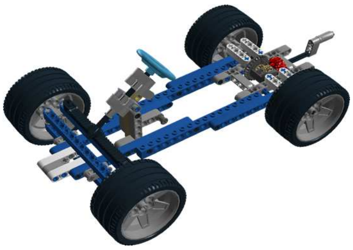
Exploring Car Tech

Project 0: Brakes

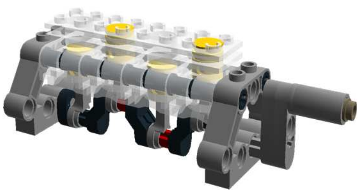
Project 1: Suspension

Project 2: Steering

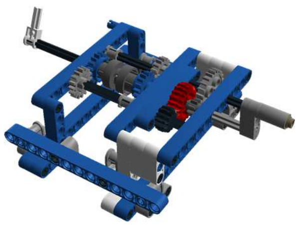
Project 3: Differential



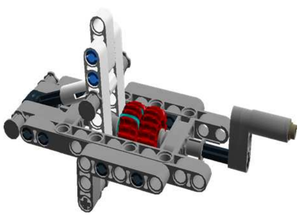
Project 4: Engine



Project 5: Gearbox



Project 6: Clutch



Project 0 - Brakes

Most of our time with this set will be spent exploring various devices that make our car going. However, I am pretty sure that when our furry forefathers invented the first cart and took it up a hill, they quickly get to work inventing their first brake. As you surely know, a brake makes a car slow down or stop. I dare to say that not counting wheels, brakes are the most important part of any moving contraption, even those that do not have engine, suspension and any of the other components we will explore here.

Thus it is only fitting that we start our exploration of automotive technology with brakes. By the way, how come that we do not have any brakes on our main car? Things are different in the world of Lego, where we rarely worry about a runaway car, so brakes are usually left out. Which is a good thing, because making working brakes on a Lego car is complicated, our set would stop being small and simple.

Project 0a. Friction brake.

The most common approach to slow down a vehicle is to apply friction to its wheels in some way. Their kinetic energy then turns into heat, which is one of the things a brake designer may have to worry about. Our model shows the basic setup of a friction brake: A pad is pushed against the wheel with a lever, the more you push, the more you brake. Try it for youself.

This is the simplest brake one can get - unless you want to push against the wheels with your feet. Brakes like this were used on farm wagons hundreds of years ago. They are not best suited to cars, in particular because of the wear on tyres, but in many situations this is not a concern, so brakes of this kind are still in use. You can find them for instance on trains (that do not have any tyres to start with), bikes (where the pads push against rims from the side), kick scooters, and baby carriages.

However, for our car we want something better.

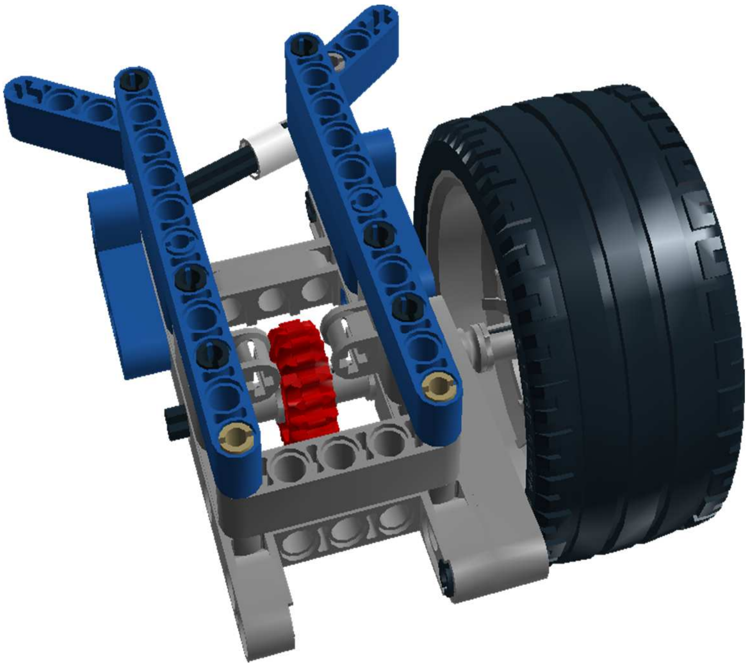
Project 0b. Drum brake.

Wheels in passenger cars are in fact hollow, there is a free space inside. A drum brake uses this space to place two devices called "shoes" there (also called break pads). Normally they do not touch anything, but when we want to slow down, these two shoes are pressed against the inner side of the drum. To increase friction (and handle the heat that is generated while braking), there is a special lining on those shoes.

You can try it with our model. Just hold the model in your left hand, with your thumb on the lever. Spin the wheel with the other hand and then push the lever. The wheel should stop. If you are left-handed, just build the model the other way around.

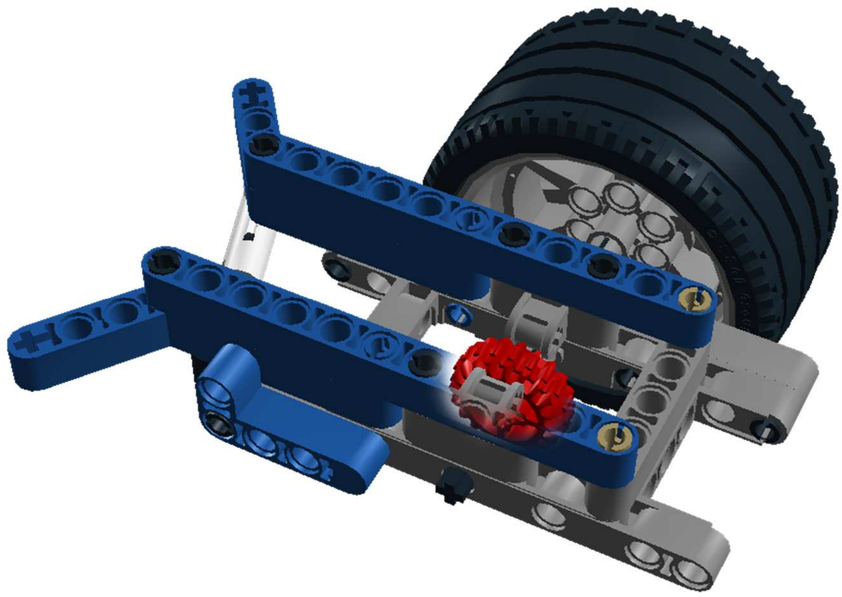
Drum brakes started to appear around year 1900 and they have been widely used in cars and motor bikes. In the last 50 years they started to be replaced with disc brakes, but many passenger cars still use drum brakes with their rear wheels. They are cheaper and more compact, and do not require as much maintenance. They are also better suited for hand brake (emergency/parking brake).

Project 0c. Disc brake.



While the basic idea for disc brakes has been around for a while, they came to prominence in the middle of the 20th century, when they have proved their superior performance in racing cars. Since they are more expansive, they have been slow to appear in common passenger cars, but these days most cars have them in front and many also in the back.

The basic idea is very simple, a disc is attached to the wheel axle and two pads push against sides of it when we want to stop. It is easy to make disc brakes as powerful as we wish, simply by enlarging the disc, they also dissipate heat well and one can control better how hard to brake, so they are the default brakes for racing cars.



You can try it for yourself. Hold the model with your left hand so that your index finger and thumb hold the levers. Spin the wheel with your other hand and then push the levers together. The wheel should stop.

Next time you are out, check out cars that you meet. Sooner or later you are bound to see a car whose front wheels have large holes in them and behind those holes there is a shiny disc with pads attached at one side. You can also see disc brakes on motor bikes, more sophisticated bycicles, and once I actually saw a baby carriage with a disc brake. It felt sort of funny, a baby carriage with more advanced type of brakes than my car, but I never had a reason to complain about the drum brakes in the rear of my car.

Project 1 - Suspension

When we ask our car to do something (turn, slow down, speed up), it does so through its contact with the ground. Thus if we want our ride to be safe, we need the best contact we can get, that is, we really do prefer all four wheels to be firmly on the ground. Given that roads are rarely perfectly flat, we need to allow wheels to move up and down relative to our car. And that is exactly what a suspension does.

In order to get the wheels back and to smooth their motion we also add springs and dumpers, then we talk of so-called sprung suspensions. As an added benefit our cars lasts longer as it they not try to shake itself into pieces every time we go a bit faster. Last but not least, it makes our ride comfortable.

People invented different ways to allow wheel move up and down, with different advantages and disadvantages. We will look at some typical examples and test them. What do we expect form a good suspension? Obviously, it needs to be able to negotiate obstacles on the road (bumps, potholes). Another important requirement is that a suspension should not harm handling of a car. This is especially important if we expect the car to be driven fast. One factor that influences handling is the position of wheels relative to the ground. We generally prefer our wheels to stand upright (or almost upright, on passenger cars wheels usually lean outward just a tiny bit). Sometimes it happens that a wheel tilts. When a wheel leans away from the car or towards it, it has the tendency to turn the car into the direction that it is leaning. This is not welcome, since we do not want the car to turn on its own. So suspension designs that cause wheels to tilt have a big minus on their score sheet.

You will be able to try common suspensions with our models. We will build a test bed (rear wheel assembly and a frame) that will serve us well for this and the next two projects. With one exception (the very first experiment), we will keep this basic frame intact and only make changes to the front to get a new suspension for testing. To make our life easier we kept the rear simple.

Tests.

What kind of tests can we run? With our Lego cars we can simulate most basic situations.

1. A bump on a road. We ride over some obstacle (Lego brick) and see how it goes. All suspensions should handle this easily, it is useful to observe whether wheels change their position relative to ground (camber).

2. A drain ditch across the road. Wheels suddenly drop. We can simulate this by taking our car by the nose and pulling it up. How do the front wheels react? The same thing happens when a car gets lighter than its normal weight.

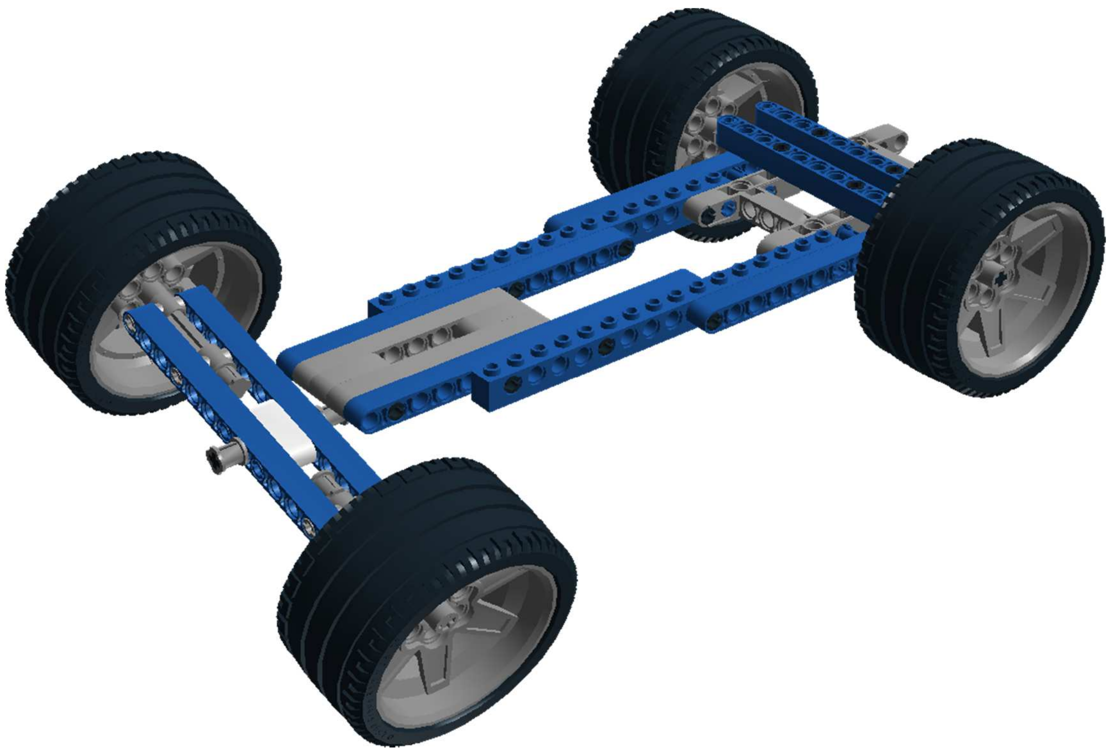
3. We load the car with some heavy cargo. We can simulate this by pushing the nose of our car down. (We will not be able to do this test with the first model.)

We will always try these tests without the spring units, so that the wheels are free to move around and we can see nicely what is happening. However, most of these cars cannot stand up without those shock absorbers, so we will have to keep the nose up when driving them around.

If you want, you can then add shock absorbers to our test cars and see how they ride. They will also keep the car up. On the other hand, they have only a limited travel and the movement of wheels will be restricted, so you will not be able to test our suspensions with those shocks as well as without them.

Project 1a. Beam axle.

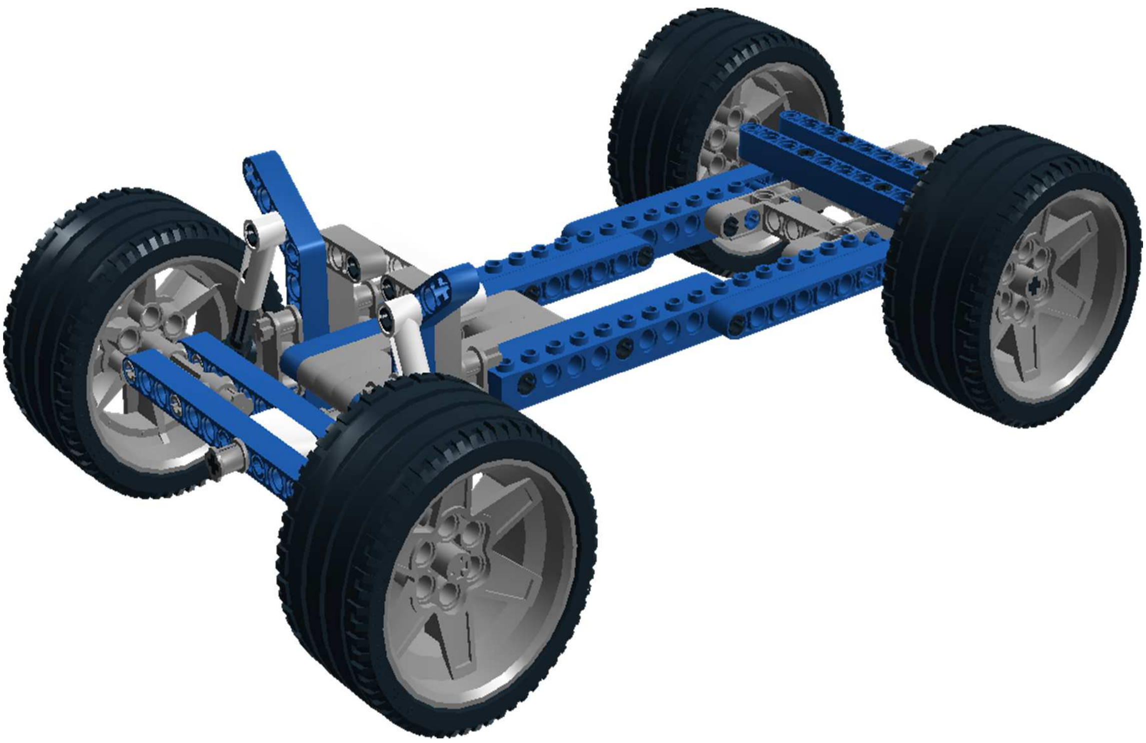
This setup is also called a rigid axle or a solid axle.



It is one of the simplest solutions to the suspension problem. You can see for yourself that it can easily handle a bump or a hole in the ground. We have a simplified version here, in fact the whole front wheel assembly should be also able to move up and down a bit, so this suspension also reacts nicely when we load the car or when wheels drop to a ditch.

On the other hand, you saw that when one wheel encounters an obtacle, then the whole axis tilts and both front wheels lean to one side, so we have a noticeable camber and whatever problem we have on one side is immediately felt on the other side as well. This is not very good.

If both axles were like this, it could easily happen that the car falls over to one side. We want to have some mechanism in place that would force each axle back to its natural position (and keep the car straightened up). To this end we add two shock absorbers.



