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# The Art of LEGO Design

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There is a real need for better resources for both fledgling and intermediate LEGO builders. The plans that the LEGO company distributes with its kits are very good at showing how to build specific models, but not so good at teaching how to design from one's own ideas. At the MIT Media Laboratory, we're working on a project we call the *LEGO Constructopedia*, a hypermedia resource for LEGO designers that will include LEGO building plans, design principles, textual descriptions, and rendered animations, all interlinked, indexed, and browsable. The project is just beginning and is still in the conceptual stages; this article is my attempt to present some of the content of our proposed LEGO Constructopedia in a more traditional form.

The article begins with an analysis of the structural principles of the LEGO system, continues with a discussion of gears, gear reduction, and geartrains, and finishes with a visual assortment of various building tricks or "clichés." Interspersed throughout are numerous diagrams and sample models to illustrate the ideas being presented. I hope that LEGO aficionados at all levels from novice to expert will find something of interest here.

## Structure

### The Vertical Dimension Relation

Let's begin by examining the LEGO brick in detail. Most people realize that the LEGO brick is not based on a cubic form. The height of the brick is a larger measure than the length and width (assuming the normal viewpoint of studs on the top). But few people know the secret relationship between these dimensions: the vertical unit is precisely 6/5 times the horizontal ones. Put another way, a stack of five LEGO bricks is exactly equal in height as a six-stud LEGO beam is long.

The origins of this obscure relationship remain shrouded in mystery, but it has real practical value: by building structures with vertical heights equal to integral horizontal lengths, it is possible to use beams to brace LEGO constructions. This technique is greatly facilitated by the one-third-height plates, which allow a number of vertical spacing possibilities.

The most common trick is to create two horizontal units of space in the vertical dimension by separating two beams with two plates (Figure 1). This $1\frac{2}{3}$ vertical measure is two units of horizontal measure since $1\frac{2}{3}$ times the conversion factor of 6/5

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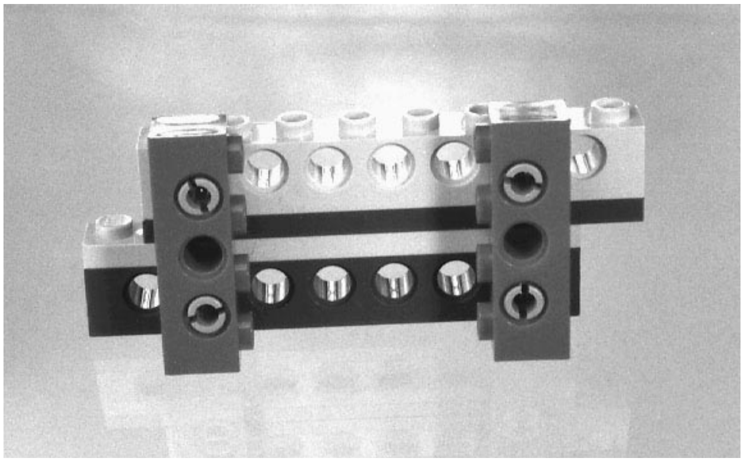


Two beams are separated by two $\frac{1}{3}$-height LEGO plates, creating a vertical interval of $1\frac{2}{3}$ units, which is equal to 2 horizontal units. Hence the beams can be locked into place using cross-beams and connector pegs—*the* way to make your LEGO construction quite sturdy.

Figure 1: Two Beams Locked Using $1\frac{2}{3}$ Vertical Spacing Relation

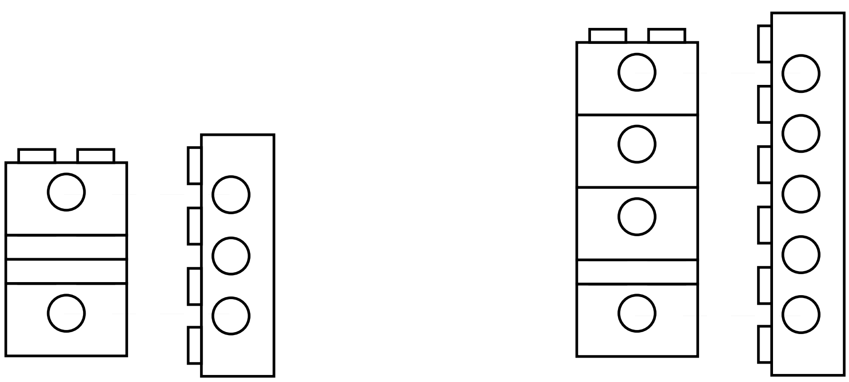


Figure 2: Creating Vertical Spacings with Two-Unit and Four-Unit Horizontal Measures

The black connector peg vs. the gray connector peg: what is the difference? The answer is that the black peg is *slightly larger*, so it fits quite snugly in the beam hole, while the smaller gray peg rotates freely. Use the black pegs to binding structures together, as suggested by the discussion on locking cross-beams, and use the gray peg when making hinged joints.

Figure 3: Black Connector Peg Versus Gray Connector Peg

equals 2. Another useful pairing is $3\frac{1}{3}$ vertical units (i.e., two beams separated by two beams/bricks and one plate) which equals 4 horizontal units (see Figure 2).

In addition to constructing perfect spacings vertically, it's possible to make diagonal braces. A 3-unit horizontal spacing with a 4-unit horizontal spacing vertically yields a 5-unit diagonal by the Pythagorean relation. This is an example of a perfect diagonal spacing, but near-perfect spacings that are "close enough" exist. Experiment, or spend some time thinking about the numbers.

Figure 1 shows the practical application of this dimensional relation: two beams locked together with cross-beams and connector pegs. You can use the vertical spacing trick for at least two purposes. First, use it to lock vertical structures on LEGO machines in place with beams and connector pegs (see more about connector pegs in Figure 3). Second, create vertical spacings that are the right intervals to allow gears to mesh properly (more on this later). This trick will go a long, long way in making sturdy, reliable LEGO designs.

## Gearing

Turn on a small DC motor, like the stock LEGO motor, and what do you get? The shaft spins really fast, but with almost no torque (turning force). You can easily pinch the shaft with your fingertips and stop the motor from turning.

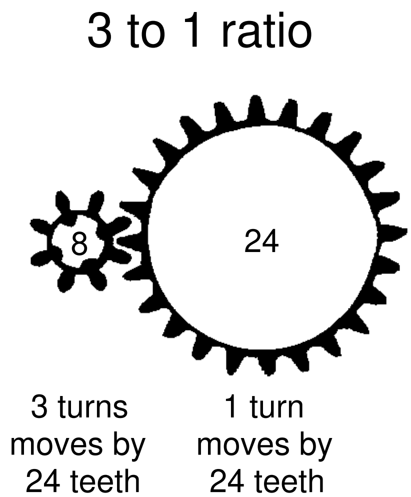
Through the magic of gear reduction, this fast-but-weak motor energy can be transformed into a strong but slow rotation, suitable for powering wheels, gripper hands, elbow joints, and any other mechanism. Along with structural issues, building effective geartrains is the other half of the challenge of creating working LEGO machines.

