LEGO Gears and Motors

Motors are devices that convert electrical energy into mechanical movement. For a motor of a given design and operating voltage (LEGO motors are designed to operate at 9 volts) there is a maximum rate at which electrical energy can enter the motor and, because energy is "conserved", a maximum rate at which energy can be added to the mechanical system.

Consider the example below where a motor is used to lift an elevator. The (potential) energy of the elevator is equal to mgh, where h is it's height above the ground and m is its mass.

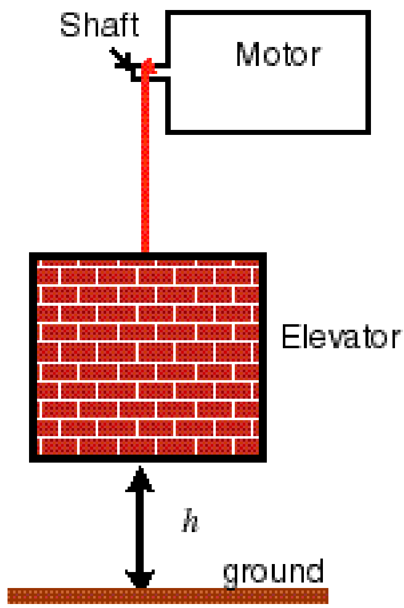


Figure 1

If h changes at a rate that is too big, then motor stalls, because electrical energy is not flowing into the motor fast enough to keep up with the demands of the mechanical system. (You might say, why doesn't the motor simply slow down, instead of coming to a complete stop? The answer lies in the fact that motors are designed to be most efficient when their output shaft spins at a certain, typically fairly high, speed. If they start slowing down, they become much less efficient, which leads to their slowing down even more. So things go from bad to worse quickly, and while a slightly overloaded engine will indeed spin slowly, stall conditions are quickly reached as the load increases.) The above example illustrates a *very general principle* that exists when using a motor to move something: There exists what we can call a:

"Stall Avoidance" vs. speed *tradeoff*

That is, to avoid stalling the motor, we must design our mechanical system so that the elevator is not required to rise "too quickly".

The concept of **tradeoffs** is one of the “big ideas” of engineering. Understanding this particular tradeoff is the key to the Vehicle Race Challenge.

A familiar example of this type of stall avoidance vs. speed tradeoff occurs when you cycle up a hill. If you try to climb too fast, the “motor” (*i.e.* the rider) stalls (collapses.)

Alternatively we can invoke the concept of **torque** = r x F to describe what’s going on. Torque is a measure of the ability of the force (F) to cause a body to rotate. Consider opening a door for example. How easy it is to open the door depends on the torque exerted, which in turn depends on how hard you push (F), how far from the door’s hinge you push (r) and the angle between F and the plane of the door. (Torque is maximized when F is perpendicular to the plane of the door.)

Motors (or cyclists!) can be characterized by the maximum torque they can exert without stalling. We can demonstrate this by grabbing the shafts on the gray motors and seeing what torque it takes to make them stall them. Or try climbing a steep hill on a bike without gears. Your leg is only capable of exerting a certain maximum torque on the pedals. And like a motor, your body is most efficient in turning the pedals at a certain fairly high cadence (around 60 rpm). On a bike without gears you won’t be able to keep up this ideal cadence on a steep hill without exceeding your maximum torque, (and collapsing).

Building a Gear Train

Use axles, beams, and gears to build a simple gear system using an 8-tooth gear and a 24-tooth gear. Start by meshing an 8-tooth gear with a 24-tooth gear as shown below:

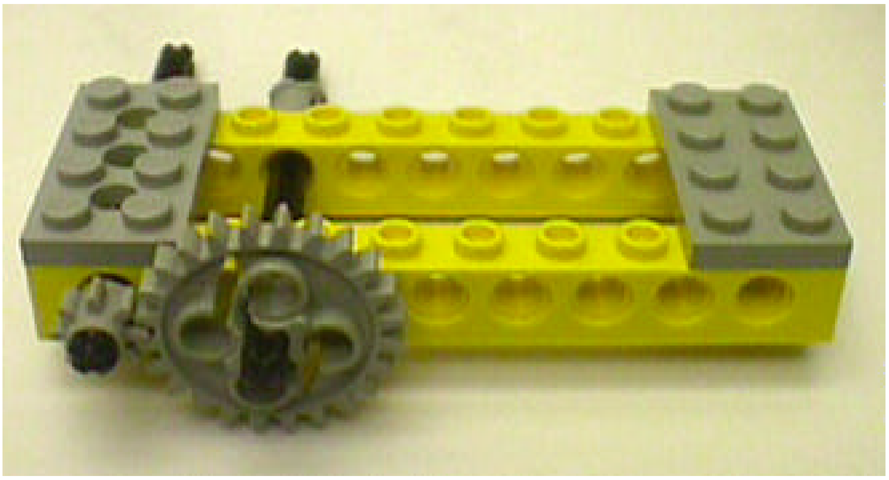


Figure 2 – The first stage of a simple gear train.

Try rotating the shaft with the small gear with your fingers. (That is, your fingers will play the role of the motor.) Note that the relative rate of rotation of the two axles is different, by a factor of three, which is equal to the ratio of number of teeth on the gears (24:8). (This is also equal to the ratio of the radii of the two gears.):

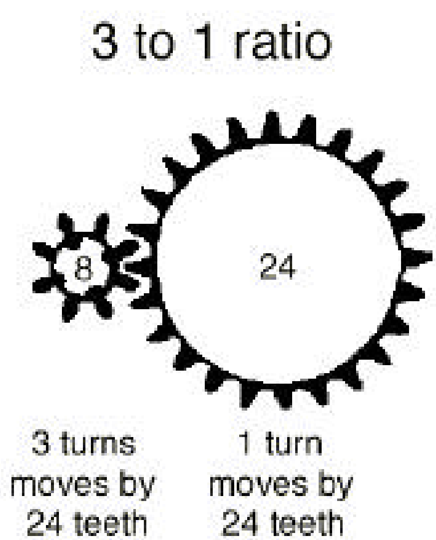


Figure 3- When the 8-tooth gear rotates 3 times, it advances the meshed gear by a total of 24 teeth. Since the meshed gear has a total, it rotates exactly once. Hence this configuration produces a 3:1 ratio of gear reduction.

In terms of torque, since the forces between the teeth of the two gears are equal in magnitude but act opposite in directions. (This is a direct consequence of Newton's 3^{rd} Law of Motion.) Therefore, the torque exerted on the right axle is three times the torque exerted on the left axle (since the radii of thee gears differ by a factor of three.) Thus this gear system as acts as a "torque converter", increasing the torque at the expense of decreasing the rate at which the axle turns.