The main advantage of this suspension design is its simplicity (and low cost), it also does quite well in heavy terrain. Concerning the disadvantages, they are not as important if the car drives slowly, and engineers tried to improve this design to make them less serious. As a result, various versions of this type of suspension have been used for many years in utility cars (like pickups in North America) that were expected to do some work off the roads and fast driving was not a big priority. One can still find it in some heavy (and slow) vehicles (truck, special machinery for miners and such).

If we want to have a better suspension, we need to give each wheel a chance to react on its own by splitting the axle and working with each wheel separately. This is called independent suspension.

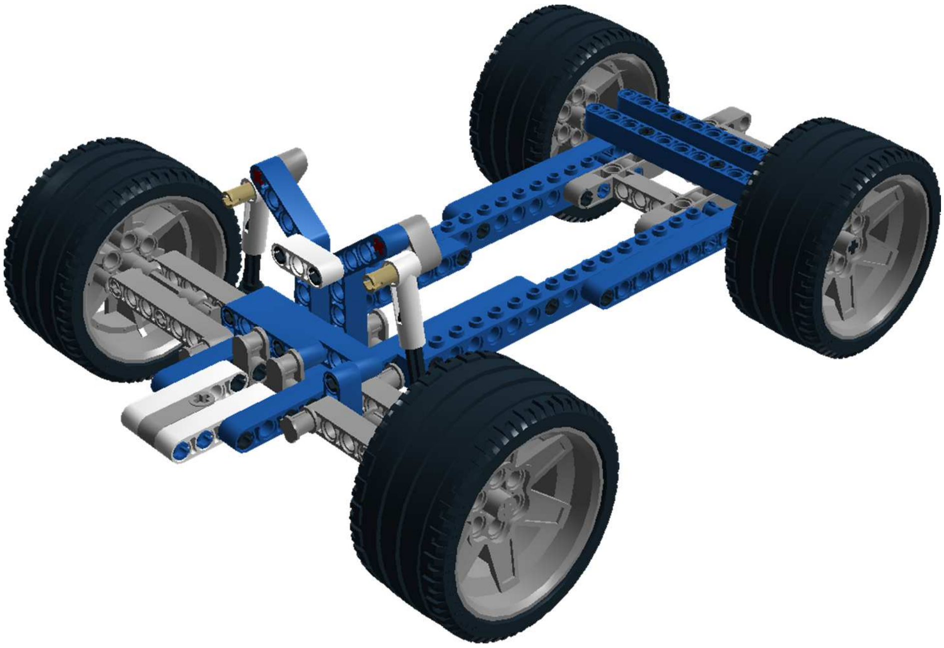
Project 1b. Swing arm suspension.

We have to work a bit on this model, but this is the last time we will be messing with the main part of the car in this project.

You have to hold the nose up, but as a reward the wheels are free to show you what they can do. Try the three tests described above. You will see that this design has no problem going over a bump and the independent solution allows just one wheel to deal with it. It can also react to heavy load or a lightened car (push the nose down or lift it up).

This suspension is definitely capable, but you also saw that it makes the wheels move about a lot. In all testing situations, the wheels have a pronounced camber (move away from a perpendicular position). This is the main disadvantage of this type of suspension.

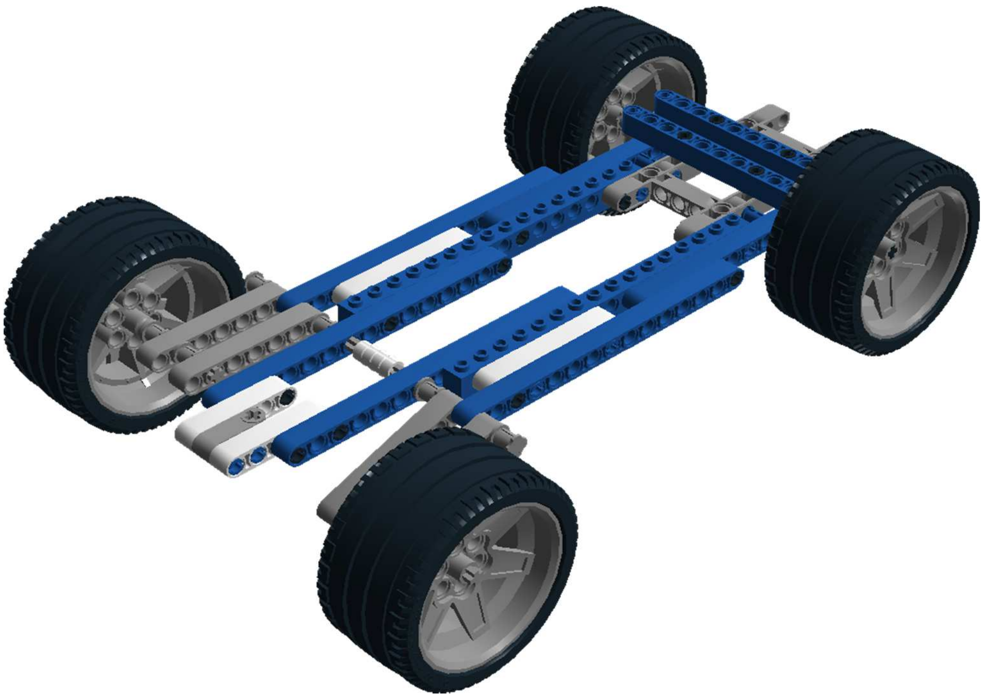
Adding shock absorbers means that you no longer have to support the front when riding around, but as expected, the wheel travel is quite restricted. Still, you can see for yourself that this suspension can still handle small obstacles with grace.



The swing arm suspension is perhaps the simplest way to obtain an independent suspension. Simple usually means cheap, which is something that car manufacturers like. Simple often also means reliable (and easy to fix), which is something that outdoors people appreciate. In a fast moving car it can be unpredictable and therefore dangerous, so car makers eventually gave up on it when it comes to passenger cars, but you can find it on some heavy trucks that need to have good terrain going abilities.

Project 1c. Trailing arm suspension.

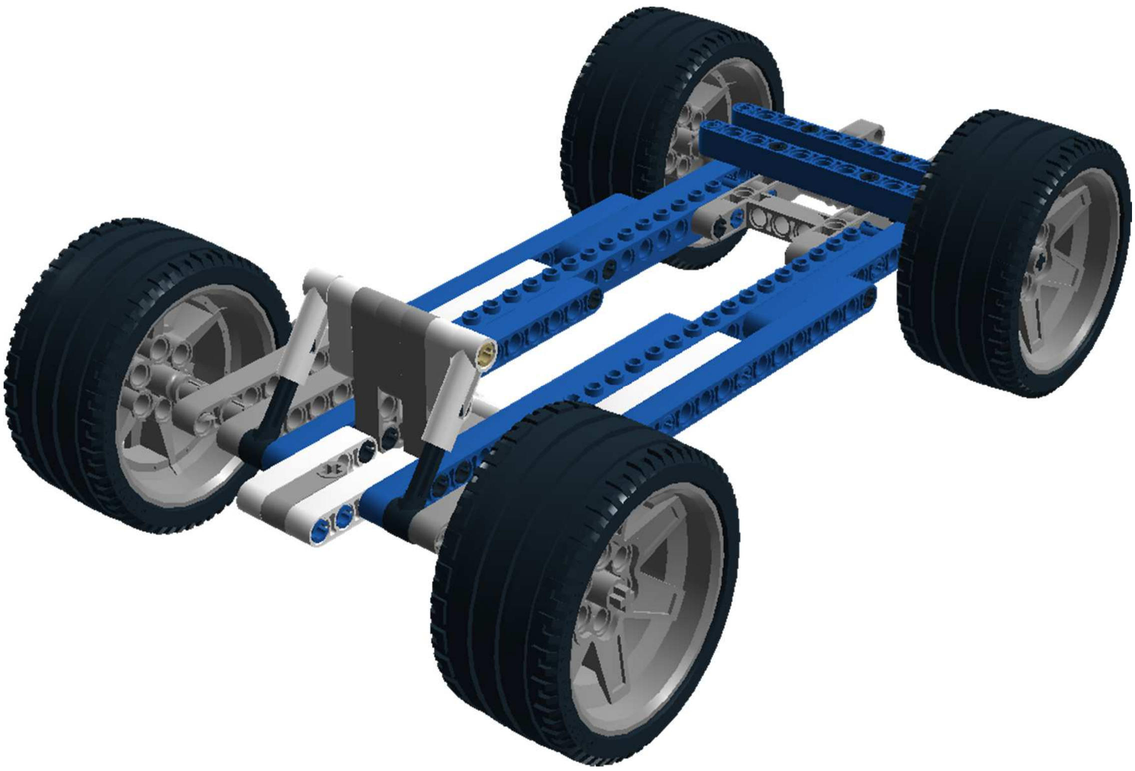
This kind of arrangement is also called the towed axle suspension.



The word "towed" suggests that we should drag the axle when moving, so in this project we will make an exception and consider the sprang wheels to be the rear of the car. Try to move it around, now going with the fixed axle first, and go through our three tests.

This suspension is definitely capable of handling the usual problems. What is even better, the wheels do not tilt (no change in camber) when the wheels negotiate bumps or when they both move up or down (when the car gets lighter or heavier). Designers were not exactly happy with this suspension when it comes to turning, when a car tilts a bit to the side, so they actually prefer a modified version called semi-trailing arm suspension. It is quite popular and you can find it on many passenger cars, typically in the rear. One particular advantage then is that this suspension does not reach up a lot, so one can have a nice flat room for cargo in the back.

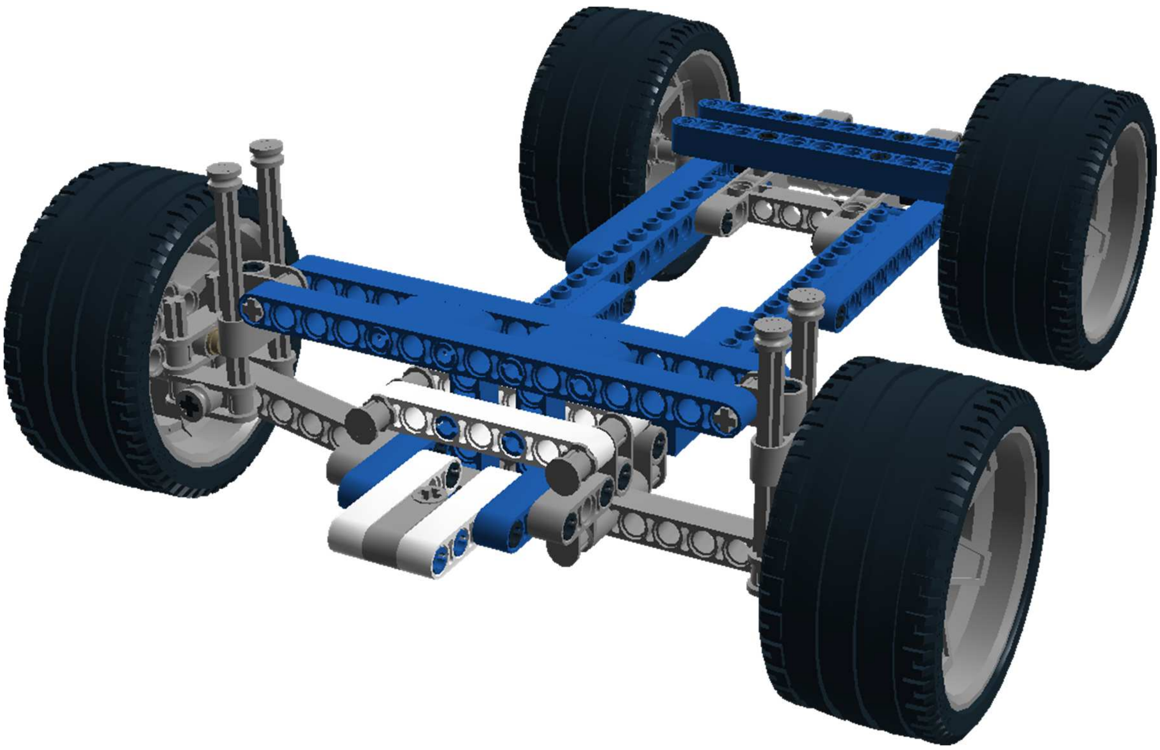
If you want, add shock absorbers and try it out. It is possible to do a quick fix with the existing model.



However, this design suffers from twisting. If one is willing to do a more substantial rebuild, a better model is available.

Project 1d. MacPherson suspension.

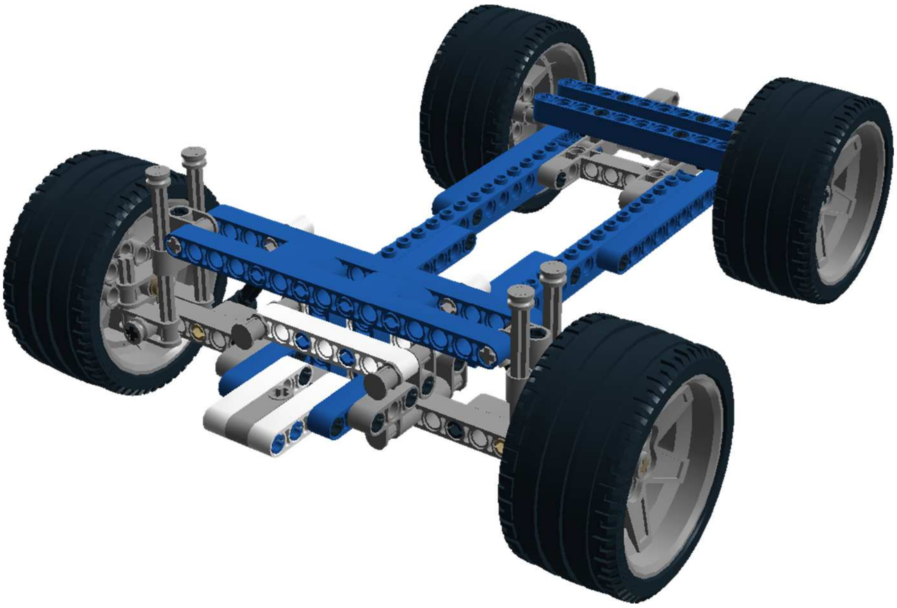
It is also called McPherson suspension.



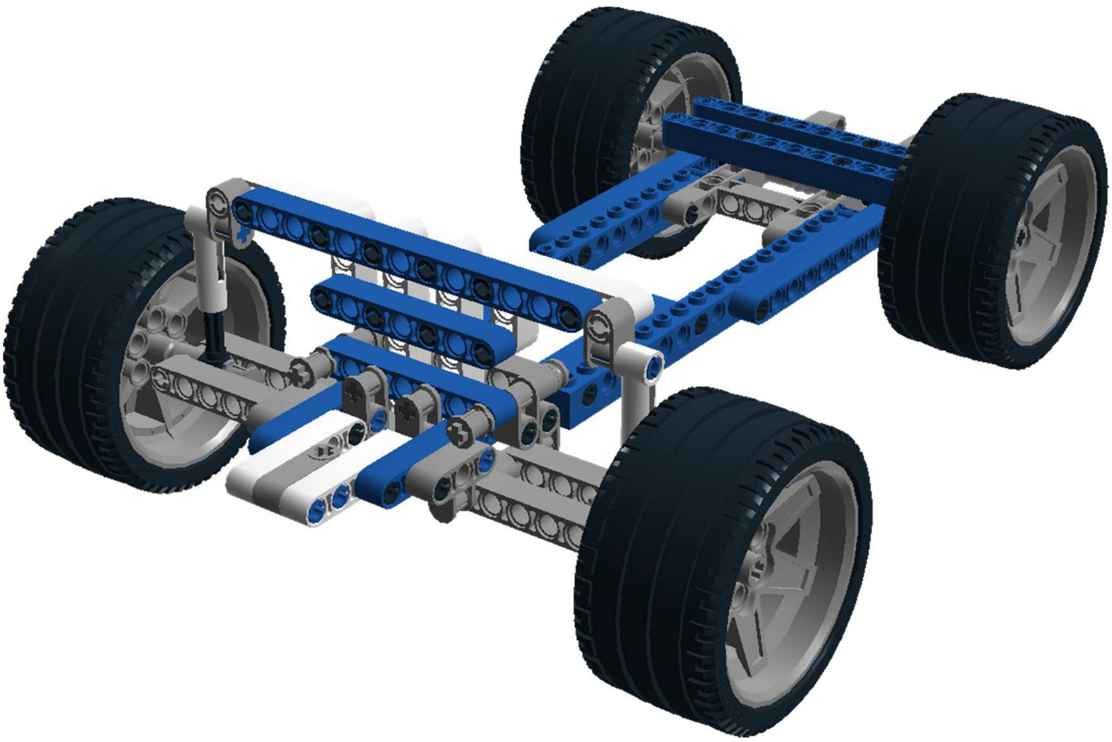
This type of suspension tries to cure the main weakness of the swing arm design by controlling the wheel position through a telescopic tube that goes up and attaches to the car. As the arms swing up and down, the wheels are kept upright. Almost, that is. You can see for yourself that if the wheels move up or down more, then they still tilt, but not by much.