### Counting Gear Teeth

Gear reduction is achieved by intermeshing gears of different sizes with compatible teeth. Figure 4 shows the effect of meshing an 8–tooth gear with a 24–tooth gear. When the 8–tooth gear rotates three times, it has advanced the 24–tooth gear one revolution. Hence this configuration produces a 3-to-1 gear reduction ratio.

More gear reduction can be achieved by meshing gears with greater disparities of teeth count. Using the LEGO 8–tooth and the LEGO 40–tooth gears produces a 5-to-1 reduction. But the more general solution is to gang together—or multiply—single pairs of gear reduction. Figure 5 shows how two 3-to-1 reductions may be ganged to produce a 9-to-1 reduction, by using a shaft that holds a 24–tooth input gear *and* an 8–tooth output gear.

The gear ganging concept is the foundation of gear trains. Figure 6 shows a model LEGO gear train that produces a 243-to-1 reduction from the motor shaft to the output wheel. The example is a bit of overkill—this much reduction will




When the 8–tooth gear rotates 3 times, it advances the meshed gear by a total of 24 teeth. Since the meshed gear has 24 teeth, it rotates exactly once. Hence this configuration produces a 3:1 ratio of gear reduction: three turns of the input gear causes one turn of the output gear.

Figure 4: 3-to-1 Gear Reduction Ratio

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 large input gears (e.g., a 24–tooth) and small output gears (e.g., an 8–tooth).

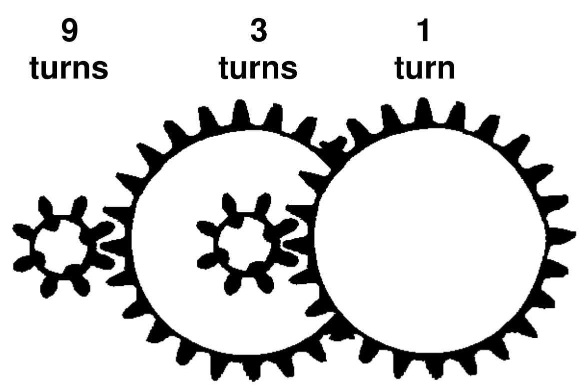
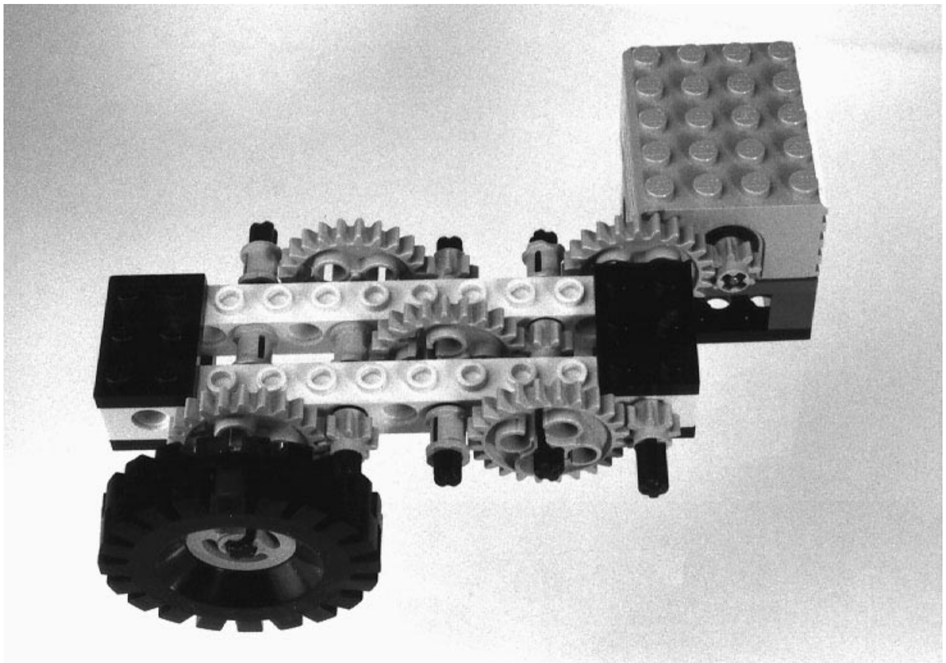



Figure 5: 9-to-1 Gear Reduction with Ganging



A five-stage reduction using 8– and 24–tooth gears creates a 243-to-1 reduction in this sample LEGO geartrain. Note the need for three parallel planes of motion to prevent the gears from interfering with one another. Four 2×3 LEGO plates are used to hold the beams square and keep the axles from binding.

Figure 6: Sample LEGO Geartrain

produce too slow a final rotation for the typical robot drive train—but it serves to illustrate the point.

When I present gear reduction to kids, I find it difficult to give a direct explanation of why it works. More precisely, by counting teeth it's evident enough that subsequent gears run slower, but why do they have correspondingly more torque? I generally appeal to a vague "energy must be conserved" line of reasoning. Ultimately, there's no substitute for holding a live geartrain in your hand and feeling the power as gear reduction does its work.

## The Worm Gear

The worm gear is a fascinating invention, sort of a Mobius strip in the world of gears. When meshed with a conventional round gear, the worm creates an *n*-to-1 reduction: each revolution of the worm gear advances the opposing gear by just one tooth. So, for example, it takes 24 rotations of the worm to revolve the 24–tooth round gear once. This forms quite a

The worm gear is valuable because it acts as a gear with one tooth: each revolution of the worm gear advances the round gear it's driving by just one tooth. So the worm gear meshed with a 24-tooth gear (as pictured) yields a whopping 24 to 1 reduction. However, the worm gear loses a lot of power to friction, so it may not be suitable for high performance, main drive applications.

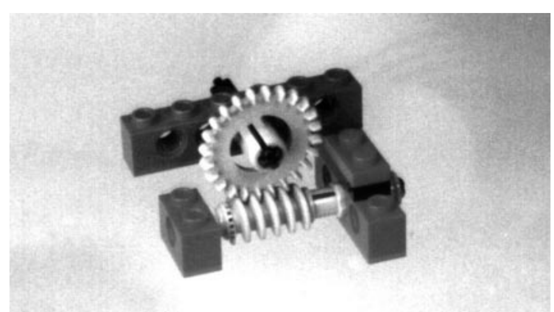
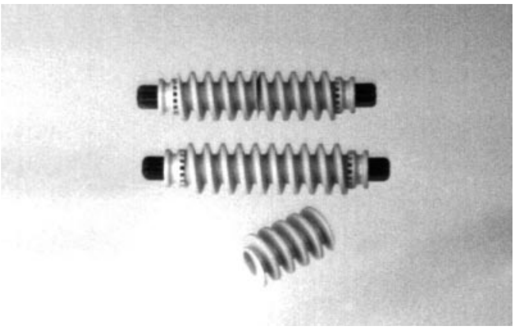


Figure 7: Using the Worm Gear



This diagram shows an arrangement of worm gears. At the bottom is the basic worm gear, two horizontal LEGO units in length. At the top is an unsuccessful attempt to put two worm gears on the same shaft. In the middle is the successful attempt. When placing multiple worm gears on a shaft, the trick is to try all four possible orientations to find the one that works.