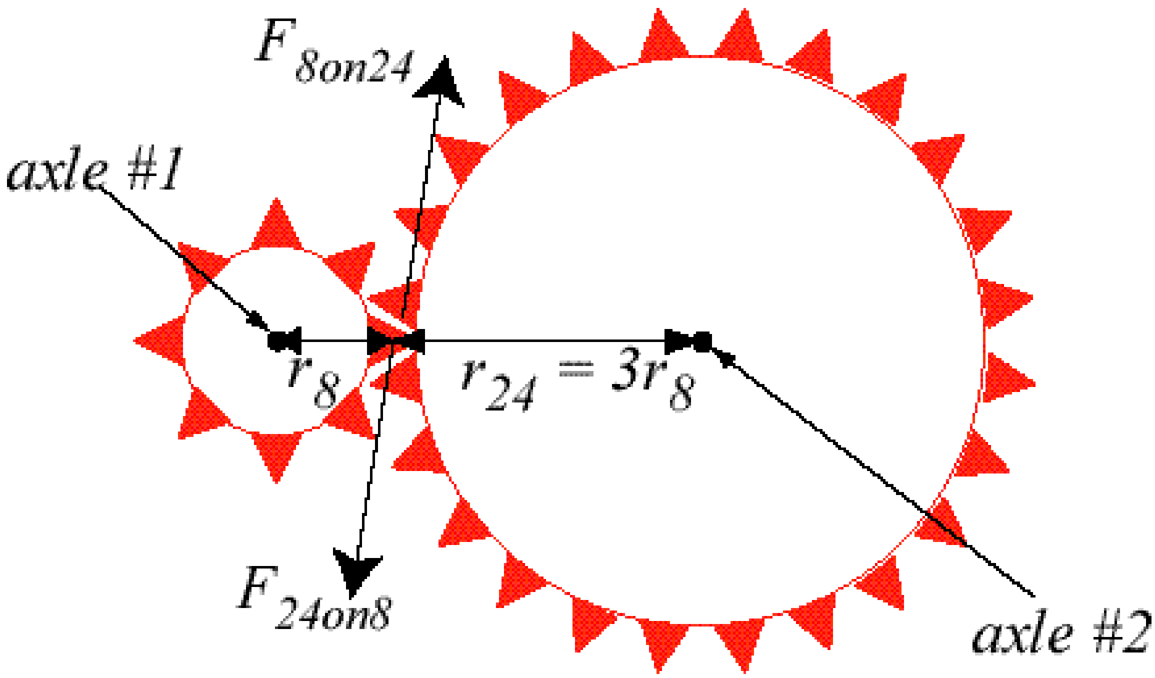


Figure 4 - Since torque = r x F, the torque about axle #2 is three times greater than the torque about axle #1; the gear train acts as a "torque amplifer".

Key Rule of Thumb:

Going from small gears to big gears increases the torque and lowers speed of rotation.

Gear Trains: Ganging Gears

Here’s an absolutely brilliant trick:

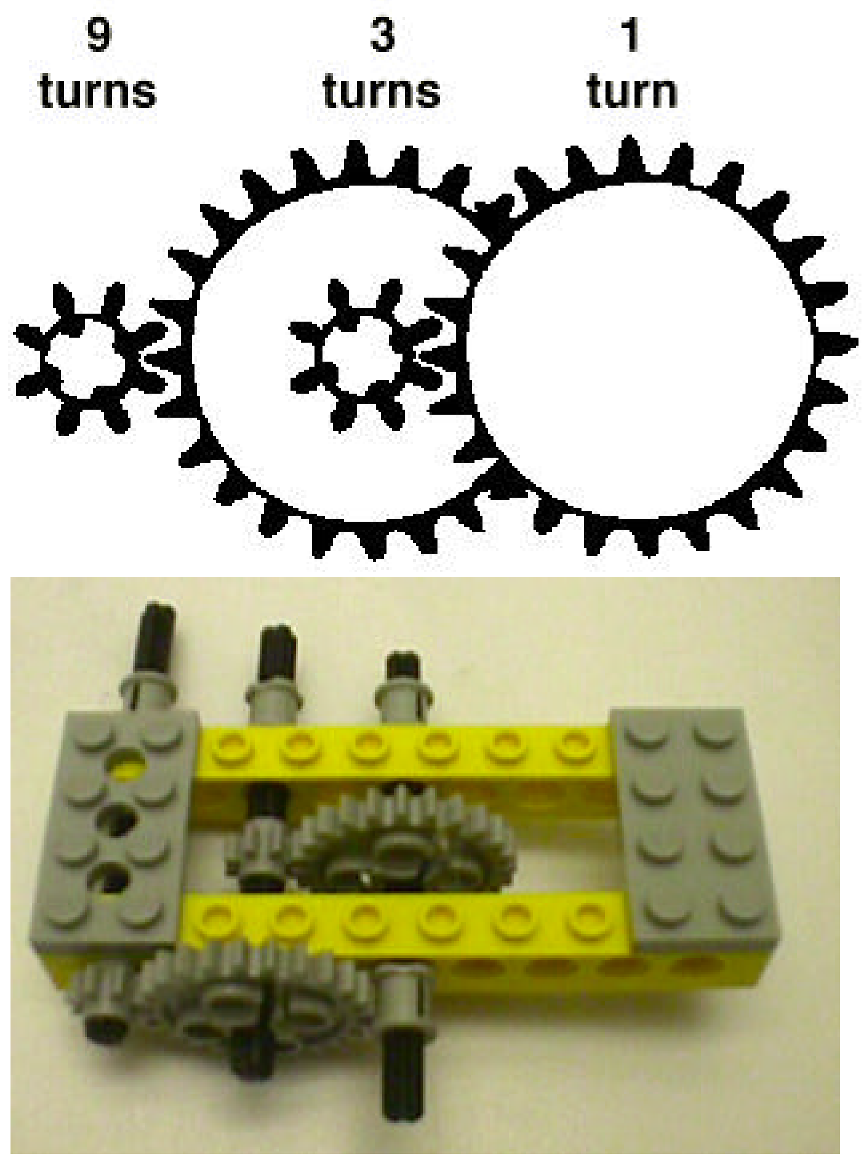


Figure 5 - By “ganging together” – or multiplying – two 3-to-1 gear reductions, a 9-to-1 output reduction can be achieved. The key is to use intermediary shafts that hold both a large input gear (e.g. a 24-tooth) and a small output gear (e.g. an 8-tooth).