Run our tests to see that this suspension handles obstacles well and in all tests the wheel tilting problem does not get too serious.

You can add shock absorbers and see how the car rides. This is a quick-fix version and suffers from the usual problem of limited travel.



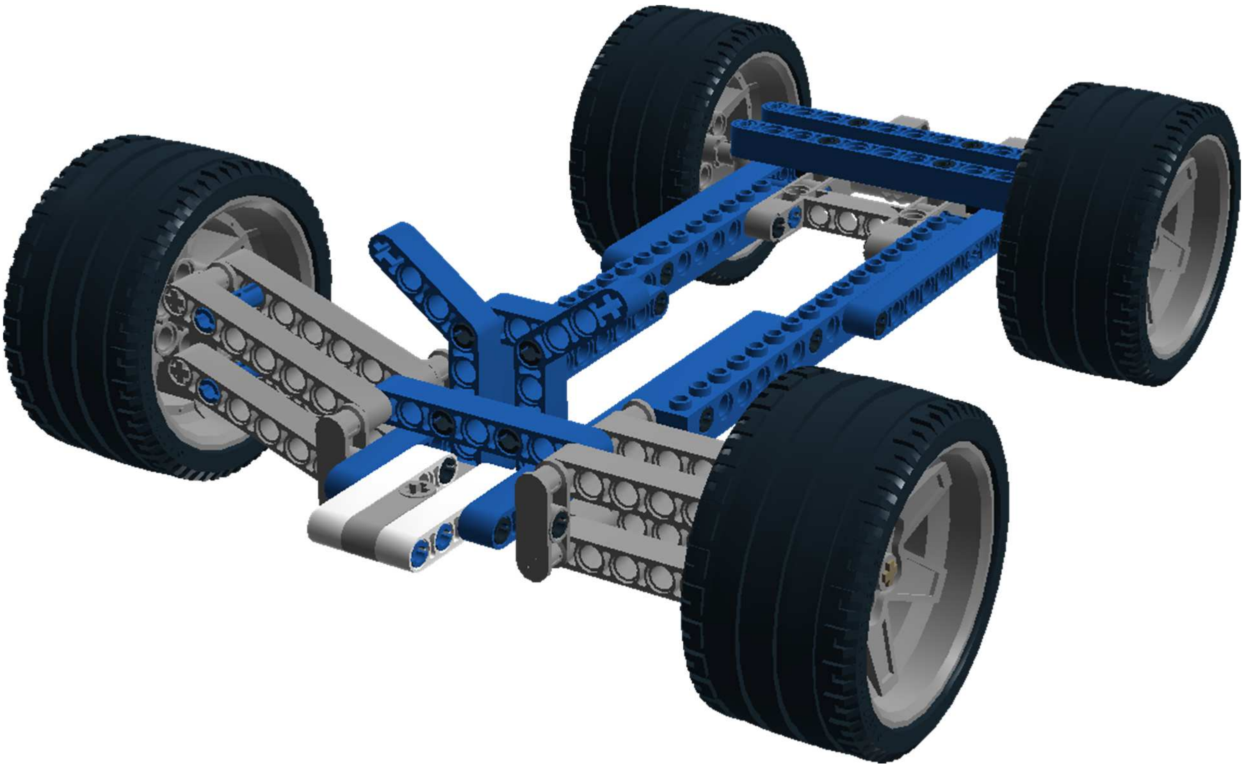
In a real car they actually do it differently. To make the construction simple, they use the shock absorber itself to keep the wheel upright. You can try it with our Lego car, but you would have to make a new front.



Since Lego absorbers are not made for this job, this construction is not too rugged. Be careful when riding it around.

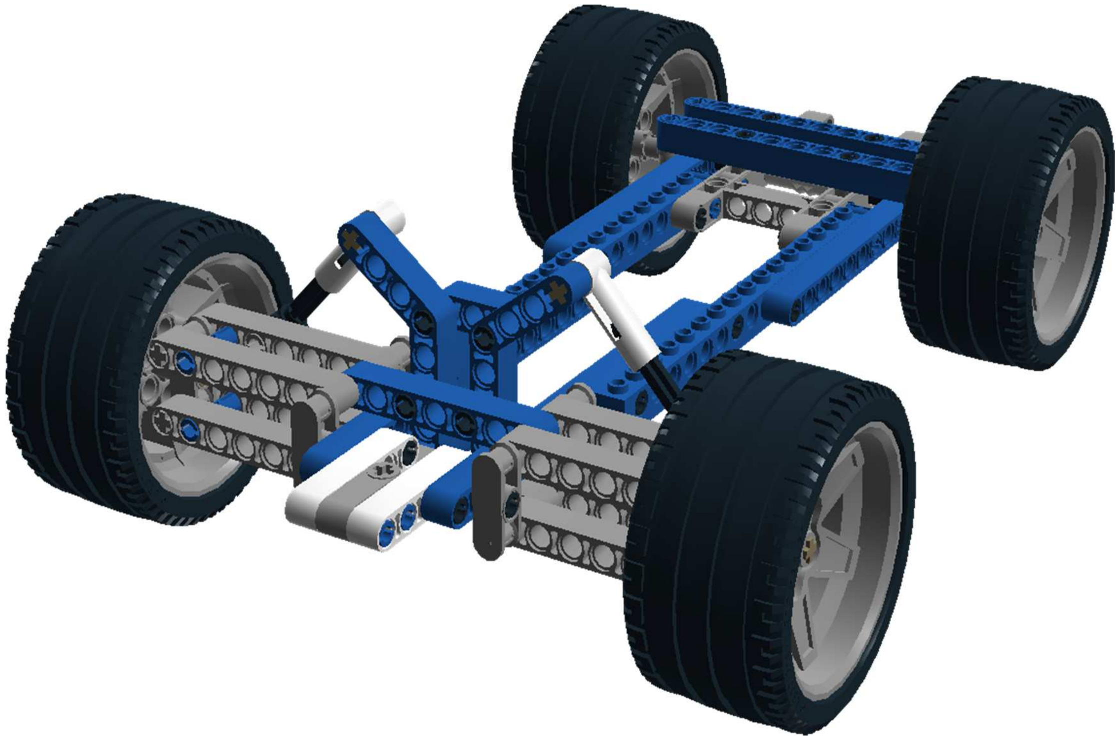
So we have a suspension design here that handles the usual obstacles well, has a small cambering problem, has a reatively simple construction and does not take up much room in a car. No wonder that it is probably the most popular suspension in passenger cars, above all for the front wheels, becuase it leaves ample room to fit an engine between the shocks.

Project 1e. Double wishbone suspension.



This is a high end suspension. Note how the wheels always stay upright when they negotiate an obstacle or when the car gets lighter or heavier. In the Lego world, it is quite simple to make (Lego even has special parts for it) and it is quite sturdy, so it is the suspension of choice when making a sprung Lego car.

If you want, add shock absorbers and try it out.



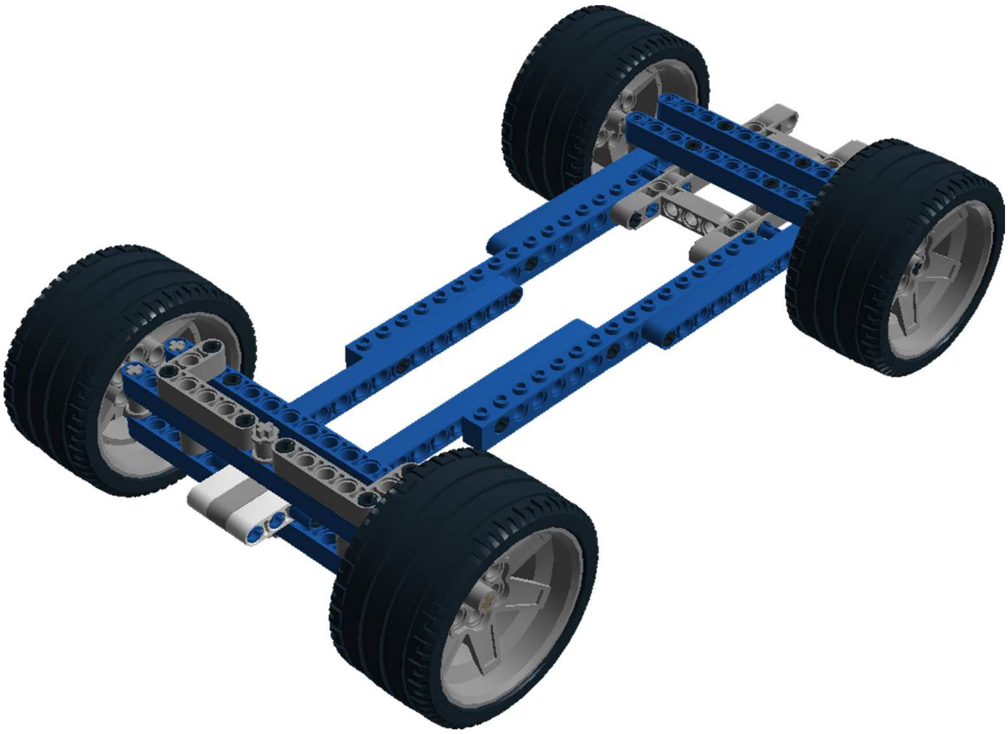
This suspension behaves very well in various situations and it can be tinkered with and set up to perfection, which makes it a sure bet for high performance cars and racing cars. However, for passenger cars it is too complicated and large, so it is not used much (especially when it comes to ordinary cars).

The most advanced kind of suspension used in passenger cars is a multi-link suspension. It is too complicated for our set, so you would have to read on it elsewhere.

Project 2 - Steering

Everybody knows that we make a car turn by turning the steering wheel. But how is this arranged? And how can we make the wheels turn given that they are attached to the car?

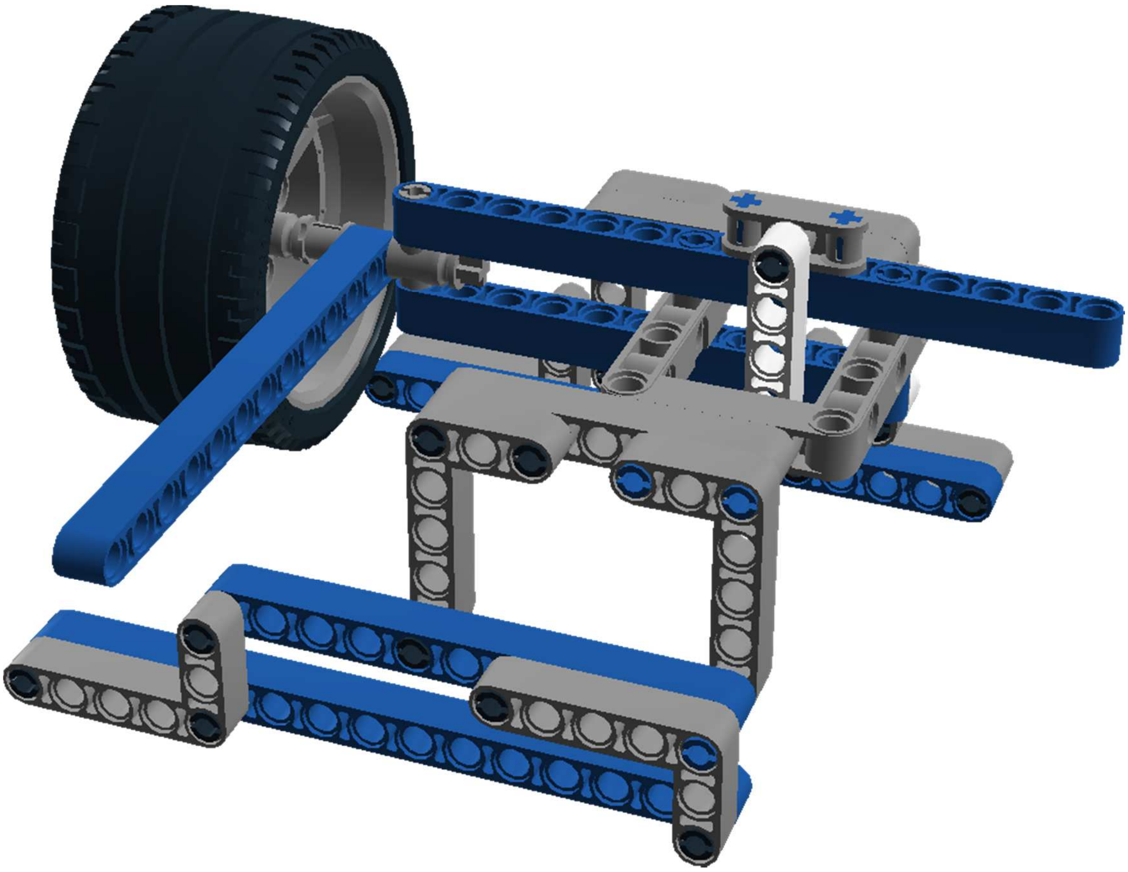
Project 2a. Axle on a pivot.



This is the simplest (and oldest) steering system. Since it is easy to make, one can still find it in toys, wagons, and homemade go-carts or street trolleys (where the steering is sometimes done simply by pushing the front axle around using feet, with a more sophisticated approach one pulls at the axle using a rope). One practical point: The axle pivot should be forward of the front axle, just like we have it on our model. The front wheels then return to their straight position automatically when we let go of them while driving.

This steering has some disadvantages, an obvious one is that the front axle requires lots of room to turn. This for instance explains why on farm wagons the front wheels were often smaller, then they can turn more before they bump against the sides of the wagon. Around year 1800 people started to use a better design. Just like with suspension, the trick is to treat each wheel separately. We will start by looking at just one front wheel.

Project 2b. Basic steerable wheel assembly.

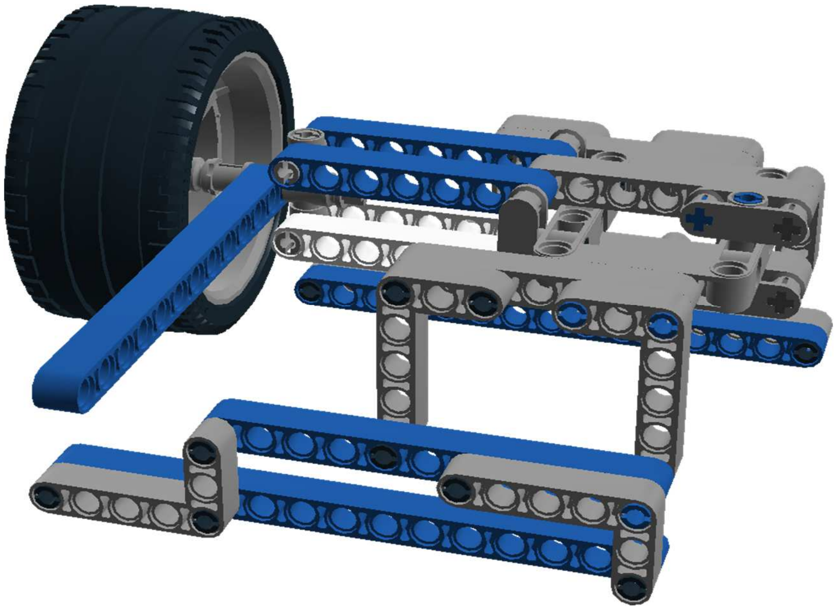


You can imagine that the stand on the right is the car and we are attaching the front left wheel in such a way that it can turn. Our testing rig shows the basic idea. The wheel with its small axis is attached to the car (that is, to suspension) using a pin around which it can pivot. This pin is called the kingpin. To control the position of this wheel we attached a lever called steering arm and by moving it we turn the wheel.

To get into the spirit of the thing, imagine that you are sitting in that gray rectangle on the right and you are puling and pushing at the steering arm using another rod connected to its end (it is called the tie rod). We will see this arrangement later.