Figure 8: Multiple Worm Gears on One Shaft

compact gear reduction—it would take about three gangs of the 3-to-1 reduction, forming a 27-to-1 relation, to do the same work as a single worm meshed with a 24–tooth round gear.

There is a drawback, however. The worm gear uses predominantly sliding friction when advancing the teeth of the round gear. The teeth of round gears are generally designed to minimize sliding effects when they are meshed with each other, but there's no getting around the problem with worm gears.

Thus worm gears create more frictional losses than round gears. At higher torques they have a tendency to cause a geartrain to stall. If your robot's too heavy, a worm gear drive may not work well as its main drive.

Worm gears have another interesting property: they can't be back-driven. That is, if you rotate the gear being driven by a worm, you'll just push the worm gear forward and back along its axle, but you won't get it to turn. Take advantage of this property. For example, if a worm gear is used to raise an arm lifting a weight, then the arm won't fall down after power is removed from the motor.

Figure 7 shows how to mesh a worm gear to a round gear, and Figure 8 illustrates putting two LEGO worm gears onto the same shaft.

## Changing Axis of Rotation

In a geartrain with only round gears, all of the axles must be mutually parallel. With the worm gear, the output round gear's axis of rotation is at right angles to the worm's. Two other kinds of gears, the *crown gear* and *bevel gear* are available in the LEGO kit for changing the axis of rotation within a geartrain.

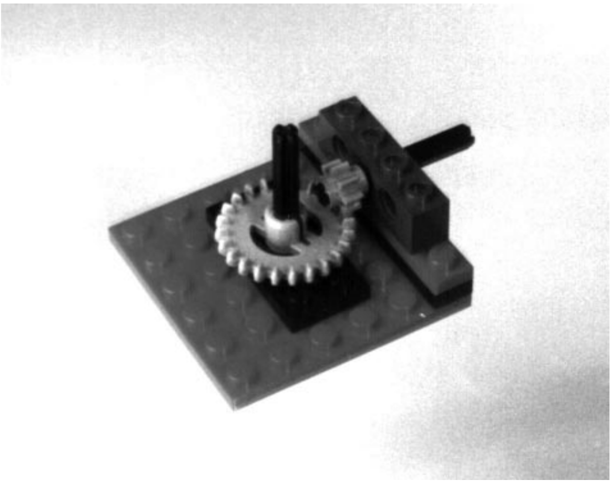
### The Crown Gear

The crown gear is a round gear that is specially designed to mesh at right angles to the standard round gear (Figure 9). In the diagram, the crown gear is shown meshing with the 8–tooth gear. Meshing to the round 24–tooth and 40–tooth gear is also possible, though using the 8–tooth to drive the 24–tooth crown gear is an effective way to build in a gear reduction while changing the rotation axis.

The 24–tooth crown gear is the same size as the standard 24–tooth round gear, so it can be used as a replacement for that gear when a parts shortage occurs.

### The Bevel Gear

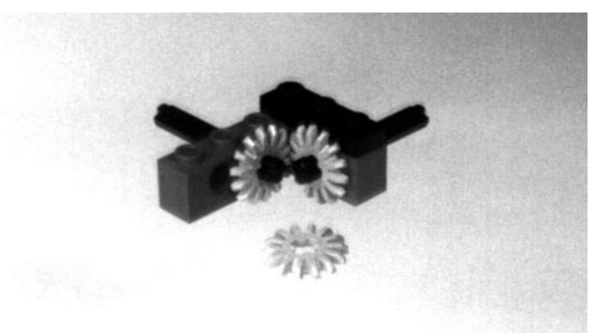
The bevel gear is used in pairs to provide a similar function to the crown gear, though without the capability for gear reduction. There are two styles of bevel gear: the older style (Figure 10), which is fairly flat, and a newer style, which is



The 8–tooth gear, in conjunction with the 24-tooth *crown gear*, is used to change the axis of rotation in a gear train.

In this instance, the configuration provides for a vertical shaft output. Horizontal output also possible.

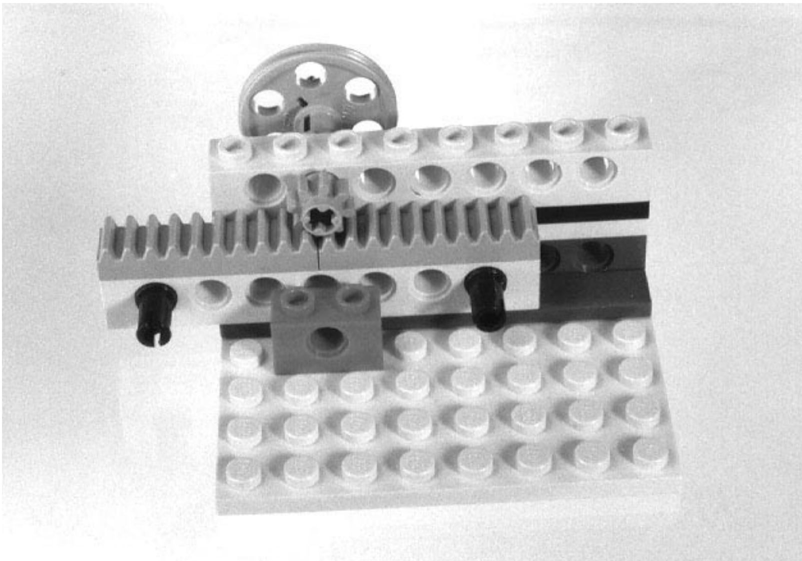
Figure 9: 8–Tooth Gear Meshing with Crown Gear



The bevel gears are used to change the angle of rotation of shafts in a gear train with a 1:1 ratio. In this case, they are used to effect a change in the horizontal plane.

This picture shows the older-style bevel gears, which have limited usefulness due to their relatively high friction and lack of strength. The newer bevel gears are thicker and perform much better.

Figure 10: The Bevel Gear



The gear driving the gear rack is often referred to as the "pinion," as in "rack-and-pinion steering," which uses the transverse motion of the gear rack to orient wheels. The 8–tooth gear is a good candidate to drive the rack because of the gear reduction it achieves—one revolution of the gear moves the rack by eight teeth.

Figure 11: Using the Gear Rack

the same diameter but thicker. The old style bevel gear is somewhat flimsy and lossy and is not suitable for delivering larger torques. The new bevel gear is a significant improvement.

Old style bevel gears can be put to good use by serving as stop bushes (Figure 15).

## The Gear Rack

The gear rack is a like a round gear unrolled and laid out flat. When driven by a round gear (the 8–tooth usually works best), it traverses back and forth in a linear motion (Figure 11).

Gear racks can be laid end-to-end to make longer stretches of motion. Underneath a beam driven by gear racks, use the smooth-topped LEGO plates as a surface for the beam to slide on.