So now the torque at the “output shaft” is *9 times* the torque provided on the left (‘input”) axle. The output shaft will of course spin 9 times slower than the input shaft, but it will be much harder to stall. Have someone grab the output shaft and try to “stall” your fingers as you spin the input axle. It’s not that easy!

Of course, once you have discovered a great idea, you might as well keep using it!. Try building an additional stage of gear reduction:

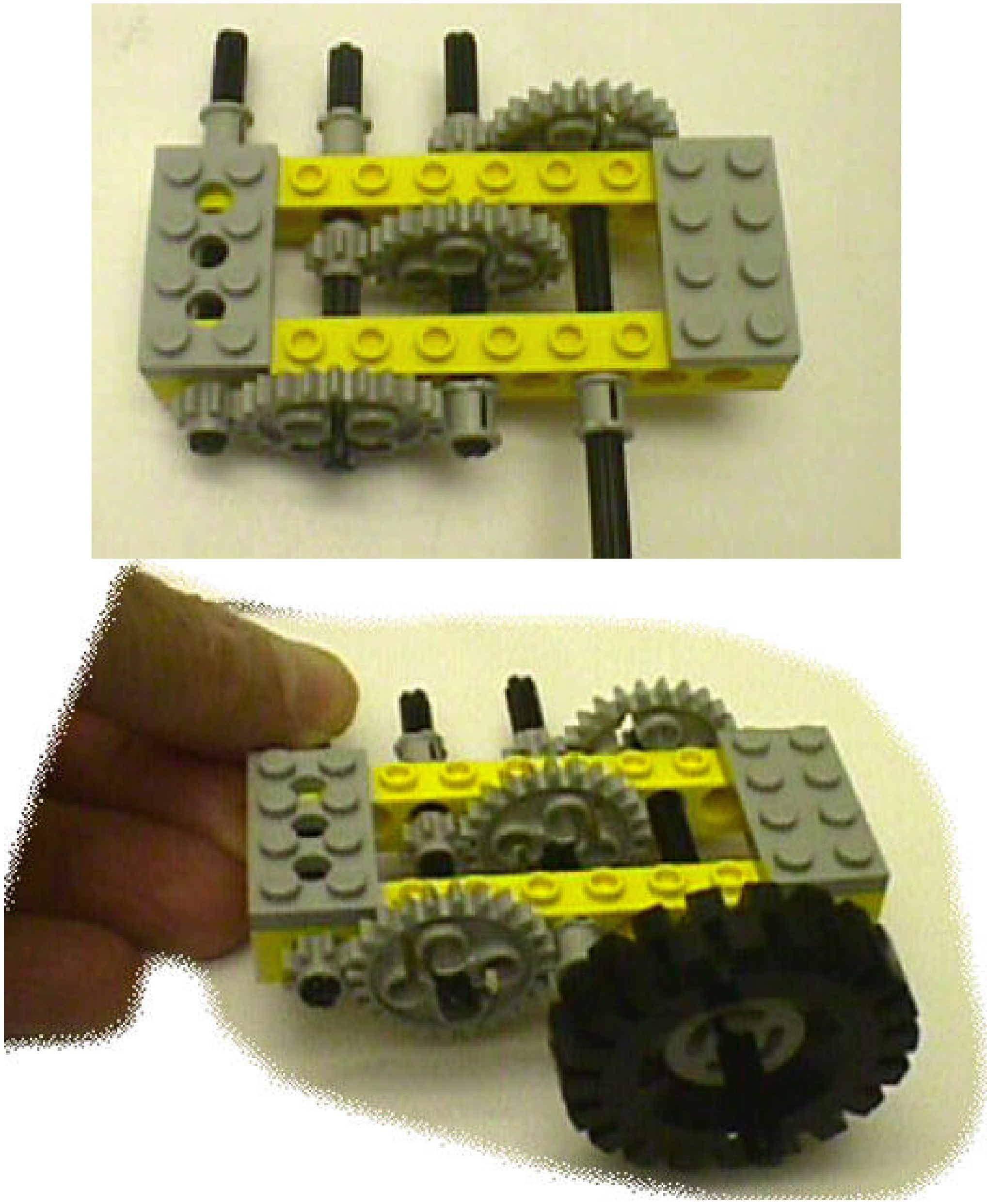


Figure 6 – A three stage gear train with a gear ratio of 27:1.