Note that as you turn the wheel, it still travels around a lot. This is because it is far from the kingpin. Later on we will try a better arrangement where the steering arm does not force the wheel this far out.

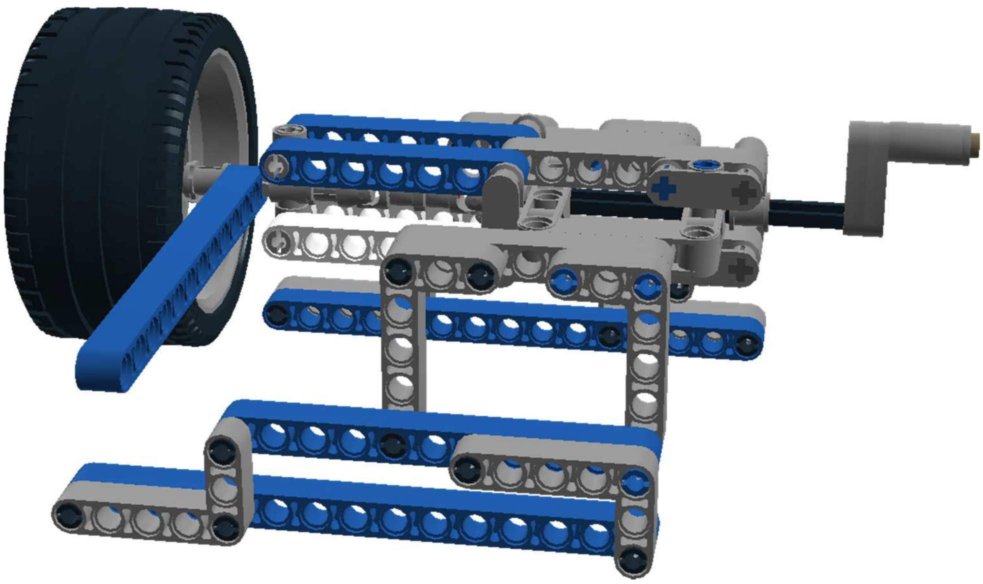
Project 2c. Steering with suspension.



In this model we connect two ideas: The front wheels should turn, but we also want them to be suspended. We chose the double wishbone suspension, as it is popular in the Lego world and makes things easy; with other suspensions we work similarly.

To get both steering and suspension we had to allow the wheel assembly to rotate in two directions. We used a simple arragement that gets the job done where the two rotations are done at different places. In actual cars they handle both movements at one place using a "ball in a socket" arrangement. Lego has special parts that can do that, we will see them in action in the main model.

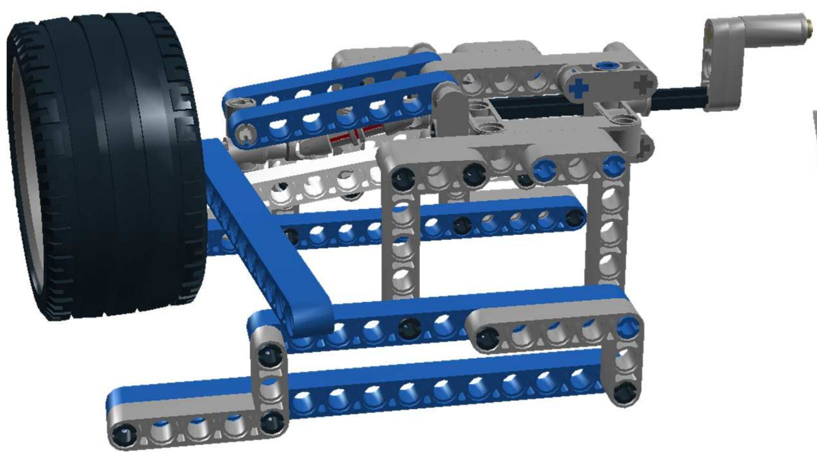
Project 2d. Steering with suspension and power.



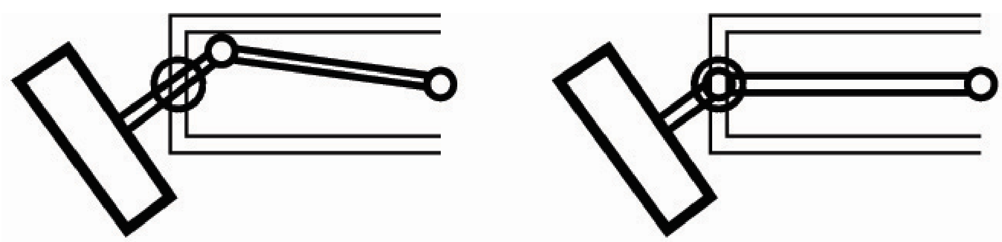
Here we look at the most complicated situation. Many passenger cars are of the front-drive type. The power from the engine has to somehow get to the front wheels that move up and down due to suspension and also turn due to steering. Is it possible to deliver spinning motion to such an elusive target?

This is actually a fairly common problem in mechanical engineering: We have a rotating axle leading in one direction and we need to pass this movement to another axle, but going in a different direction. There is a device that can do it, it is called the universal joint or the Cardan joint. Lego does have such a part, so we use it to connect an imaginary engine (crank) with our front wheel. We will actually need two such joints.

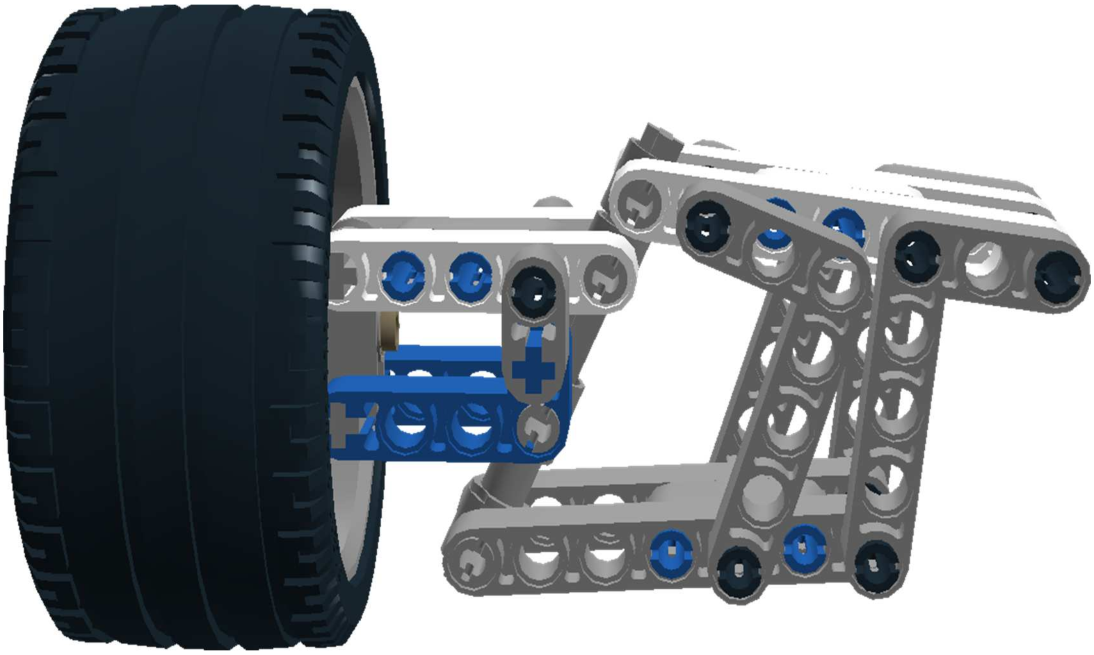
Try put the wheel in different positions, moving it up and down and turning left and right, and observe what happens when you crank the crank. The universal joints work like a charm.



Note that our model gets in trouble when we move the wheel up or down and also turn a bit more. The universal joint then bumps against the wishbones. This is not a problem of the idea itself, just a consequence of our decision to show it using a simple model. When done properly, the universal joint "bends" at the same place where the wheel assembly turns. Then everything works well. We would have to use a more complicated construction to achieve this, or use special Lego parts.



Project 2e. Wheel with oblique kingpin.



As we discussed in the suspension project, wheels are expected to be (more-or-less) upright. However, on real cars the kingpins are tilted towards the car and also a bit back. Why is that? Our model provides the answer.

The "box" represents the car. The first experiment is simple: Hold it in the air so that the wheel is upright, which means that the box itself should be about level as in the picture. You will see that the wheel has a tendency to turn left or right by itself at the slightest provocation. What makes it behave in this way? The gravity. Since the kingpin is slanted, the wheel gets lower as it turns. Because things do not want to stay up if they have a choice, the weight of the wheel pulls it down and hence to one side.

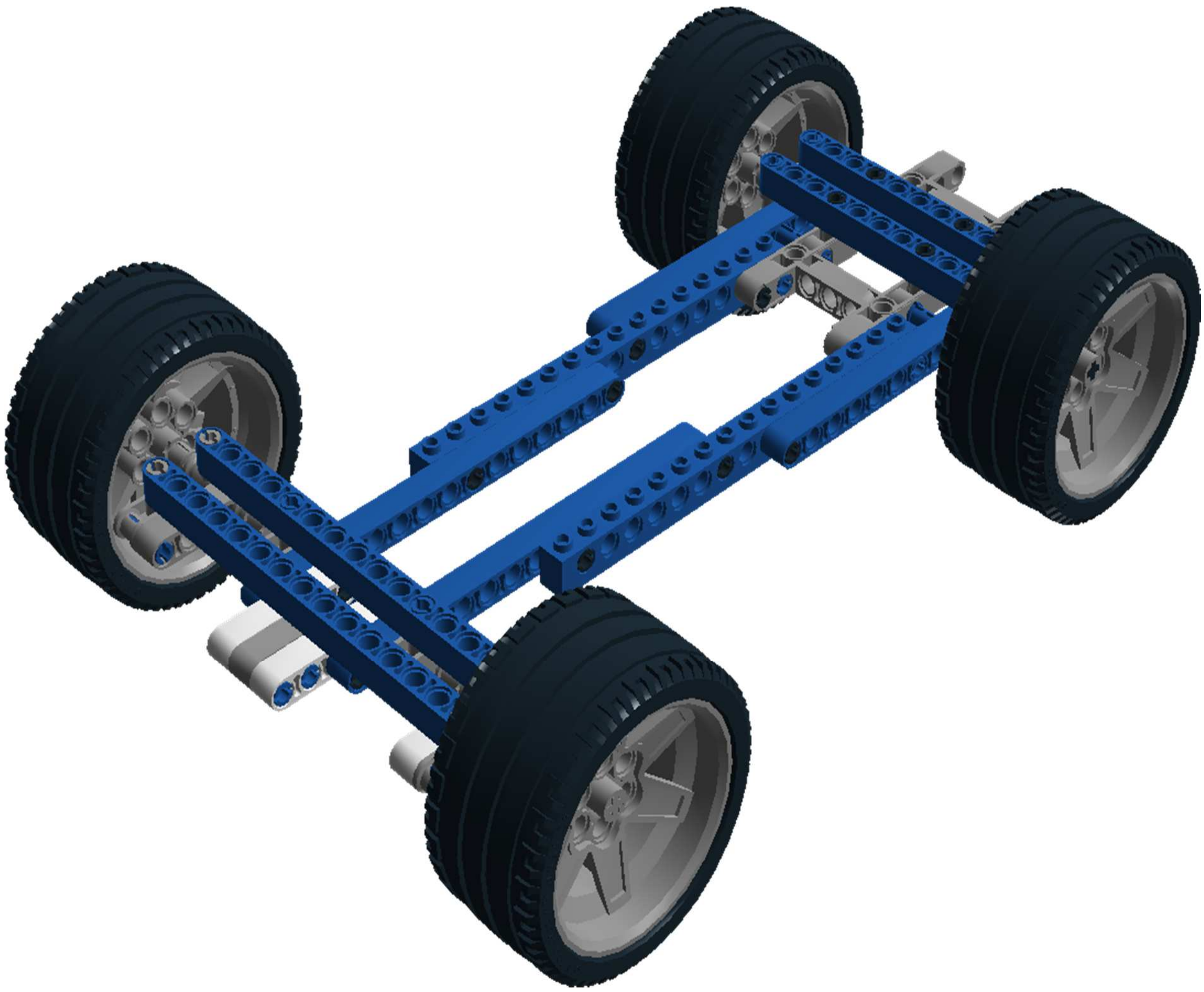
However, we are interested in a different situation. Place the model on a desk or some other flat and reasonably smooth surface and then push lightly with one hand on the "car" part (preferably close to the kingpin). This represents the weight of the car. Now use the other hand to turn the wheel. Due to the slanted kingpin, the wheel would have to go down while turning, but because the ground is in the way, it has no choice and ends up pushing the car up. Try it, move the wheel around and the hand pushing on the box should feel it rising.

Now for the final test. Turn the wheel and then release it, perhaps pushing a bit more down on the box. The wheel should flip back to its "drive straight" position. This is exactly the point of making the kingpin oblique. It gives the front wheels a natural tendency to right themselves, making the car more stable.

In order to see how it works we exaggerated the tilt of the kingpin. Since cars are rather heavy, it is enough to tilt it by just a tiny bit, so little that it is hard to notice. This is enough: When a driver turns and then lets go of the steering wheel, it will turn back all by itself and the car straightens up. Similar arrangement can be found in scooters, bikes and motorbikes, where the pin holding the front fork is tilted back. Because these vehicles are much lighter, the tilt is more pronounced and you can see it now that you know what you should be looking for. On bikes they often make this effect stronger by bending the ends of the fork forward.

Now it's time to attach our wheel to an actual car and see how things work. For simplicity we will not use suspension and just worry about turning the wheels.

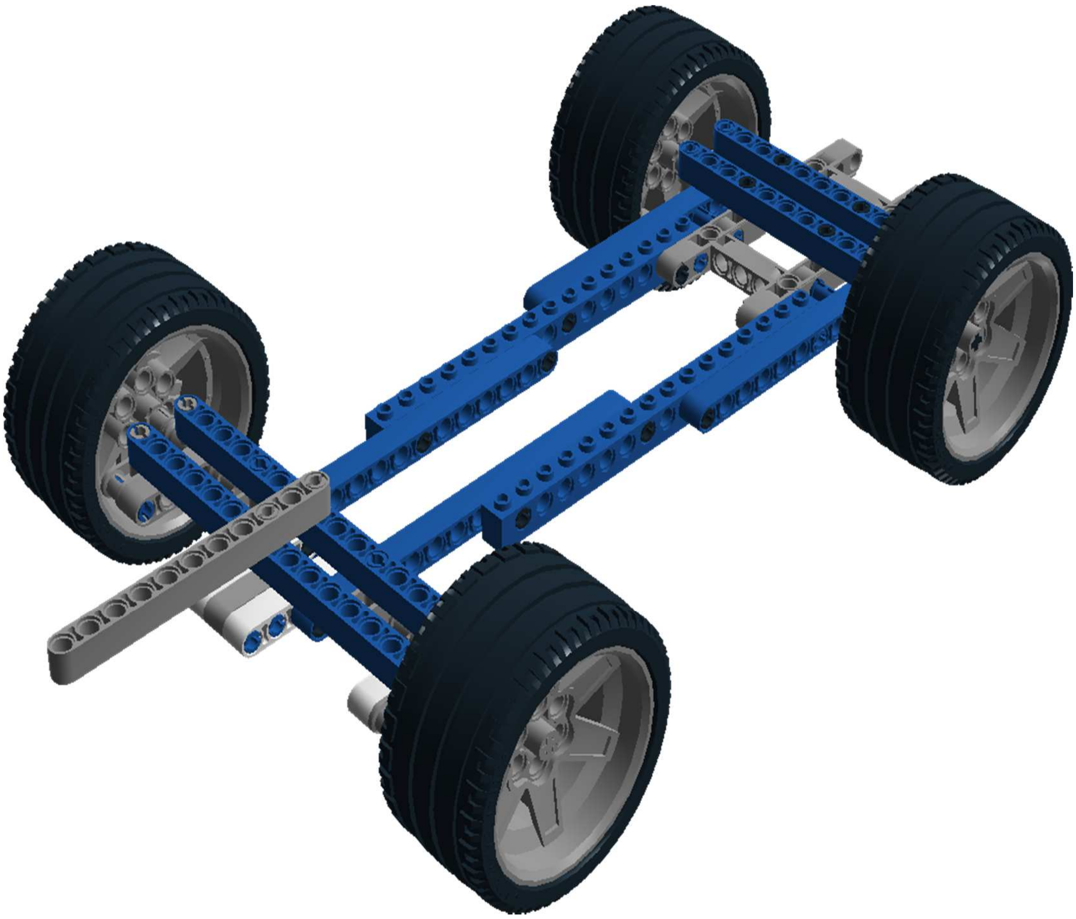
Project 2f. Tie rod in forward position.