## Practical Hints

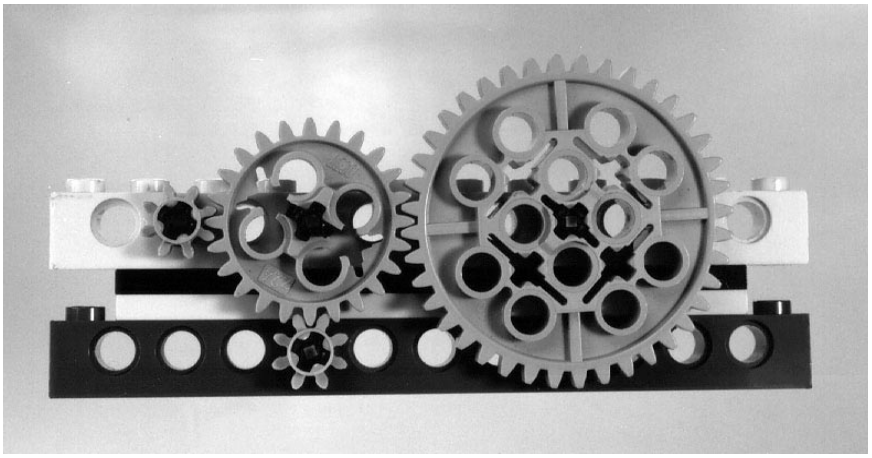
For the remainder of this section on LEGO gearing, I'll present a number of assorted tips to assist in your geartrain designs.

### Gear Sizing

It is helpful to know the sizes of the standard gears. This links back to the earlier section on the LEGO dimensional relation—creating unit horizontal spacings in the vertical dimension can be used not only to lock structures into place, but to mesh gears properly above and below one another.

Of the four round gears, three of them—the 8–tooth, the 24–tooth, and the 40–tooth, have a radius that is a whole number of horizonal LEGO units *plus one-half of a unit*. Therefore, these three gears form an whole-unit spacing when their radii are added—i.e., when they are meshed together in a geartrain.

For example, the 8–tooth gear has a radius of one-half of a unit, and the 24–tooth, $1\frac{1}{2}$ units, so when properly meshed together, their centers are spaced at two horizontal units. A spacing of two horizontal units is readily available on LEGO beams, or can be constructed using the $1\frac{2}{3}$ vertical spacing relationship discussed earlier. Figure 12 shows how the three half-radii gears mesh with one another.



The 8–tooth, 24–tooth, and 40–tooth round gears all mesh properly along a horizontal beam because they have "half unit" radii. For example, the 8–tooth gear has a radius of $\frac{1}{2}$ LEGO units, and the 24–tooth gear, $1\frac{1}{2}$ units, so they mesh at a spacing of two horizontal LEGO units.

The example shows the 8– and 24–tooth gears meshed horizontally at two units, and, using the $1\frac{2}{3}$ vertical spacing trick, vertically as well (a common and useful configuration).

Figure 12: The Half-Radius Round Gears

The 16–tooth gear, on the other hand, has a radius of one LEGO unit, so it meshes properly only with itself (at the standard horizontal unit spacing). A pair of two 16–tooth gears thus requires a space of two LEGO units, which happens to be the same interval as the pair of an 8–tooth and a 24–tooth gear. Thus these respective pairs of gears may be easily interchanged—a useful trick for adjusting the performance of an existing geartrain without a performing major overhaul (Figure 13).

### Odd Gear Spacings

It's possible to mesh gears at odd spacings using diagonal mounting. Generally, the gears work better when slightly too far apart than when too tight, which causes them to bind.

Many combinations are possible when creating a space diagonally, and some of them work. For example, and 8– and 16–tooth gear will function when spaced along the diagonal of one horizontal unit and one vertical unit.

An interesting exercise is to calculate the effective spacings (in horizontal units) of various diagonal measures using the Pythagorean formula, and then see which come close enough to a pairing of gears to be useful. But I suggest experimentation.

### Supporting Axles

It's important to keep axles well-supported in a geartrain. Practically, this means using at least two beams to carry the axles. More importantly, all beams with common axles running through them must be held together squarely. If the beams not held together, the axles will bind and lock up inside the beam-hole bearing mounts.

As suggested in Figure 14, use the $2\times$ parts, not the $1\times$ parts, to hold beams in place. Figure 6, the sample geartrain, uses $2\times3$ plates to squarely support the beams.

### Using Stop Bushes

The stop bushes, or axle holders, are to keep axles from sliding back and forth in their mounts. In addition to the standard full-width stop bush, the small pulley wheel and the bevel gear may be put into service (Figure 15).

The 16–tooth gear has a radius of 1 LEGO unit, so two of them mesh properly together at a spacing of two units (left side of diagram). Since an 8– and 24–tooth gear also mesh at two-unit spacing, these respective pairs of gears can be swapped for one another in an existing geartrain—a handy way to change the performance of a geartrain without rebuilding it from scratch.

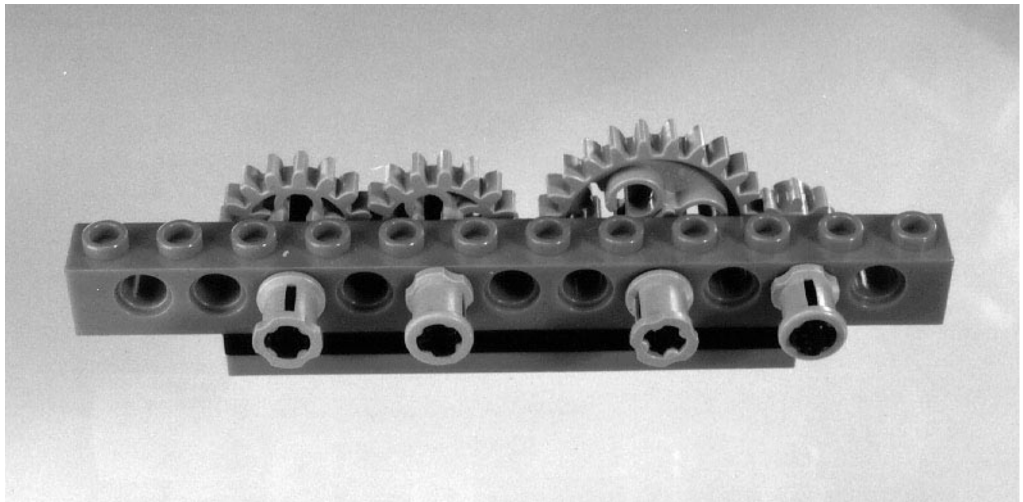


Figure 13: The 16–Tooth Gears

It seems like an obvious point, but using the 2× parts to hold beams parallel is quite important when the beams will be carrying common axles. If beams are not held squarely, the axles will bind and freeze inside the beam-hold bearing supports.

