Using LEGO® Gears

TJ Avery, c. 2001
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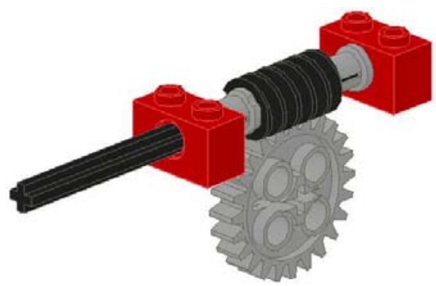
This is a simple guide to using LEGO® gears based on my experience. In my experience, I've had gears crack apart, wear down, and suffer mashed teeth because of high torque applications. I believe the key to using gears without damaging them is to control your torque and speed, and use the appropriate gears for the given situation.

I. Worm Gears

Worm gears are NOT well suited for high torque applications



There is a lot of friction (and potentially destructive friction) between a worm gear and 1) the gear being driven by the worm gear, and 2) the supports keeping the worm gear in place (i.e. the red Technic bricks in the figure above). When used in high torque applications, a few bad things happen:

1) The friction causes wear on the gear teeth. You will notice a gray powder after operating the gear set for a while. The excessive friction grinds the teeth and wears them down.

2) The worm gear is forced axially (i.e. in-line with the axle the worm gear is on) into its supports. The worm gear is pushed into whatever is restraining it from sliding off the axle it is on. If the torque is high enough, the restraining surface (usually a Technic brick with a hole) will be eroded, or ground into "dust".

3) Excessive heat can build up and melt the plastic. I haven't experienced this, but I've heard that if a worm gear is operated for a long time with enough torque, it can heat up enough to melt or at least permanently distort the plastic.

Using worm gears safely and effectively

Worm gears have two characteristics that make them very useful:

1. They offer a large ratio of gear reduction in a relatively small amount of space.
2. They prevent the gear train from turning back on itself, i.e. you can rotate the worm by turning the shaft it is on, but you cannot rotate the worm by turning the gear underneath – that gear is effectively frozen (this is particularly useful for applications such as a winch).

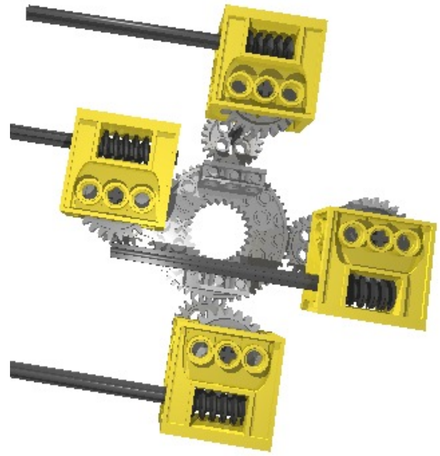
Using worm gears should be fine for low torque applications. If you have to use it for high torque applications, then don't operate it for very long. If you have to use them extensively, do it in short time intervals, or short "bursts", and take breaks to let things cool down (but you'll still likely have gear erosion).

Example 1

The figure below shows the gear train for the turntable of my marine pedestal crane. The main turntable gear is driven by 4 sets of 24t gears, each one being driven by a worm gear (and the worm gears are each driven directly by geared 9V motors).

This application of worm gears could be problematic if the system is loaded (i.e. the motors approach stall torque). However, two things made this set up work without noticeable gear erosion:

1. The crane turntable was operated in bursts no longer than a few seconds, so it didn't have time to heat up.
2. The load was distributed amongst 4 worm gears. I could have used two or even one, but then the torque required would have greatly increased, thus posing a danger of erosion or even gear breakage.