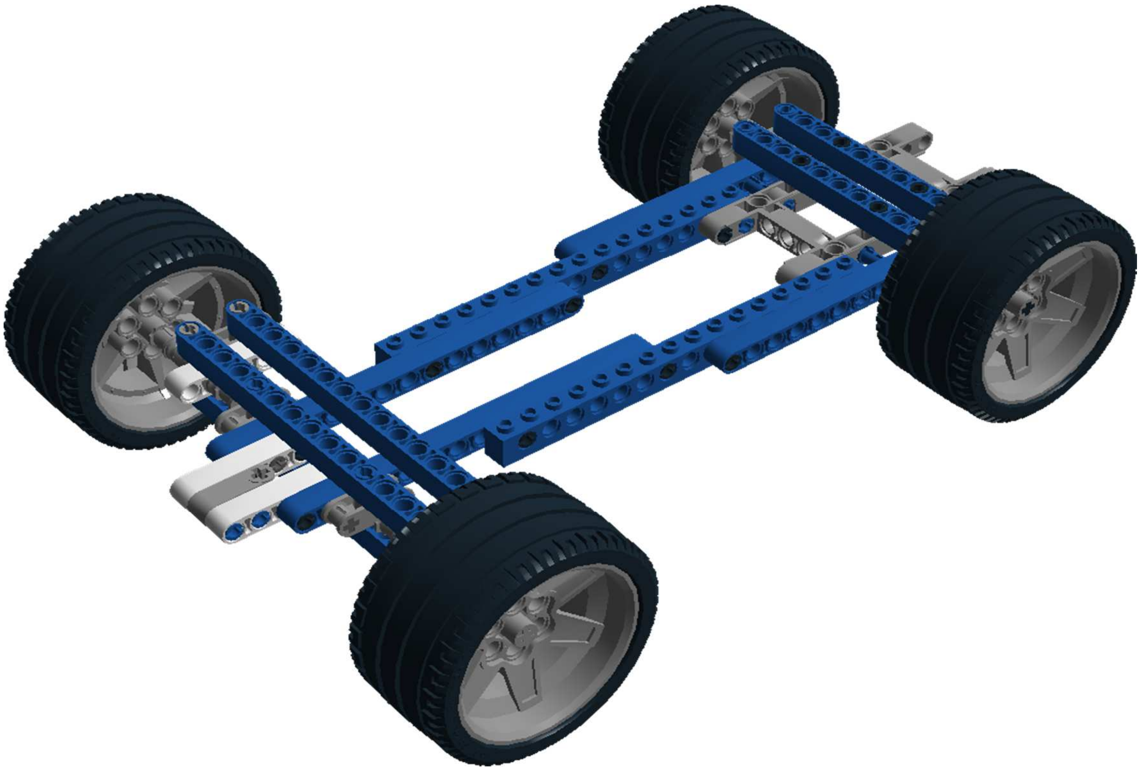
We prepared a wheel assembly here that will serve us well in almost all remaining models in this project: the wheel, its axle, the kingpin (in red) and the steering arm (in blue). Note that this time the kingpin is closer to the wheel (in fact just next to it), so now the wheels will not wobble around that much when we turn them.

We connected the wheels to the car frame using two beams, which is simple and gets the job done. To control the steering arms we also used the simplest arrangement possible, we simply connected them using another rod, this is called the tie rod. This makes sure that the wheels work in unison. In this model we put this tie rod in the forward position. Try to move it left and right and see what it does with the wheels. You can see that steering is natural, if you want to turn right, you move the tie rod right.

This setup is quite useful with pulled vehicles (wagons and such). Attach another lever (pulling lever) and use it to pull our test car around. It goes really well, when we want to turn and start pulling at the lever sideways, the wheels automatically turn the right way.

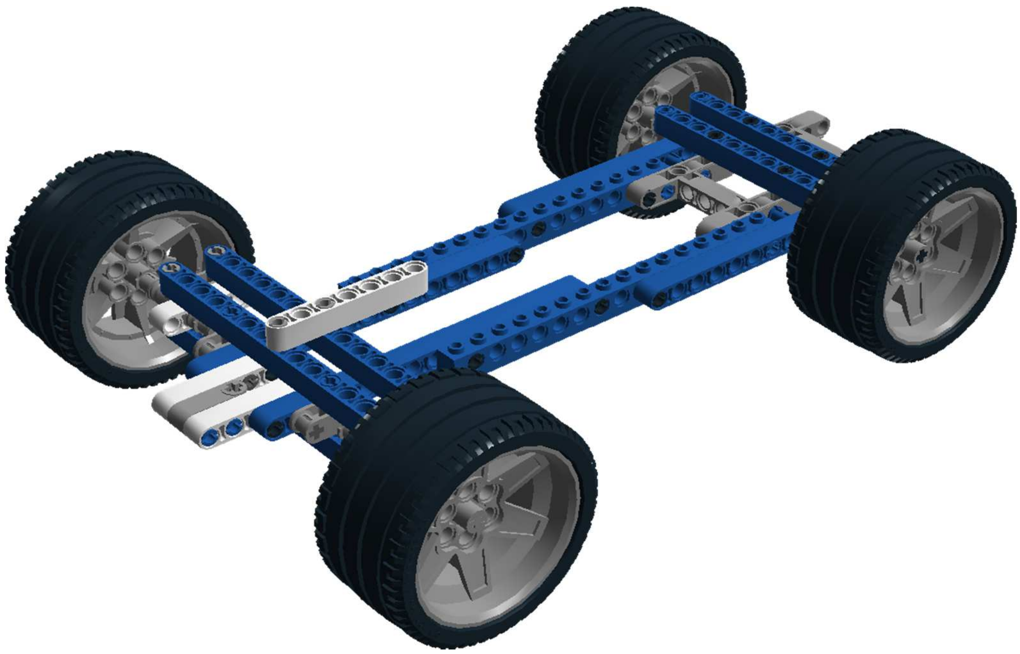


Project 2g. Tie rod in back position.



This arrangement is more common with cars, as it positions the tie rod closer to the driver. Try how it controls the wheels. To turn the wheels right we need to move the tie rod left now. This difference has to be considered when designing steering systems.

An interesting thing is that if we put a pulling lever protruding forward, like in the previous model, we could still pull the car and wheels would turn in the right direction. If you want, try it out. However, with this model we try something different. We position the lever towards the driver in the car.

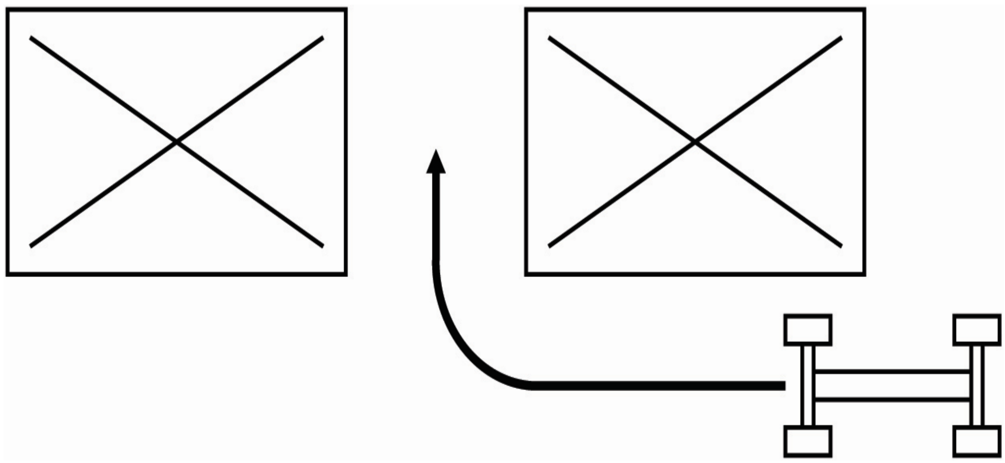


Steering using a lever has been used in early automobiles. Try to ride the car and see how it works. When we want our car to turn right, we have to move the steering lever left. This may seem unnatural, and it is possible to use a simple mechanical linkage to change this. Or we can just get used to it. It is not too hard, we may look at it this way: If we want to turn right, we position the steering lever so that its front points to the right. Think of the steering lever as of an arrow that you point the way you want to go.

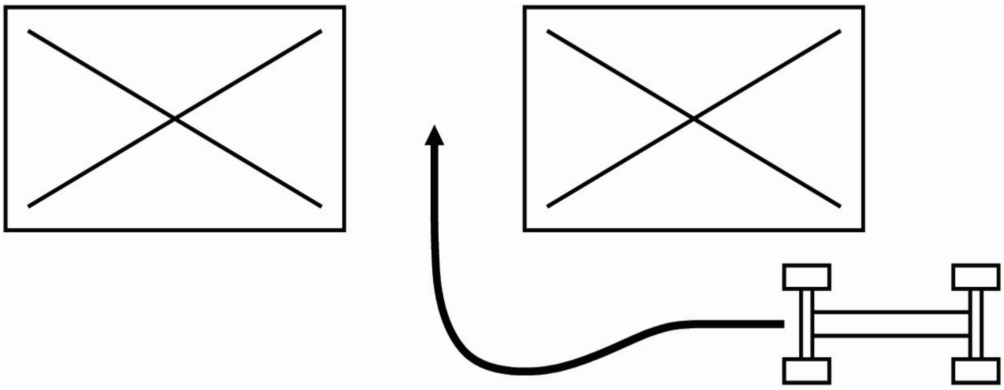
Early car inventors soon passed from levers to steering wheels, which is a more complicated construction, but more convenient for the driver. Before we explore this topic, we make a little side trip.

Exploration:

Steering is sometimes done using the rear wheels. What is the difference? Try the following experiment. Imagine that you are driving along a straight street and you want to slot your car into a parking space that is perpendicular to the street. You need to fit in between two cars that already occupy neighboring parking spots. Set up this situation with suitable props (boxes etc).



Try it out with our car: Drive along the street with the steerable wheels in front and try to somehow put your car into that parking spot. You will soon make an important observation: The rear axle is dragged by the front wheels, so it "takes shortcuts". When we turn around an obstacle, the side of our car or its rear has a tendency to bump into this obstacle. If we want to turn safely, we need to make our turns very wide, by first turning in the opposite direction in order to distance us from the corner we are taking. This is a lesson every driver learns very quickly.



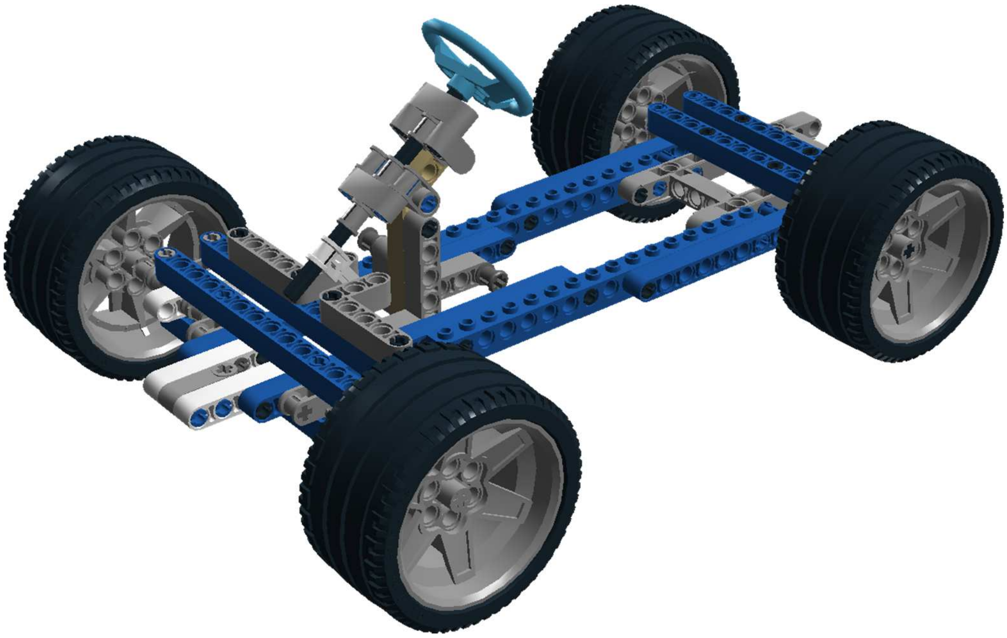
You may have already noticed that longer vehicles (trucks, buses) do just that when turning at intersections. This is especially important in cities. If a bus driver simply turns right at an intersection, the bus would collect pedestrians standing at the corner. They most likely would not like that.

Now turn the car around so that the steerable wheels become the rears, and try the same experiment again: Drive along the street and then try to park the car. It takes a while to get used to this kind of steering, but once you do, you should find the parking task easier. When we are steering using the rear wheels, it actually feels as if we first point the car in the right direction and then drive into that space.

Passenger cars use front steering because it is easier to learn and also more stable, hence safer. Some drivers prefer to go backward into parking spaces using reverse, because then it is as if they had rear steering. The rear steering is used in vehicles where manoueverability is important, for instance forklifts that must navigate narrow aisles in warehouses.

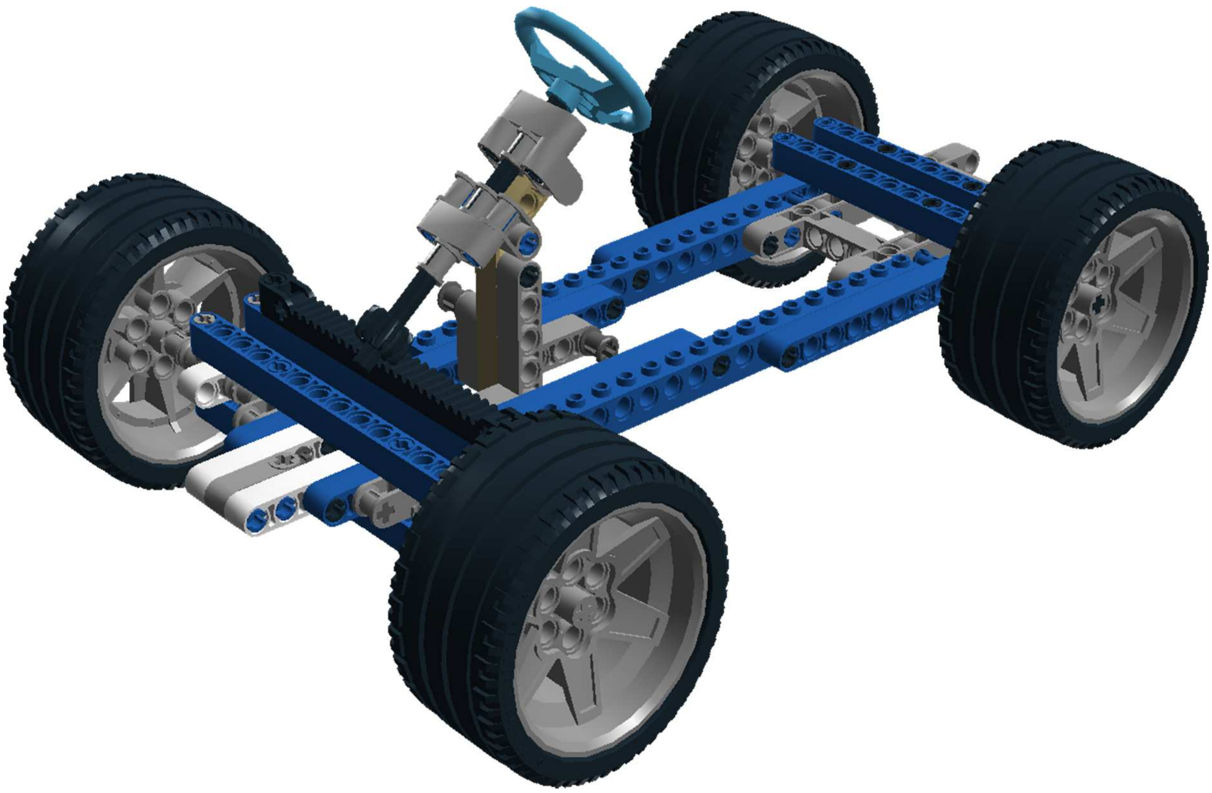
Now it is time to ask how does it happen that when we turn the steering wheel, the front wheels turn as well.