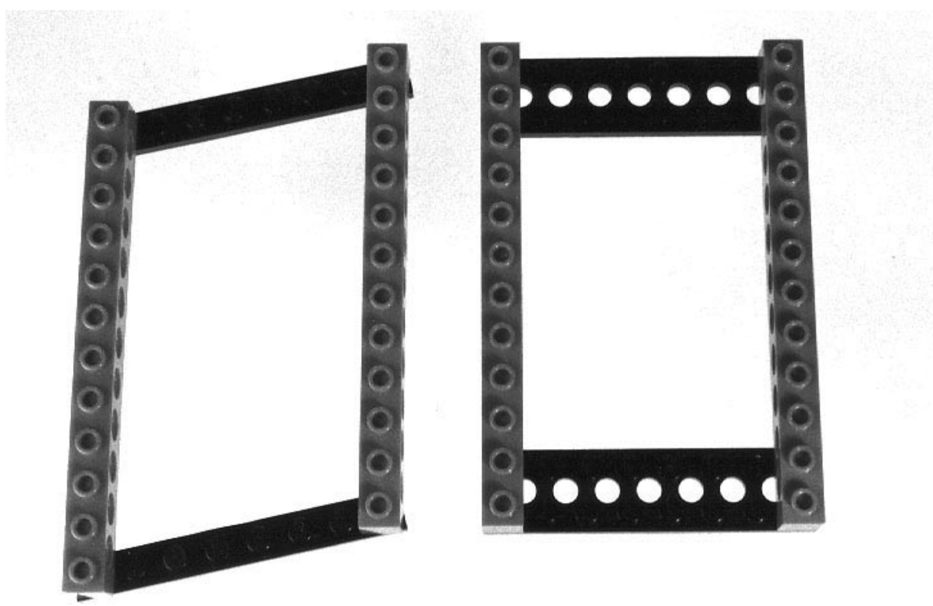
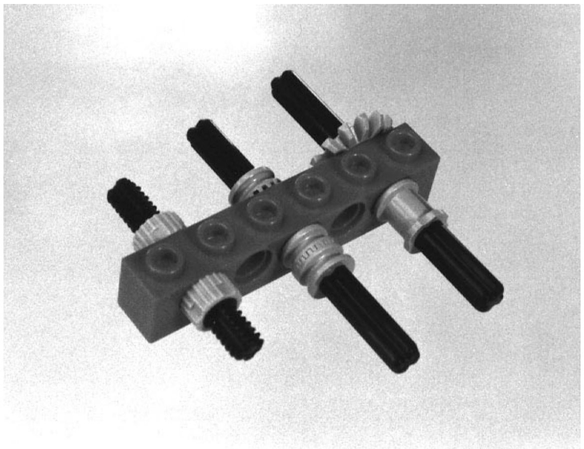


Figure 14: Locking Parallel Beams Together with 2× Parts



The standard 1-LEGO-long stop bush (upper axle, front) is not the only part that can act as a bushing (axle holder). Use the small pulley wheel (middle axle) to act as a half-sized spacer—it also grabs tighter than the full bush. In a pinch, the bevel gear (upper axle, back) makes a great bushing. Finally, the nut-and-bolt parts (lower axle) can be used to make a tight connection (if you can find them).

Figure 15: The Stop Bushes and Other Parts

### Reducing Noise with Pulley Wheels

Sometimes a geartrain will be quite noisy. Usually most of the noise is generated by the very first meshing of gears from the motor. Here is the ideal place to use a pulley wheel drive (Figure 16).

Use the small pulley wheel on the motor shaft, and the medium or large pulley wheel on the driven shaft. The ratio of the circumferences of two pulleys creates a reduction just like the ratio of the gear teeth of a pair of meshed gears.

LEGO pulley drive belts—thin rubber bands—are best when used in high speed, low torque situations, because they can't transmit a lot of force. So the first stage is really the best place to use a pulley drive.

Be careful, though, about using pulleys in a competitive situation. They have a penchant for breaking or falling off at the most inopportune moment.

### Chain Link Drive

Chain link drives are best suited for the final stage of a geartrain—transmitting power down to the axles holding the wheels, for example. This is because they can easily deliver the necessary torques, and they impose frictional losses that are minimized when rotational speeds are low.

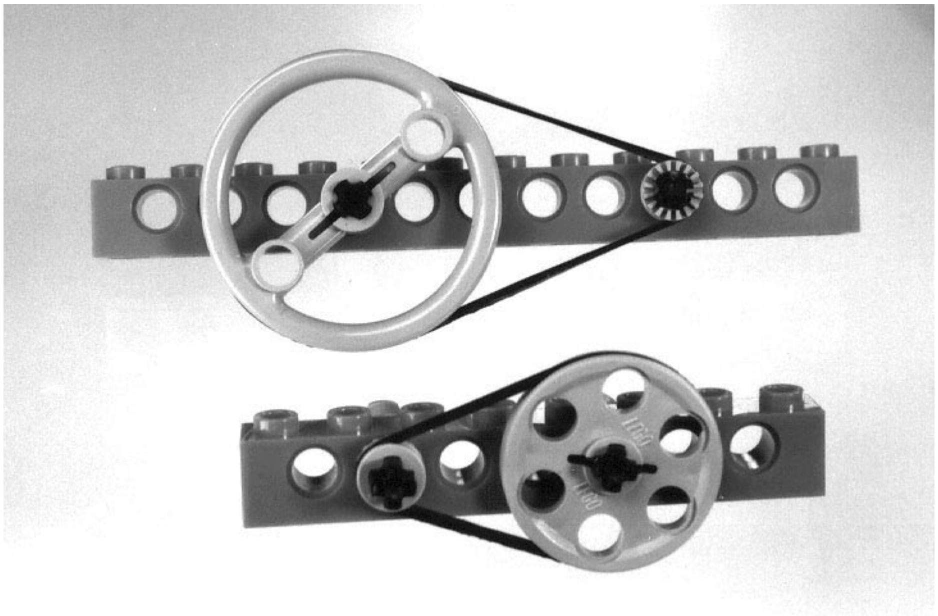
Getting the right amount of chain links can be tricky. Generally a looser chain works better—chains that are too tight will bind up. But too loose a chain will skip when the going gets tough.

### Design Strategy

When designing a new geartrain into a model, I find it best to work *backward from the final drive*, rather than forward from the motor. This makes sense because usually there is a fair bit of flexibility about where the motor is ultimately mounted, but much less in the placement of drive wheels or leg joints (for example).

So start by mounting the axle shaft that will carry the final drive, put a wheel and gear on it, and start working backward, adding gearing until there is enough, and finally mount the motor in a convenient spot.

When designing a vehicle, don't forget about the role of the tire in determining the relationship between the rotational speed of the final drive axle and the linear speed that is achieved. Small tires act as gear reductions with respect to large tires, and this may have an effect on how much gear reduction is necessary. Experiment!



There are three sizes of pulley wheel: the tiny one, which doubles as a stop bush, the medium-sized one, which doubles as a tire hub, and the large-sized one, which is sometimes used as a steering wheel in official LEGO plans.

Figure 16: Using Pulley Wheels

Chain link can be an effective way to deliver large amounts of torque to a final drive, while providing a gear reduction if needed.

Chain link works best at the slower stages of gearing, and with a somewhat slack linkage. Use the larger gears—the 8–tooth one won't work very well.

