. On the other hand, if you turn your system in place, the body stays put and the bevel gear rotates. In any other intermediate case, both of them rotate at some speed, adapting the system to the situation. Differentials offer a way to put power to the wheels without the restriction of a single fixed drive axle.

Figure 2.22 Connecting Wheels with the Differential Gear

To use this configuration in a vehicle, you simply have to apply power to the body of the differential gear, which incorporates a 24t on one side and a 16t on the other.

The differential gear has many other important applications. You can think of it as a mechanical adding/subtracting device. Again place the assembly from Figure 2.22 on your table. Rotate one wheel while keeping the other from turning; the body of the differential gear rotates half the angular velocity of the rotating wheel. You already discovered that when turning our system in place, the differential does not rotate at all, and then when both wheels rotate together, the differential rotates at the same speed as well. From this behavior, we can infer a simple formula:

(Iav1 + Iav2) / 2 = Oav

where *Oav* is the *output angular velocity* (the body of the differential gear), and *Iav1* and *Iav2* are the *input angular velocities* (the two wheels). When applying this equation, you must remember to use *signed* numbers for the input, meaning that if one of the input axles rotates in the opposite direction of the other, you must input its velocity as a negative number. For example, if the right axle rotates at 100 rpm (revolutions per minute) and the left one at 50 rpm, the angular velocity of the body of the differential results in this:

(100 rpm + 50 rpm) / 2 = 75 rpm

There are situations where you deliberately reverse the direction of one input, using idler gears, to make the differential sensitive to a difference in the speed of the wheels, rather than to their sum. Reversing the input means that you must make one of the inputs negative. See what happens to the differential when both wheels run at the same speed, let's say 100 rpm:

(100 rpm – 100 rpm) / 2 = 0 rpm

It doesn't move! As soon as a difference in speed appears, the differential starts rotating with an angular velocity equal to half this difference:

(100 rpm – 98 rpm) / 2 = 1 rpm

This is a useful trick when you want to be sure your wheels run at the same speed and cover the same distance: Monitor the body of the differential and slow the left or right wheel appropriately to keep it stationary. See Chapter 8 for a practical application of this trick.

Summary

Few pieces of machinery can exist without gears, including robots, and you ought to know how to get the most benefit from them. In this chapter, you were introduced to some very important concepts: gear ratios, angular velocity, force, torque, and friction. Torque is what makes your robot able to perform tasks involving force or weight, like lifting weights, grabbing objects, or climbing slopes. You discovered that you can trade off some velocity for some torque, and that this happens along rules similar to those that apply to levers: the larger the distance from the fulcrum, the greater the resulting force.

The output torque of a system, when not properly directed to the exertion of work, or when something goes wrong in the mechanism itself, can cause damage to your LEGO parts. You learned that the clutch gear is a precious tool to limit and control the maximum torque so as to prevent any possible harm.

Gears are not the only way to transfer power; we showed that pulley-belt systems, as well as chains, may serve the same purpose and help you in connecting distant systems. Belts provide an intrinsic torque-limiting function and do well in high-speed low-torque situations. Chains, on the other hand, don't limit torque but do increase friction, so they are more suitable for transferring power at slow speeds.

Last but not least, you explored the surprising properties of the differential gear, an amazing device that can connect two wheels so they rotate when its body rotates, still allowing them to turn independently. The differential gear has some other applications, too, since it works like an adder-subtracter that can return the algebraic sum of its inputs.

If these topics were new to you, we strongly suggest you experiment with them before designing your first robot from scratch. Take a bunch of gears and axles and play with them until you feel at ease with the main connection schemes and their properties. This will offer you the opportunity to apply some of the concepts you learned from Chapter 1 about bracing layers with vertical beams to make them more solid (when you increase torque, many designs fall apart unless properly reinforced). You won't regret the time spent learning and building on this knowledge. It will pay off, with interest, when you later face more complex projects.