Project 2h. Lever steering (bell-crank steering).



This is one of the simplest methods to connect steering wheel with the tie rod. It has been widely used and can be still found in toys and go-carts. A more sophisticated form has been used in cars in the early 20th century. Since it has some disadvantages, for instance it is not easy to apply power steering to such a system, it has been soon replaced with better designs.

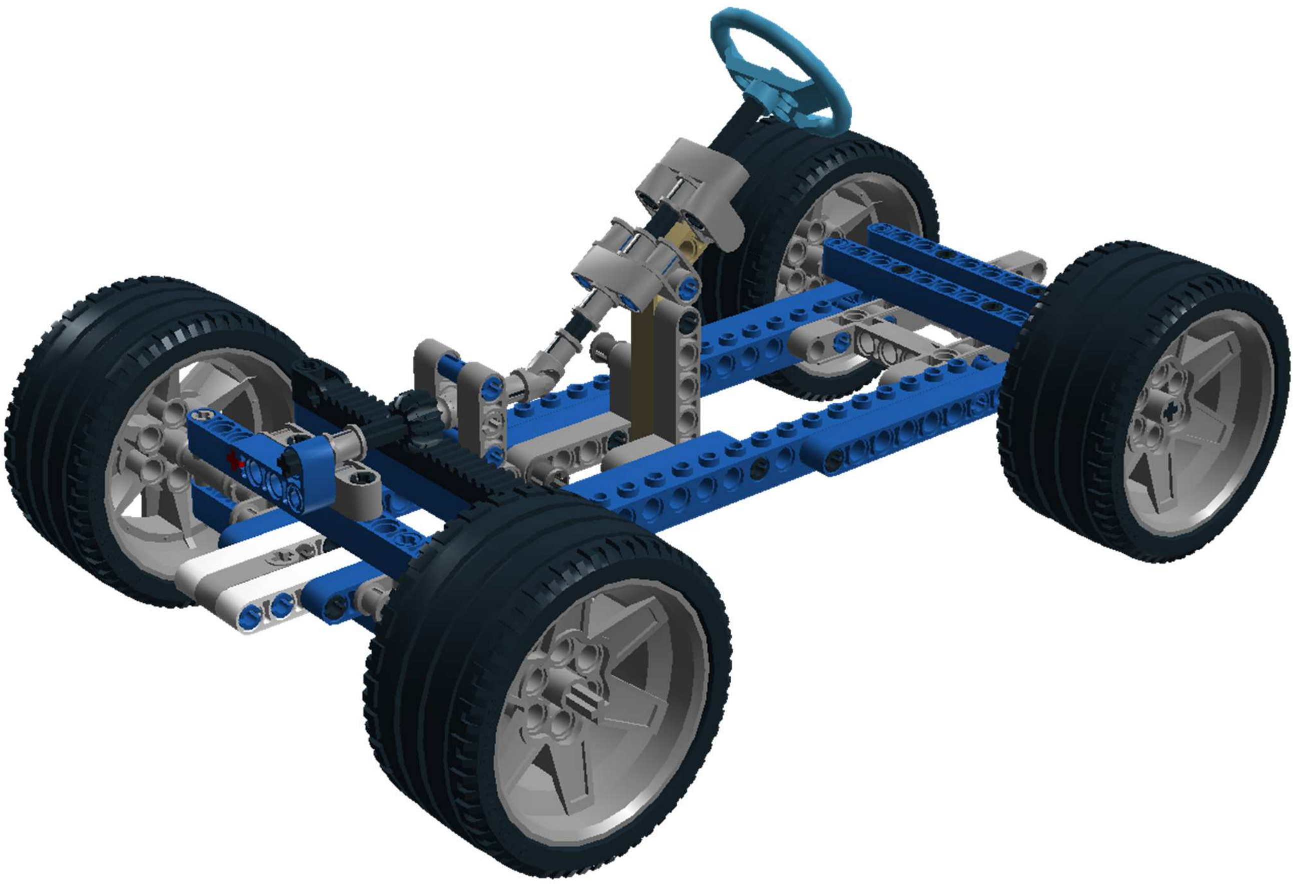
Project 2i. Rack-and-pinion steering.



This is the most popular type of steering. Our model shows that it can be very simple: An oblique steering shaft uses a special gear (a pinion) to move the rack left and right. In the real world this pinion has a conic shape to catch the rack well. Car makers sometimes use different devices to connect the steering wheel shaft with the rack, but the substance stays the same.

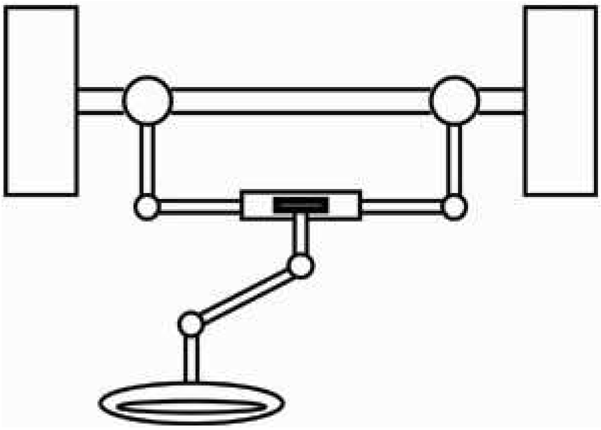
Try to drive the car around, see how nicely it works. If a Lego car has steering, you can bet that it has some form of this system.

Project 2j. Steering with universal joint and Ackermann geometry.



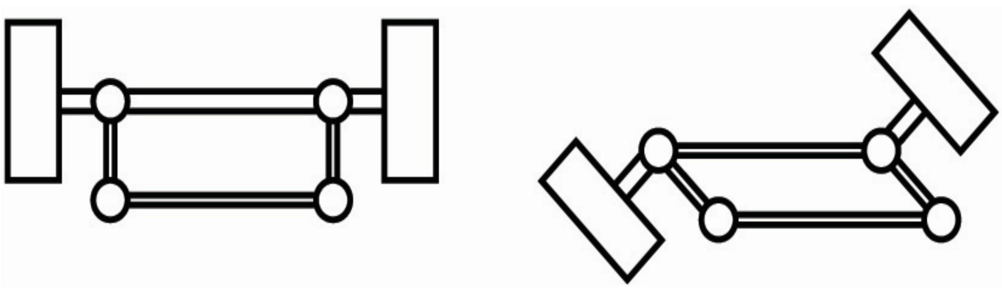
The setup we had in the previous model was simple (which is good), but it had one problem, the gear does not interact with the rack properly in the slanted position. In this model we show one possible solution to this problem, we change the direction of the steering shaft using the universal joint. By the way, this is your opportunity to see how good it really is. If you want, move the gear forward a bit so that it does not interact with the rack. Now you can spin the steering wheel as much as you want and observe the universal joint in action. We bent it quite a bit here, but it still works well.

Back to our model. Setting up the steering with universal joint is fairly common both in the real world and in the Lego world, and it also serves another role. We usually position the steering wheel on the left (or perhaps right), but fitting the rack there may be a problem. The universal joint allows us to re-route the gear (and rack) to the center of the car.



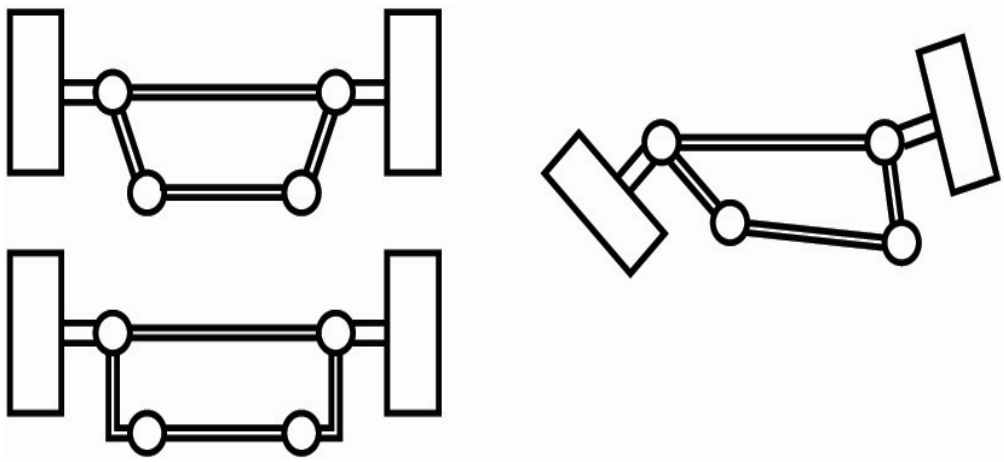
We used this model to show another interesting feature. Note that when a car turns, then the wheel that is closer to the centre of the turn goes along a smaller circle. Thus it should be turned more than the one on the outside. If we let them point in the same direction, they are forced to slide along the ground, which is not very good. Can we do something about it?

We start with another look at our basic steering setup. Note that the steering arms are perpendicular to the wheel axes. Actually, the important part is not the shape of the steering arms, but the position of the pins that connect them to the tie rod. In our previous model, the line connecting a kingpin with the connecting pin was perpendicular to the wheel axle. This means that the connecting pins and kingpins formed a rectangle. In this arrangement, when we move the tie rod sideways, the rectangle changes into a parallelogram, which means that the sides (and therefore also the wheels) are still parallel, they point in the same direction.



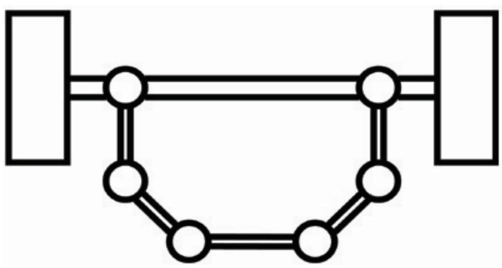
Note that the tie rod also moves forward a bit when we turn, this has to be taken into account when positioning the gear that moves it. Anyway, the rectangular arrangement keeps the wheels aligned, pointing in the same direction, and we observed that we would prefer something different. To arrange that we changed the setup of wheel assemblies in our current model.

Again, the shape of steering arms is not important, the key thing is that we moved the connecting pins closer to the car. This means that now these pins and the kingpins no longer form a rectangle but a trapezoid. This shape behaves differently when we move the tie rod sideways. The picture suggests that now when we turn, then the inner wheel turns more than the outside wheel.



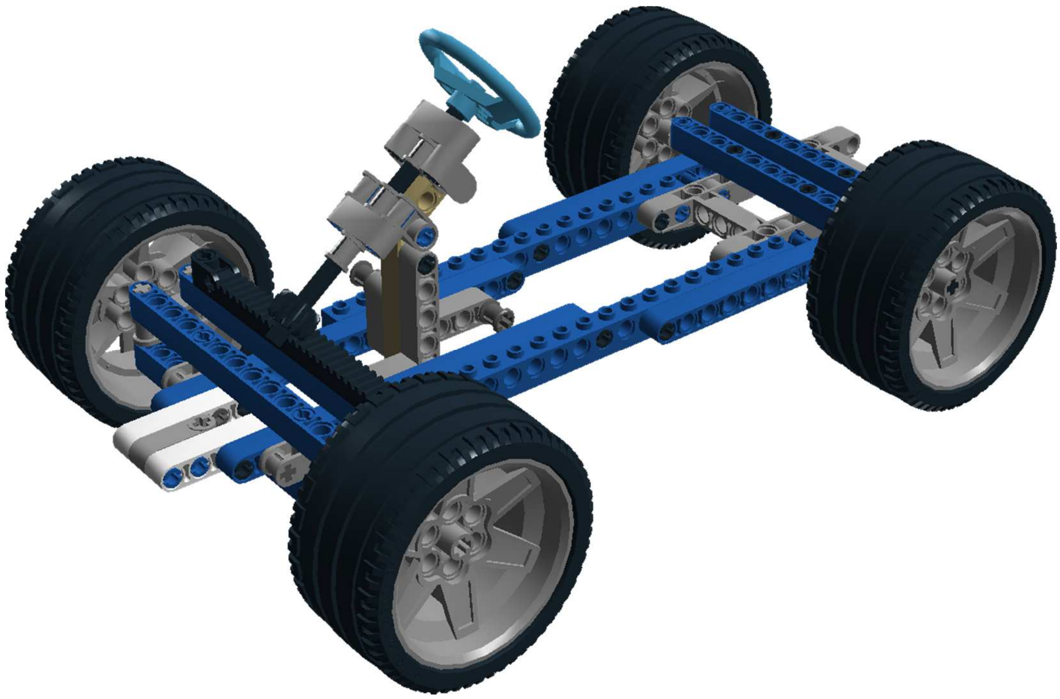
Try that it works also with our car. This kind of arrangement is called the Ackermann steering and every car is set up in this way. Note that this time when we turn, not only does the tie rod move forward, it also gets slanted. This is unpleasant, because the teeth on the rack no longer mesh properly with the gear driving it (pinion). You may experience some trouble with skipping teeth when the wheels are turned more. This trouble would be much bigger if we left the pinion in its oblique position as in the previous model, I tried and the teeth skipping problem became quite severe. So going to this more complicated setup with universal joint really paid off. In our main model we will use another approach to put the pinion upright, it is more complicated but takes up less room.

In real cars, the Ackermann geometry is usually achieved by using a polygon rather than a simple trapezoid. Such systems have the advantage that the rack stays in the same direction, only moving left and right. We will use such a system in our main model and also in the B model.



A small observation: By repositioning the pinion we made it possible for the wheels to move closer to kingpins. In fact, now the kingpins are inside the wheels! This is how real cars have it, the wheels now travel around even less when we turn them. As usual, there is something bad coming with the good. If we try to turn the wheels while our car is stationary, the wheels must turn on the spot, scraping against the ground. The friction is not severe in our small model, but an actual car weighs much more and pushes the wheels to the ground with a big force, so turning them on the spot requires a lot of force. Modern cars use power steering to assist the driver, so it is no longer necessary to wrestle with the steering wheel. Even so, it is always preferable to turn the wheels while the car moves, even a little bit helps.

Project 2k. Simple steering setup.

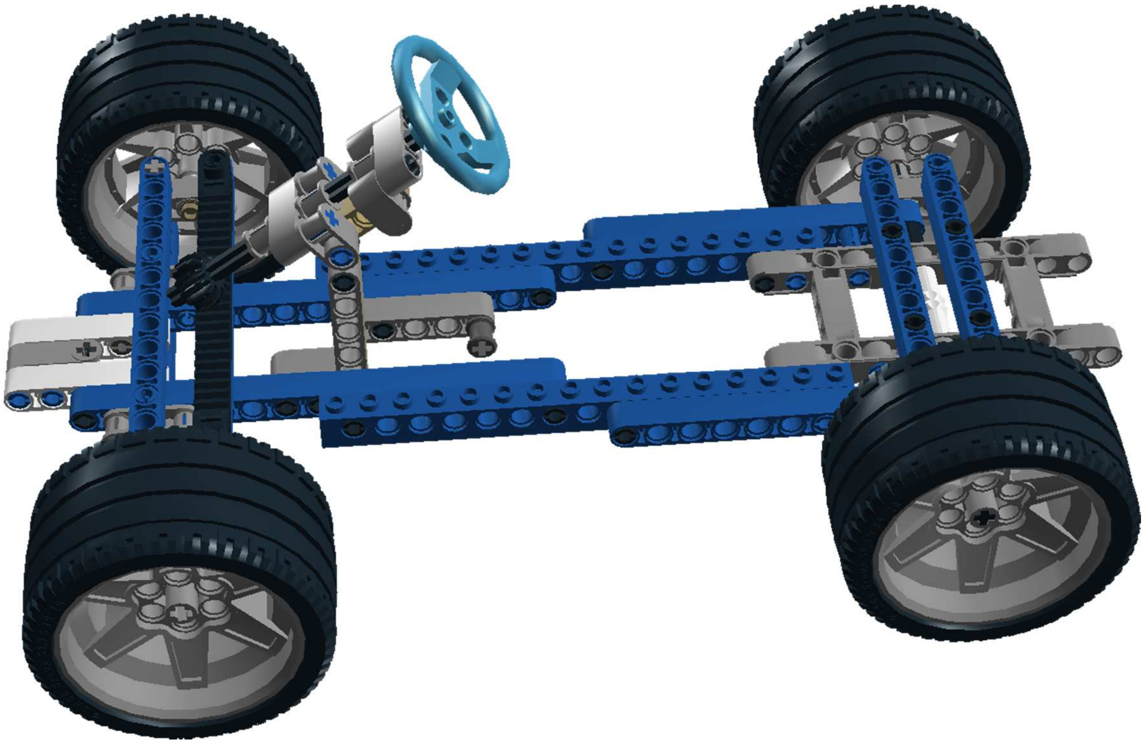


After exploring various fine points of real life steering we return to the world of Lego. Often we are happy with a just simple steering. Lego can help us there with special parts, for instance one can find a complete wheel assembly including the kingpin and steering arm all in one piece. But perhaps you do not have those in your spare parts bin. Here we show a simple arrangement for steerable wheels that can be done with common parts. This construction is used in the C model. Drive it around for a bit, you will see that it drives well. With this arrangement, our car has a very tight turning radius (it can turn sharply), which is something that will come handy in our next project. You can keep this car and use it there.