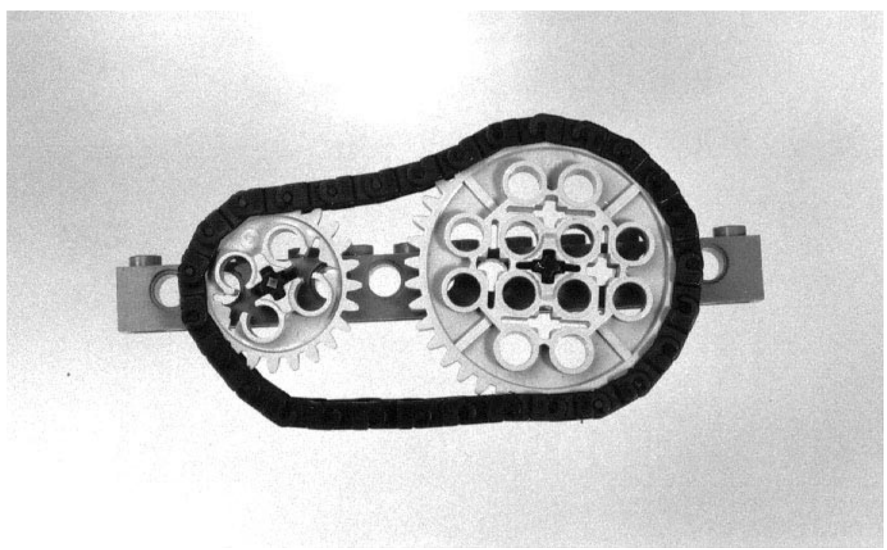
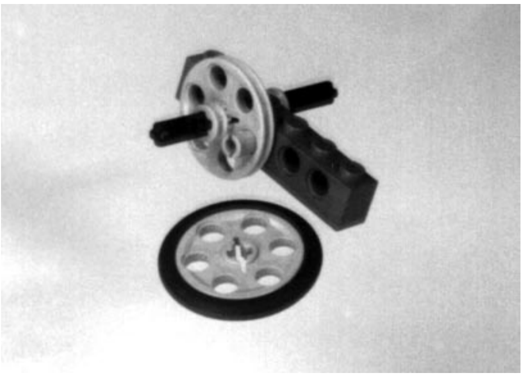


Figure 17: Chain Link Drive



On occasion it is necessary to lock a beam to an axle. This figure shows how to use a medium pulley wheel, which rigidly locks to an axle, to hold the beam in place.

Figure 18: Axle Locked Through Beam Using Pulley Wheel

The special “gear mounter” piece is an axle on one side and a loose connector peg on the other. It can be used to mount gears used as idlers in a gear train—used simply to transmit motion or to reverse the direction of rotation.

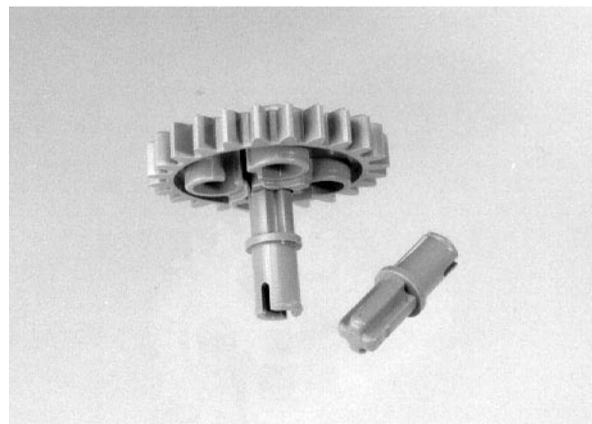


Figure 19: The Gear Mounter Part

If a geartrain seems to be performing badly, there are a few things to check. Make sure the stop bushes aren’t squeezing too hard—there should be some room for the axles to shift back and forth in their mounts. Check that all beams holding the axles are squarely locked together. The most common cause of poorly performing geartrains is beam mounts that aren’t square.

To test a geartrain, try driving it backward. Remove the motor, and gently but firmly turn the final drive wheel or shaft. If there isn’t too much friction, all of the gears in the train will start moving, with the motor’s gear spinning around rapidly. If your geartrain can be readily back-driven, it’s a sure sign that it’s performing well.

## LEGO Design Clichés

This section presents a miscellaneous assortment of ideas in a visual fashion. I’ve come to call these LEGO ideas “clichés” because I hope that they become common, everyday knowledge, rather than secrets held by some small group of LEGO experts. I find myself inventing them time and again, on the spot, when working with kids helping them with their LEGO designs. Part of my intention in writing this article is to collect these clichés and share them with others.

Browse through this collection and perhaps you will find one or more of these techniques useful in your own LEGO designs.

This configuration of parts can be used as a compact axle joiner. LEGO now produces a part designed for this purpose, but in lieu of that part, this is a useful trick.

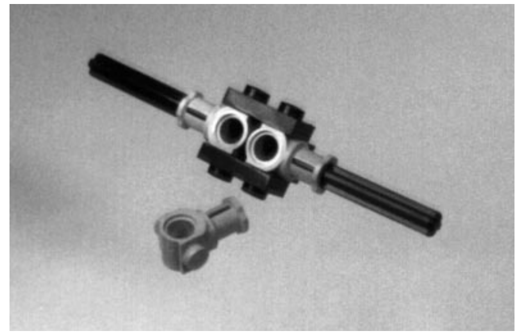


Figure 20: An Axle Joiner

In order to build outward from a vertical wall of axle holes, a smaller beam may be mounted with its top studs in the holes of the beam wall.

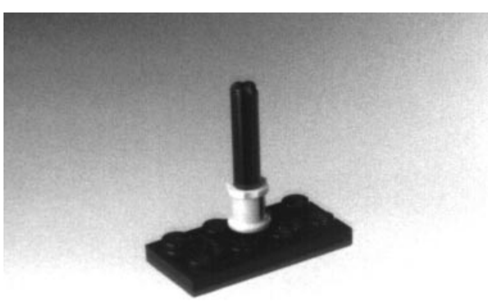
You will not see this configuration in LEGO's model plans, because the top studs are *slightly* too big for the axle holes, and a model left in this state will gradually experience solid flow as the stressed plastic expands. The official LEGO solution is to use the "connector peg with stud" parts (see Figure 22), but this method is actually stronger (or at least until the LEGO parts deform).

Figure 21: One Method of Building Outward from a Vertical Wall

The recommended way to build outward from a beam wall is to use the connector-peg-with-stud piece, which is a loose-style connector peg on one end and a top stud on the other.

This method is somewhat weaker than the method of simply plugging top studs into axle holes (Figure 21), but will not deform the plastic.

Figure 22: The Connector-Peg-With-Stud Part



The full-size stop bush can be used in one orientation to hold an axle through a plate hole so that the axle can freely rotate. In Figure 24, an additional plate is used to trap the axle, but allow it to rotate freely.

Figure 23: Using a Stop Bush to Retain an Axle

By using the stop bush to hold an axle in place between two plates, a vertical axle mount can easily be created. Depending on the orientation of the stop bush, it can be made to either lock the axle in place or allow it to rotate freely. In this diagram, the axle is allowed to rotate.