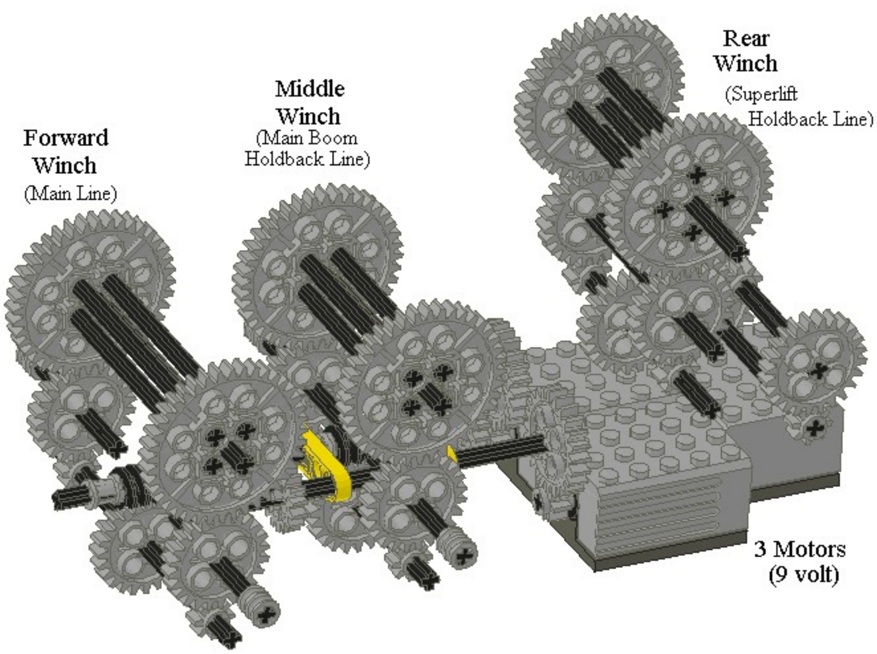


Turntable gear for the marine pedestal crane

Example 2

I used worm gears in the gear trains for the winches in a crawler crane I built a long time ago. I operated the model for long periods of time (~15 minutes) and experienced the erosion problems described earlier.

I discovered little piles of gray dust inside the model near the gear sets.



Isometric view of the winch assembly on my crawler crane – note the worm gears that drive the forward and middle winches. The motors used here are the old non-geared 9V style, this model was built a long time ago ☺

Worm gear misc.

Because of the high friction involved, worm gears are very inefficient.

When meshing two spur gears, the involute (complex curved surface) shape of the gear teeth reduces (or theoretically eliminates) sliding between the surfaces of the meshing teeth. Therefore you have negligible friction.

But worm gears do not mesh like spur gears. When meshing a worm gear with a spur gear, the surface of the worm's helical teeth slide against the radial teeth of the spur gear (24-toothed, 40-toothed, etc.). This sliding causes a lot of friction.

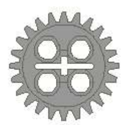
II. Spur Gears

General note on gears and friction

I think the most efficient way to gear-down using LEGO parts is to use as few sets of spur gears as possible (i.e. the 8, 16, 24, or 40 toothed gears). There are also newer 12, 20, and 36 toothed gears that can be used as spur gears.

You can compare the efficiency in using different combinations:

- three sets of 8 and 24 toothed gears makes a gear train with a 1:27 reduction.

 and 

- two sets of 8 and 40 toothed gears makes a gear train with a 1:25 reduction.

 and 

For similar reduction ratios, using only 8 and 40 toothed gears result in having only two sets of gears and less friction than using three sets of 8 and 24 toothed gears. Remember, each time you have a set of gears meshing together, it introduces friction and inefficiency into the system.

Using gears in high speed can cause erosion

(note this applies to the old style 4.5V and 9V motors that do NOT have internal gear reduction)

When gearing down a normal motor (i.e. a regular, non-geared 9V or an old 4.5V), the first few reducing gear sets nearest to the motor axle will slowly erode. You will notice the gray dust after operating the motor for a while. Again, on my old crawler crane I noticed the gray dust on the first few reducing gear sets at the output axle of the motor. The gear teeth were noticeably worn down (see arrow in graphic below).

Using gears in high torque applications

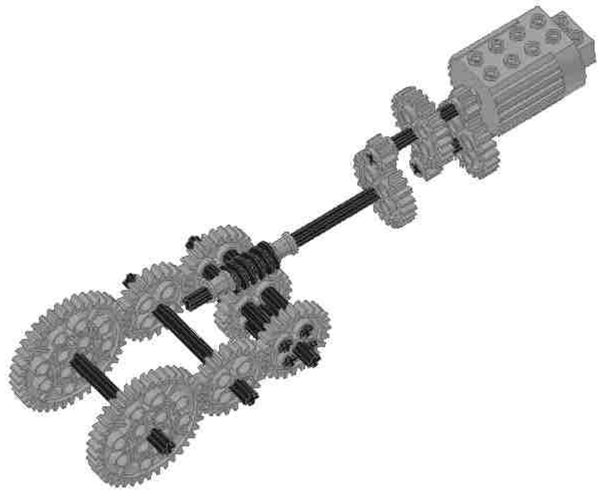
Similar to using the worm gear, do it only in short bursts and avoid prolonged operation. This is a little outdated now, since most LEGO motors come with internal gear reduction that effectively eliminates the set of reducing gears that would normally see such high speeds.