Project 3 - Differential

For this project we need a car from Project 2. Any would do, we will use pictures of the last one.

Project 3a. Solid rear axle.

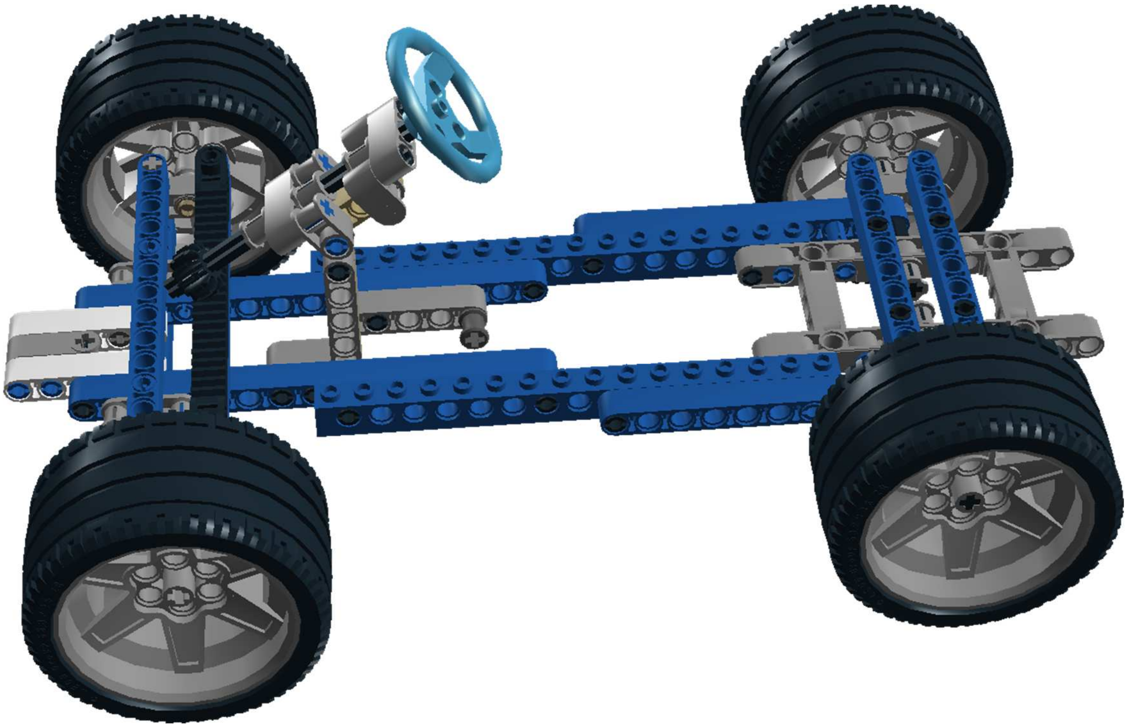


We start with an experiment. Take the car and drive it in a circle. Observe the path taken by individual wheels. You will see that outer wheels - be it the front one or the rear one - always follow a larger circle than the inner wheels. Since a larger circle has longer perimeter, the outside wheels have to cover a longer distance then the wheels inside. In order to do so they have to spin faster.

Put some markers (for instance small stickers) on the wheels so that you can follow how they turn. Now drive again in a tight turn. You should notice that the outer front wheel went around more times than the inner front wheel, exactly as expected. However, the rear wheels spin in the same way. And so they should, because they are connected by the rear axle. Thus to account for the different paths to take they have to scrap along the floor, which creates a drag and the ride is not smooth.

Already our forefathers thousands of years ago knew that wheels should be allowed to spin independently.

Project 3b. Split rear axle.



Now the rear wheels can turn independently. Try to ride the car, you should feel that the ride is smoother when turning. You can check using markers that the rear wheels spin at different rates in turns.

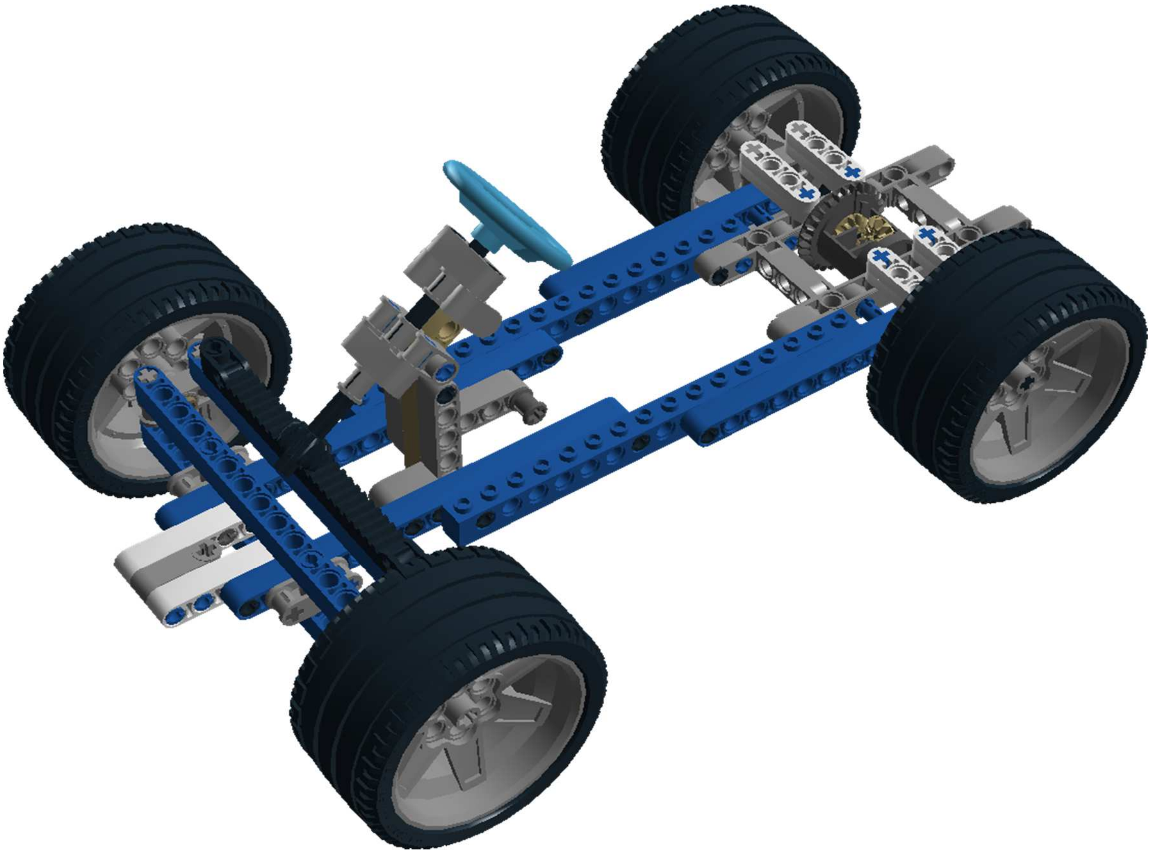
Now comes a good question: What if we actually use the rear wheels to power our car? When there is just one common rear axle, we simply attach a gear to it and power the wheels through it. But we already know that this is not a good idea.

With split axles, one could try a simple trick, attaching the gear to one of the axles. This would work, but not too well. Pushing along just one side of a car would encourage it to turn, which would require the driver to correct it all the time. There also might be a problem when one of the rear wheels find itself over a hole or on a patch of ice. If this happens to be the wheel that we are powering, it will start spinning freely and we have a problem.

If we decide to overcome this problem by powering both axles directly, the engine will force them to spin at the same rate, bringing us back to the problem we had at the beginning of this part.

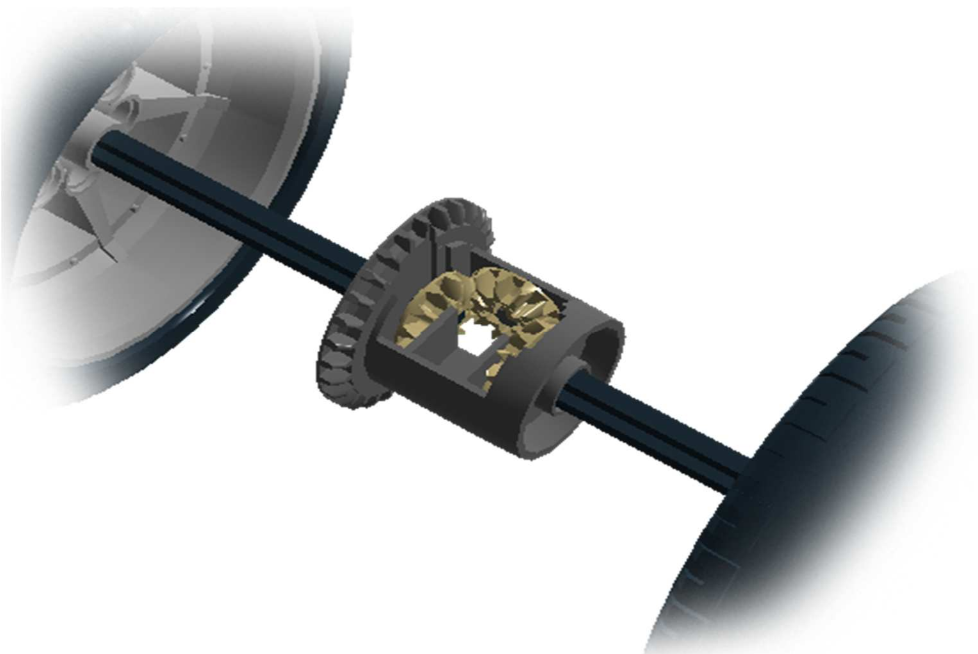
There si a solution to this quandary, it is called a differential.

Project 3c. Rear wheels with differential.



The strange box in the back can transfer revolutions from one side of the car to another. Let's try some experiments.

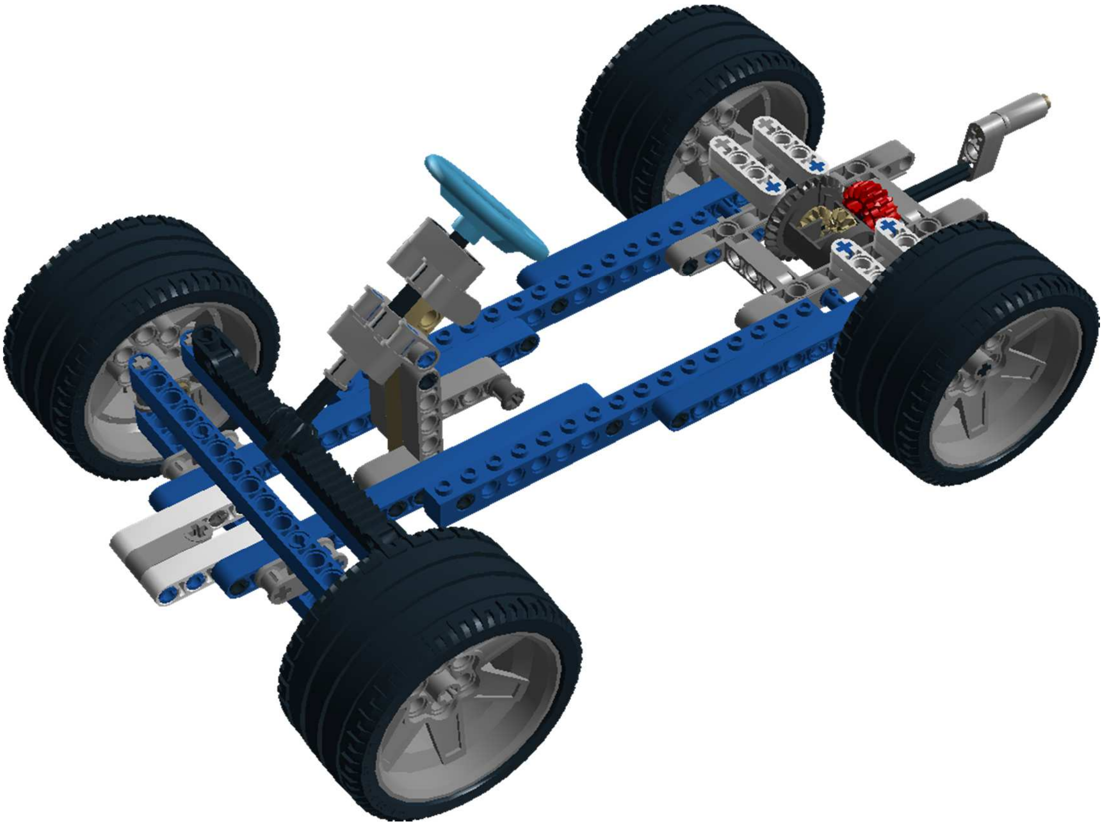
Lift the rear and keep the differential casing steady with your fingers so that you can see what is happening inside. Spin one of the rear wheels and observe what happens in the differential. The little wheel in the middle is the one that transforms rotation from one wheel to another. If both rear wheels spin at the same rate, then there is no adjustment needed and the middle wheel stays put.



When one rear wheel needs to spin faster than the other, the middle wheel in the differential takes care of the difference. You can put some kind of a mark (for instance with a washable felt pen) on the middle bevel gear to see what it does.

Put the car down and drive along a straight path. The differential casing should roll along with the wheels and the axles, but the little gears inside the differential should stay motionless relative to the differential. Why is it so? When we go straight, both rear wheels turn simultaneously, so no spinning motion needs to be transformed from one side to another.

Now ride the car in a sharp turn. The outside wheel wants to spin more, and the gears in the differential allow for it. The mark should indicate that the middle one moved.



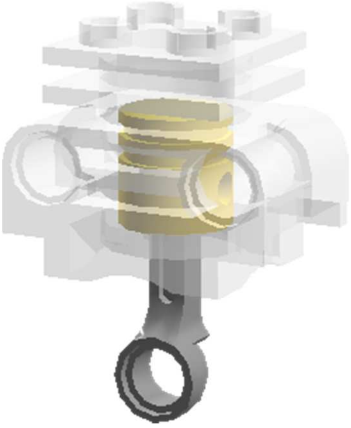
Now attach the large red gear with a crank. Lift the rear and pretend that you are an engine using the crank. If both sides of the rear wheel assembly are built equally well and parts are of equal quality, then both wheels should spin simultaneously. However, it may happen that one of the wheel assemblies has more resistance than the other, then that wheel will spin slower or even stop. Try to use your fingers to put some friction on the left wheel and on the right wheel while cranking, observe the result.

The first differentials appeared along with the first attempt at powering carriages by steam engines, so the first automobiles with gasoline engines at the end of the 19th century already had them and they remain a necessary part of any car with engine.

Project 4 - Engine

Here we will look at the most common type of automobile engine: The gas-burning four-stroke engine.

Project 4a. One cylinder engine.



The basic component of a fuel burning engine is one cylinder. We start with the casing, inside we put a "piston" (the yellow part) and its connecting rod that will allow us to move it up and down the cylinder. There should also be a lid on the cylinder that closes the opening on the top, you can put a Lego tile there or just imagine that the cylinder is closed on its top.

When an engine runs, the piston keeps moving up and down. Each movement up (or down) is called a "stroke". In a four-stroke engine there are certain four strokes that together make a basic cycle that is repeated over and over. We will explore it now.

To see it work we start with the piston up. When it is in its highest position, there is still some room in the cylinder, we will see why in a moment.