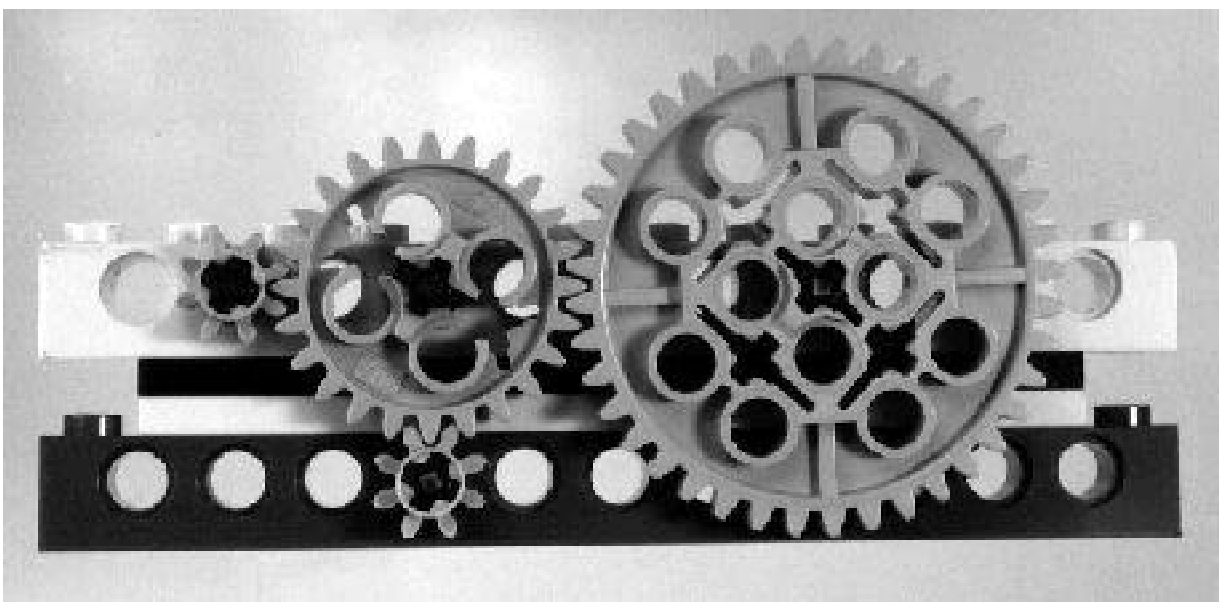
Building Tips:

- adjust “bushings” so they’re not too tight, not too loose
- build a square and rigid frame so that the holes in the beams remain lined up.
- support the axles in at least two places so that they don’t bend.
- The LEGO gears are sized so that they mesh nicely in “horizontally” aligned holes as shown above:

Number of teeth	Radius (in FLUs)
8	0.5
16	1.0
24	1.5
40	2.5

Table 1 – Radii of standard LEGO gears (in FLUs)

By use of plates, it is also possible to mesh gears in the vertical direction:



LEGO Motor Varieties

Red "micromotors" – relatively low power but high torque, since they have internal gearing inside the red box (amazing!)

Old Gray Motors - Much higher power than the micromotors but output shaft is high speed / low torque. You need to build gear trains to use them!

New Gray Motors (Gear Reduction Motors)- The best of both worlds! Similar in power to the old gray motors, but with internal gearing so that the output shaft speeds at a decent rate with lots of torque. You'll need less in the way of gear trains when you use them!

Challenges

Challenge: LEGO Design Clichés (Constructopedia)

Try building some things in the Constructopedia poster.

Challenge:

Build a vehicle that uses one old gray motor powered by a single Handy Board and carries a 1.0 kg mass to compete in a 2 meter "drag race". Understanding gear trains and the "power vs. speed tradeoff" are critical to doing well in this challenge.

An important part of engineering is the idea that one is continually looking for ways to improve upon a design. To foster this kind of "iteration", we will have a preliminary race today, followed by the "finals" tomorrow.