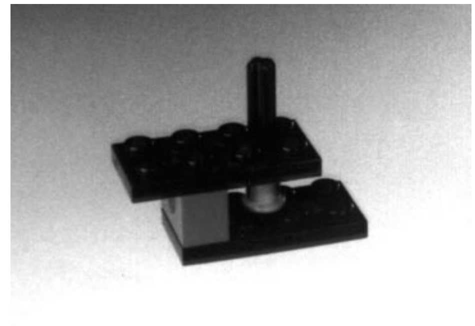
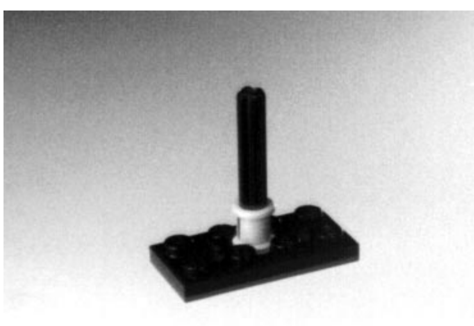


Figure 24: Trapping an Axle Between Two Plates Using Stop Bush



In the other orientation, the stop bush locks between four top studs, perfectly centered over the axle holes in flat plates. This allows the stop bush to lock a plate to an axle.

Figure 25: Using a Stop Bush to Lock an Axle to a Plate

The “toggle joint” can be used to lock two axles at a variety of odd angles. The short axle running through the two toggle joints is equipped with stop bushes on either end to hold the joint together.

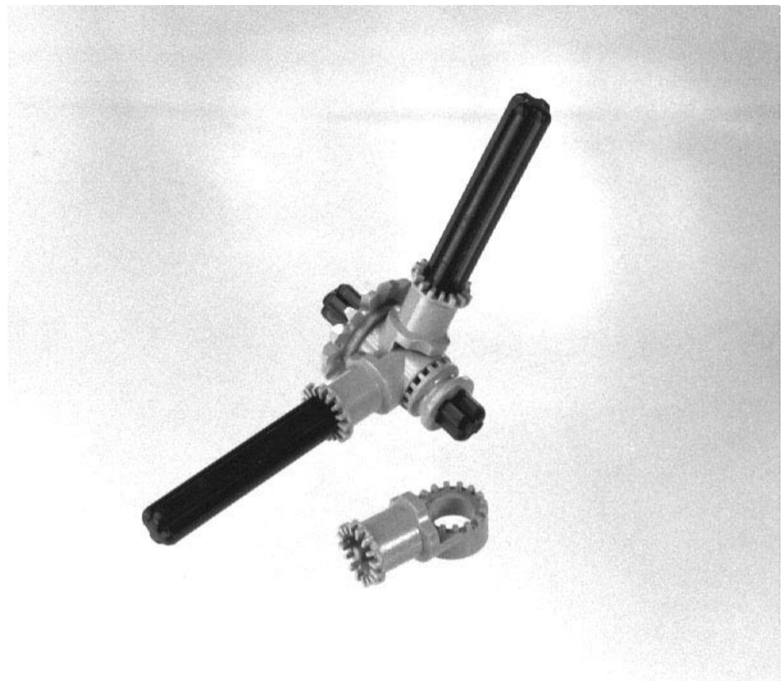


Figure 26: Two Toggle Joints

Here the toggle joint is used to connect two axles at right angles. The small pulley wheel is deployed on the axle that runs through the toggle joint to either lock the axle or allow it to rotate.

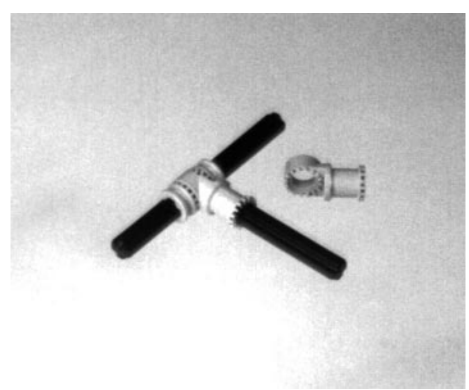
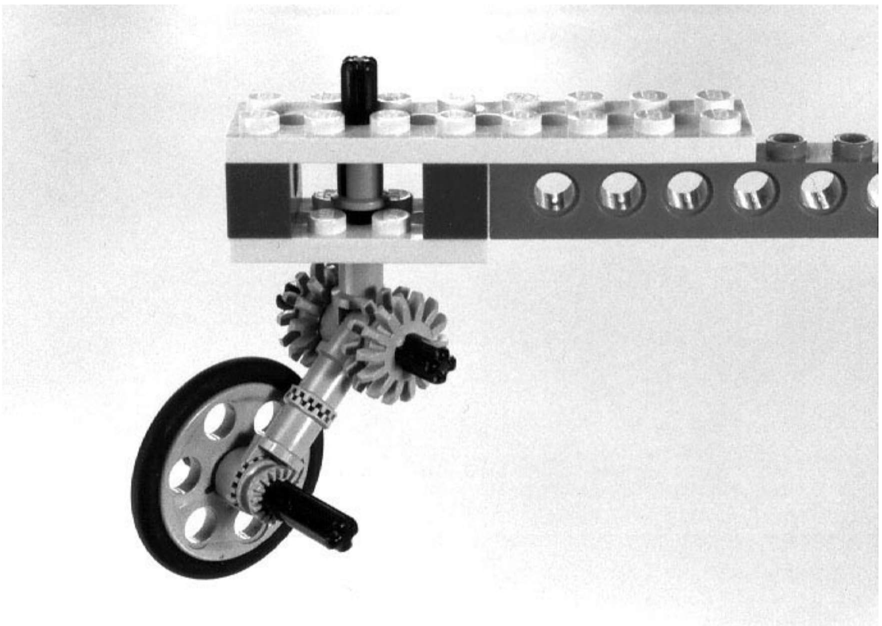


Figure 27: Toggle Joint With Free or Locked Axle



Several clichés are used to construct this caster wheel. The vertical axle is trapped between two plates, but allowed to rotate, using the trick shown in Figure 24. The angled joint down to the wheel is done using toggle joints in the configuration suggested in Figure 26, and the final mounting of the wheel is done using the toggle joint per Figure 27.

Figure 28: A Caster Design

The "piston rod" part (shown in the left foreground) is used twice in each mechanism to create a LEGO leg. By using a chain drive or gear linkage to lock legs in sync, a multi-legged creature can be designed.