After my experience with eroding gears in the late 90's, LEGO started producing efficient 9V motors that contained internal gear reduction.

These motors were (and still are if you have still have some ☺) great to use. Now, there is a new generation of 9V motors in the Power Functions system. The PF motors all contain an internal set of reducing gears.

"High torque"?

"High torque", a term I've been using in this article, is a little subjective. High torque conditions are basically experienced when using large gear reduction ratios and also loading up the output shaft of the gear train (and by "loading", I mean stalling, or nearly stalling, the motors).



The above picture is the gear train (1:1080 ratio) from the crawler tracks of my old crawler crane. The 40 toothed gears were the driving gears connected to the dual crawler tracks. You can imagine that moving the whole crane put a very high load on this gear train.

The 24 toothed gear that is being driven by the black worm gear broke. You'll notice extra axles connecting the 3 24-toothed gears. This was done later to help distribute the torque and prevent gear breakage.

Today's equivalent of this particular gear train would see one geared 9V motor applied and the elimination of the first three reduction stages (i.e. take out the first three sets of 8t and 24t gears). But then if I had to do this again, I would not use a worm gear ☺

III. Gear breakage

24 toothed gears

I've broken them (the old-style ones) at a ratio of 1:648 (using an old 4.5v motor).

Note on pictures: On the gear on the right, notice that the center axle support has been badly warped, causing the axle to slip out of the gear. The gear now has an oval shape. Also notice a small crack that has developed between the teeth at the bottom.

Broken old-style 24t gears (note that this style gear effectively had 3 axle holes)

The newer style of 24t gears are much stronger. This is apparent just by looking at them and comparing them with the old design (there is only ONE axle hole in the new design). I have now discontinued using the old style 24t gears in all my models.

Newer style 24t gear (note only one axle hole)

8 toothed gears

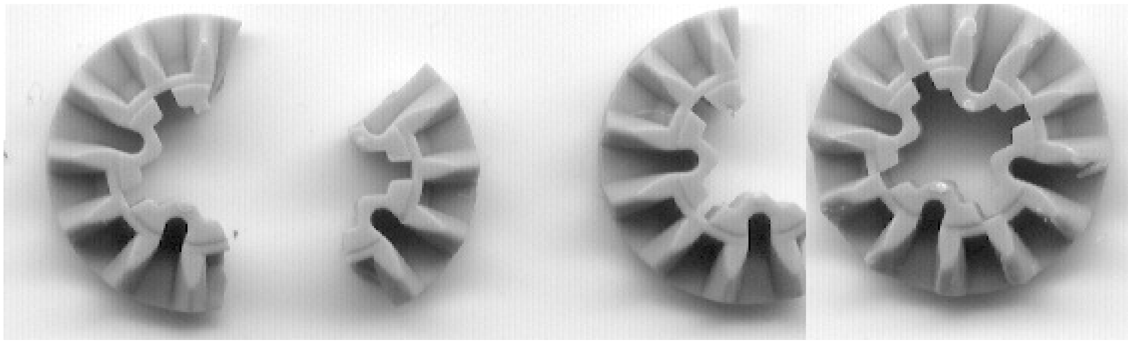
- For ungeared motors, I wouldn't use them at ratios 1:500 or greater (driven by one motor).
- For geared 9v motors, I've broken them at a ratio 1:40.5 (driven by one motor).

Broken 8t gear

12 toothed bevel gears

These gears are relatively weak. I've broken them at a ratio of 1:27 (driven by two geared 9v motors). If driven by one geared 9v motor, I estimate breakage to occur at a ratio of 1:54.

Note on pictures: On the gear on the right, notice that some of the teeth have been mashed down. This was caused by meshing with another 12 toothed bevel gear, which received similar damage, at high torque.



Note: If you have a need for bevel gears in a high torque gear train, try using the 12-toothed "double bevel" gears (the ones that are 1-stud thick). They are a little stronger.

General Note On Above: It's difficult to provide a guide to recommended maximum torque per gear size. Therefore I've simply stated the conditions in which each gear failed. Gears of the same size will vary in strength such that one set of gears may fail in a given situation, whereas another set may hold up. Also, it's difficult to account for power losses in a gear train so the torque could vary between different constructions (i.e. gear train #1 produces greater torque than gear train #2 at the same reduction ratio just because they're set up differently).