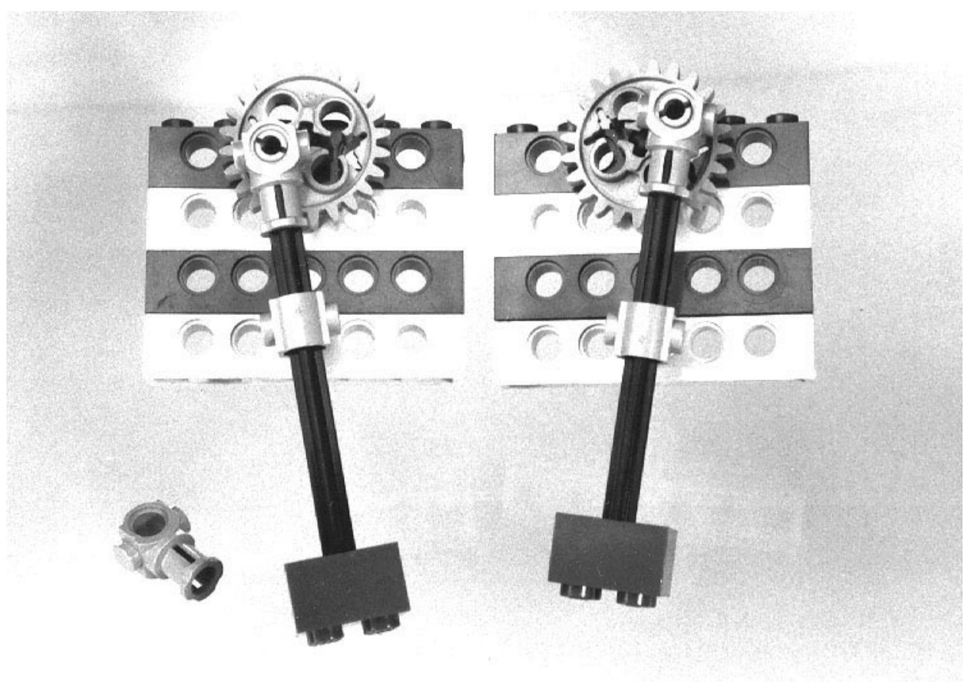
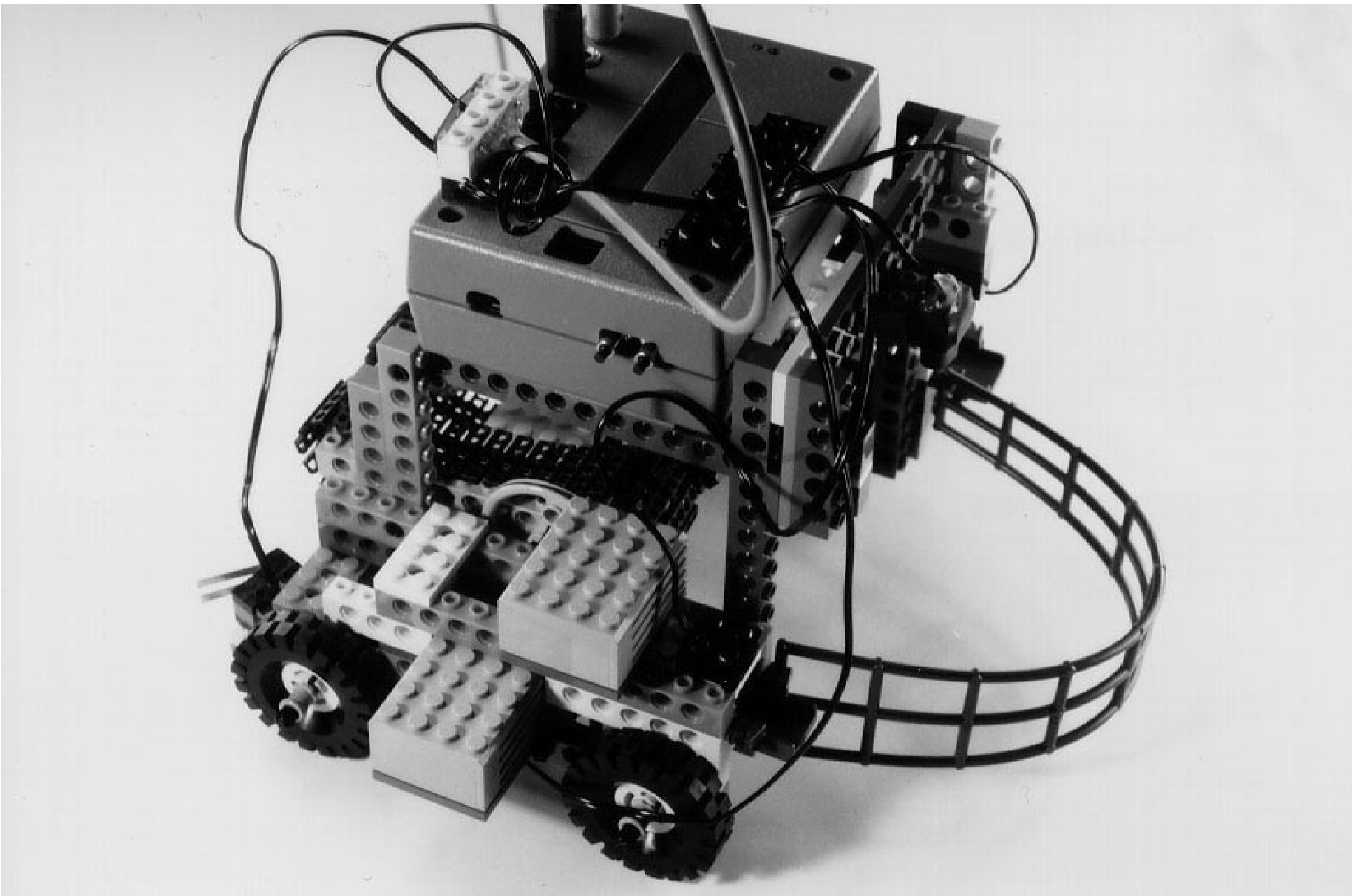


Figure 29: LEGO Legs



How many of the design clichés can you find in this robot? Look especially for the vertical spacing trick used to provide rigidity to the robot structure.

The robot, a ping-pong ball collector, was designed by the author and Brian Silverman. Sitting on top of it is the Programmable Brick, a robotics controller for kids recently developed by the author and his colleagues at the MIT Media Laboratory.

Figure 30: LEGO Ping-Pong Ball Collecting Robot

## Closing

I hope that this article inspires others to contribute LEGO design clichés from their own vocabulary to a larger collection of resources for LEGO builders. By the time this article is printed, we will open a World Wide Web site representing successive versions of our LEGO Constructopedia, presenting these ideas in a hypermedia format and soliciting the contributions of others.

## Acknowledgments

Steve Ocko guided my early work with the LEGO Technic system, and continues to inspire me with his LEGO creativity and his dedication to developing rich learning environments for kids. Mike Plusch and Randy Sargent, both LEGO geniuses, shared numerous ideas and insights with me, which I've incorporated into this article.

The LEGO Group is a continuing sponsor of our work at the Media Laboratory. They have provided both generous research funding and valued intellectual discourse on a wide range of topics related to children's learning and effective use of the LEGO materials. We are deeply grateful to their support of our work. Any criticism I make about their products should be taken in the spirit of making a great thing even better.

## About the Author

Fred Martin has been developing educational robotics technologies at the MIT Media Laboratory since 1986, and is a co-founder of the annual MIT LEGO Robot Design Competition.

Fred is interested in robotics for fun and as a vehicle for exploring sensing, control, and engineering design. He has been teaching robotics to kids, teenagers, college students, and adults for nearly ten years and hasn't gotten tired of it yet.

Currently a Postdoctoral Fellow at the Media Lab, Fred is working on a robotics textbook aimed at undergraduate engineering students. Tentatively entitled *The Art of Robotics: A Hands-On Introduction to Engineering*, the book is scheduled to be published in the fall of 1996 by Benjamin/Cummings. This article will form the basis of an expanded chapter on LEGO design in the text.

Fred welcomes any comments on this article. He can be reached at `fredm@media.mit.edu`. The URL for the LEGO Constructopedia WWW site is:

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http://el.www.media.mit.edu/groups/el/Projects/constructopedia
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