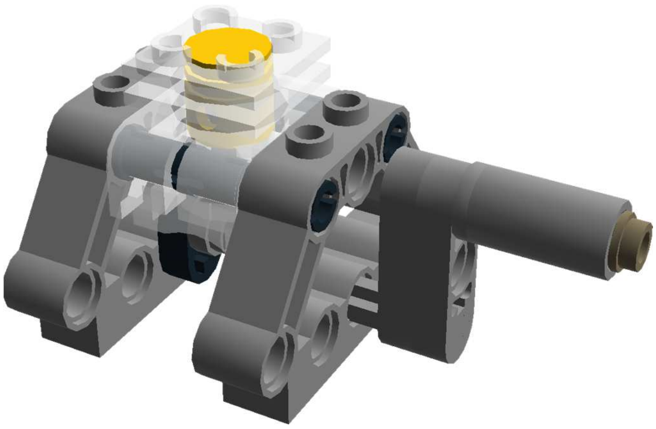
The first stroke is down. As the piston moves, the free volume in the cylinder enlarges and creates a sucking effect. We take advantage of this: We open a hole in the top of the cylinder and let in fuel mixed with air. The piston suck this mixture in while going down. This is called the intake stroke and it ends when the piston is in its lowest position.

Then the hole in the top closes and the piston starts moving up, compressing the fuel-and-air mixture into that little space left above. This is called, unsurprisingly, compression.

With the piston up, the fuel is ignited, in a gasoline engine this is done by a spark from a spark plug. This brings about the third stroke. If we just poured the fuel into the engine, it would burn slowly and there is no time for that. But we did some thing else: We injected the fuel into the air so that it forms a fine mist of droplets, and when the spark comes, it all burns in an instant. The fuel burns so fast that the word explosion comes to mind. This explosion would like to blow our cylinder into pieces, but we built it strong. With nothing else left to do, the force of explosion pushes the piston down and the engine finally does some work. This is called the power stroke, but people also call it combustion.

Now the piston is in its lowest position again. To get back to the beginning, the piston needs to move up. A hole opens in the head of the cylinder and the piston pushes out everything that is left after the explosion, namely the smelly smoke that then travels via pipes out of the car. This is called the exhaust stroke. We are ready to start again.

Now we know what a piston does in an engine, but to be of any use, this up-and-down motion needs to be converted to rotary motion. This is done using a device called crankshaft. We easily build one. We also add a crank. Now you can crank the crank and see your one-cylinder engine at work. You can see that it takes two revolutions to go through the four strokes.



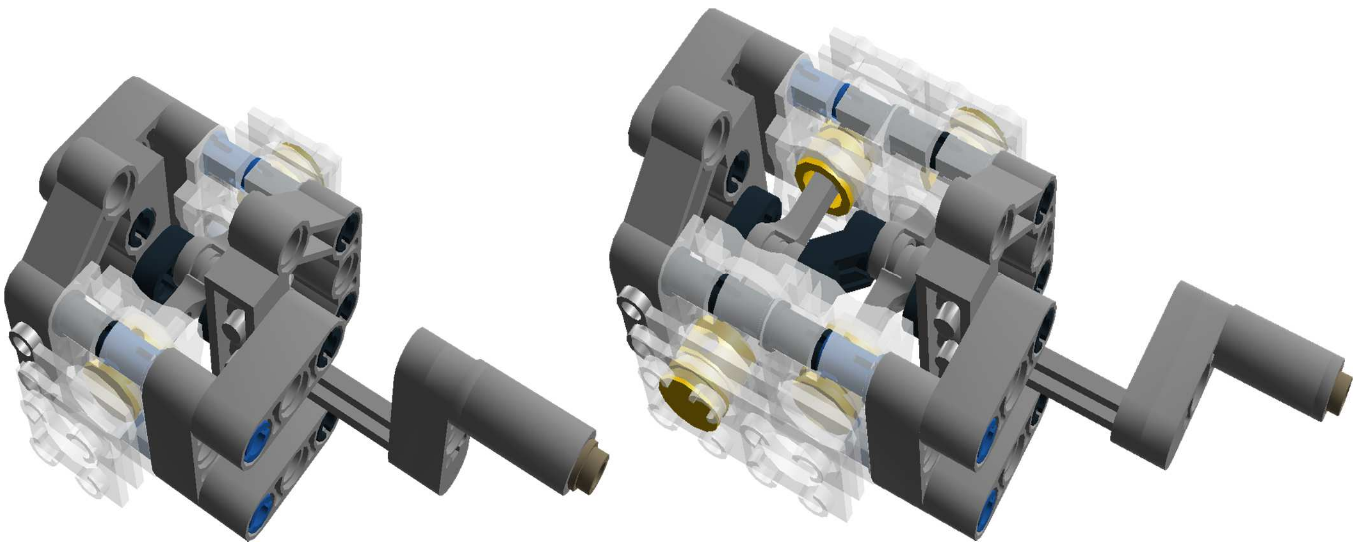
Nice, but there is a very good question: If the only stroke that does work is the third one (combustion), what makes the engine do the other three, in particular the compression part where obviously quite a bit of force is needed?

We get help from the momentum. Once we get the engine running at some speed, the rotating parts want to keep rotating. And because they are too light to actually manage the work, one-cylinder engines have (rather heavy) flywheels attached to their shafts. This means that it takes some effort to get them actually running (you surely recall people pulling at strings to start their engines in boats, lawn movers, or chainsaws), but once the wheel gets going, it just keeps going.

One-cylinder engines were used in early motorcycles and automobiles. Since they tend to be simple and light, they are still in widespread use in go-carts, small motorcycles, mopeds, lawn movers, chainsaws etc. It should be noted that one-cylinder engines are usually two-stroke engines, where the four stages we listed above are done in parallel, so that only two strokes are needed. If this piqued your curiosity, you will surely find information in books or on the Internet.

While the momentum always plays part in engine's running, we usually try to help things going by connecting more cylinders together, so that when one needs energy to keep going, another helps with its combustion stroke. Of course, more cylinders also means more explosions withing a given time and therefore also more power. There are several interesting arrangements for two or more cylinders.

Project 4b. Flat-twin and flat four engine.

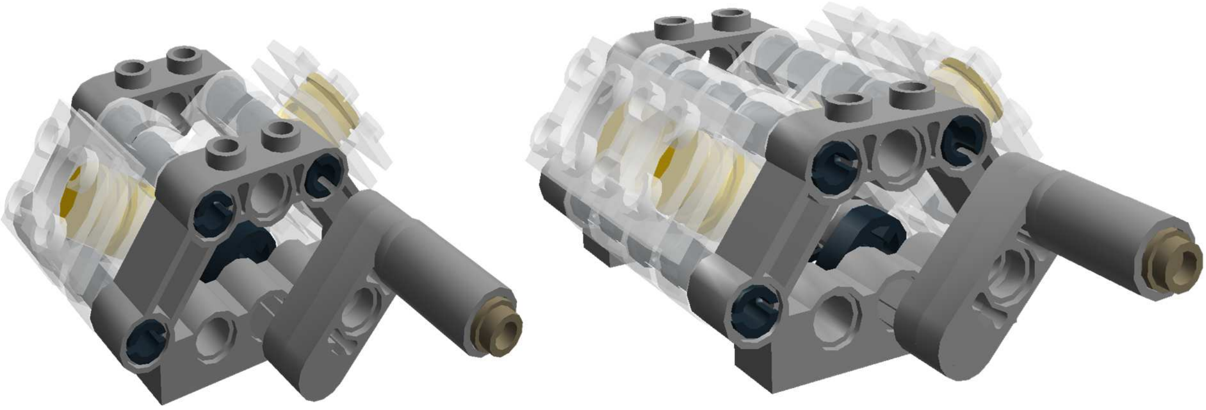


You can choose whether to build an engine with two cylinders (less work, simpler construction) or one with four cylinders, which shows better how pistons move.

This type of an engine is typically called a boxer. When it's just two cylinders, it is denoted F2. You would find such engines in motorcycles and in small airplanes, also some old small cars had it.

One can have several pairs like that arranged along a common crankshaft, our model shows how four cylinders would work. This is called F4 and four-cylinder boxers are quite popular in small airplanes. One can also build flat engines with six cylinders (F6) and so on. Some automobile manufacturers use boxer engines to this day.

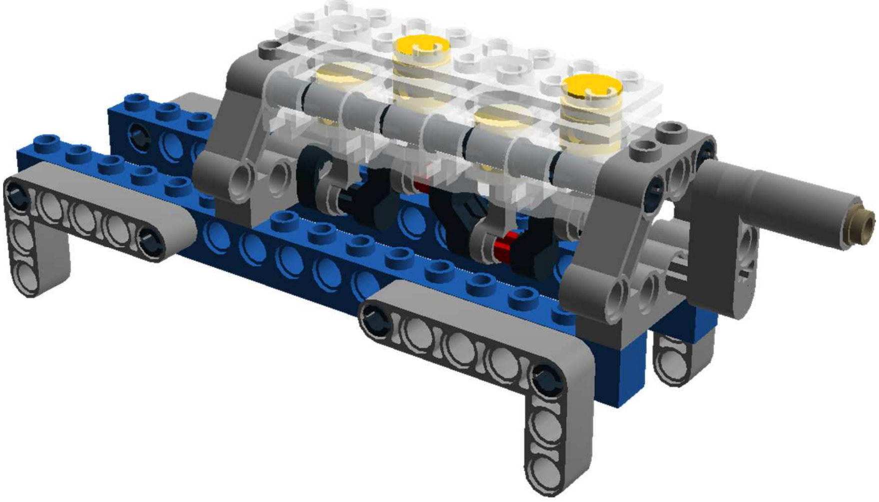
Project 4c. V-twin and V-four engine.



As you can see from the picture, the letter V is a good way to outline the basic arrangement of this engine, hence the name. Again, you can build a simpler version with two cylinders or a more complicated version with four cylinders. This time we would encourage you to go for four, since then you will nicely see how pistons take their turn in going up and down.

An engine with two cylinders would be called V2. This type of engine is often seen in motorcycles. Again, we get more power with more such pairs arranged along a common crankshaft. However, for four cylinders the complications outweigh advantages, so the V4 we offer as a model here is not a common type of engine. The real payoff for V-arrangement comes with six or more cylinders. In fact, V6 is the second most common type of engine in modern cars, but we do not have enough parts in out set to create it. Those V6 engines are quite powerful, so they are used in stronger cars. For ordinary passenger cars, four cylinders are enough, but a different arrangement is preferred.

Project 4d. Inline-four engine.



Also called straight-four engine and denoted I4, this is the most common engine in modern cars. Having four cylinders means that whenever a stroke happens, one cylinder will be in its working phase (expansion), and arranging them in one line results in a relatively simple and compact construction.

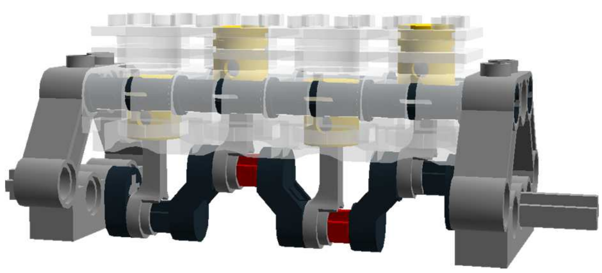
It should be noted that the engine we have in our cars have the crankshaft shaped a bit differently, the two cylinders in the middle have pistons in the same positions and the outside cylinders have them in the other position. Try to figure out how to make this with parts of this set.

How do we control such an engine? The most important input is the control over how much fuel is put in for every combustion. If we put in more, the explosion is stronger, the piston is pushed faster, and the engine starts going faster (and also provide more power). When we put less fuel for every combustion stage, the engine slows down. This is controlled by a lever on the floor of the car, the gas pedal. In older cars there was a direct linkage from this pedal to the engine, in currect cars the pedal sends signals to the car's computer and it takes care of the rest.

The revolutions of a typical engine in a passenger car run between, say, 600 and 6000 revolutions per minute (rpm). When an engine runs too slow, it may happen that there is not enough energy to actually keep it running, it would sputter and stop. In fact, those 600 revolutions mentioned above are good enough for an idle engine, but would not be able to do any work. When we want the car to start moving, we prefer something like 2000 rpm.

When an engine is run too fast, the forces involved get too much for it and it may crack, overheat, or even explode. When you look at a dashboard in your car, it will most likely have a dial there showing revolutions, and the end of the range is marked red, as a warning that it would strain the engine too much. A typical passenger car would thus use rpms between, say, 2000 and 4000 while travelling.

You can keep this engine (without the stand) for the main model, the crank will come handy in our next project.



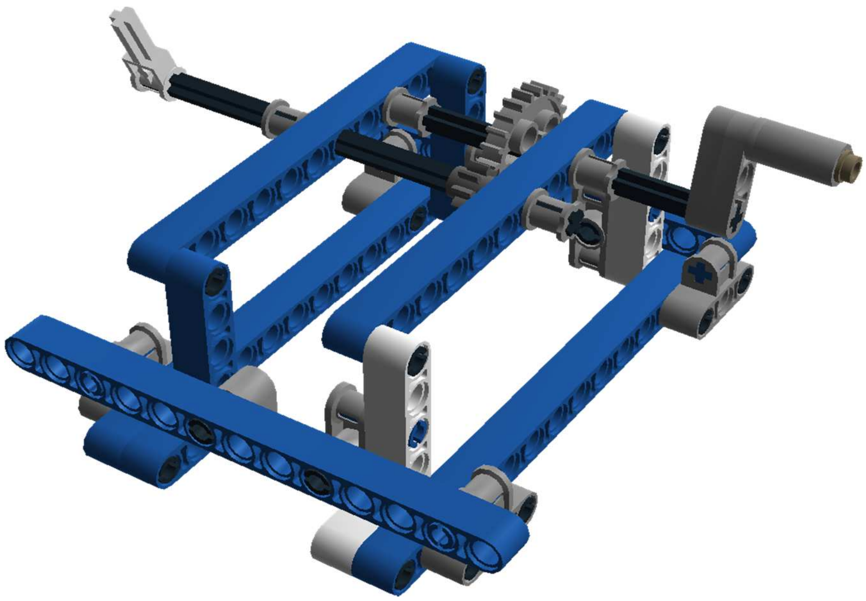
Project 5 - Gears, gearboxes

Our engine creates power in the form of a spinning shaft and we need to deliver it to the wheels. We already met one important step on the way, just before the power gets to the wheels it passes through the differential. However, there is another very important stage - the gearbox.

What does it do? Imagine a car that is just starting off. At that moment, its wheels turn very slowly. If they were connected directly to the engine, the engine would also work very slowly and the "explosions" supplying energy would happen too infrequently. Thus the engine would not have enough power to move the car, it would stall and stop going.

We need to connect our engine to wheels in such a way that it spins much faster than the wheels. Or, from the point of view of the engine, we need to slow down the revolutions before they get to the wheels. How is this achieved? By using unequal gears, that is, wheels with different numbers of teeth.

Project 5a. Understanding gears.

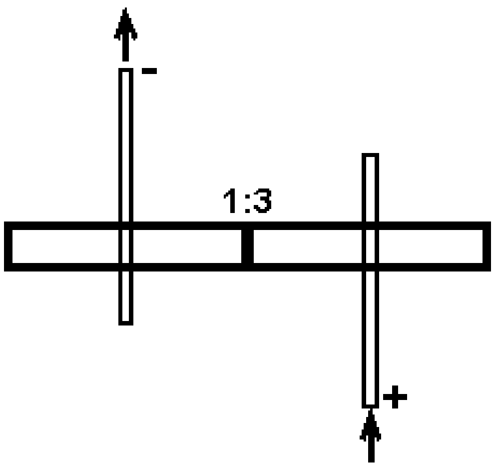


At the start we have just two gears. What happens when we crank the handle?

The key location is the place where the gears meet (contact point). Since teeth cannot skip, the number of teeth that passes through the contact point on one gear within some time period must be equal to the number of teeth that the other gear moves through it within the same time frame.

The gear that we drive directly by our crank ("input gear", attached to the "input shaft") has 24 teeth. When we turn the crank once, also the second gear (small, the "driven gear" or "output gear") must somehow arrange that its 24 teeth pass through the contact point. However, it has only 8 teeth, so it has to turn more than once. In fact, we easily see that it has to turn three times. This is simple to check: Turn the crank once and count how many times the output shaft spins. Yup, it works.

In engineering, we express the substance of this gearbox as a ratio of the number of teeth of the output (driven) gear and the number of teeth of the input wheel. In our case we would say that the gear ratio is 8:24. This can be simplified to 1:3 and we readily interpret it, the output shaft will do 3 revolutions for every revolution of our input shaft. Note the switch: When we create such a ratio, we put the output to the left, but when we want to see the relationship between revolutions, we see the output on the right.

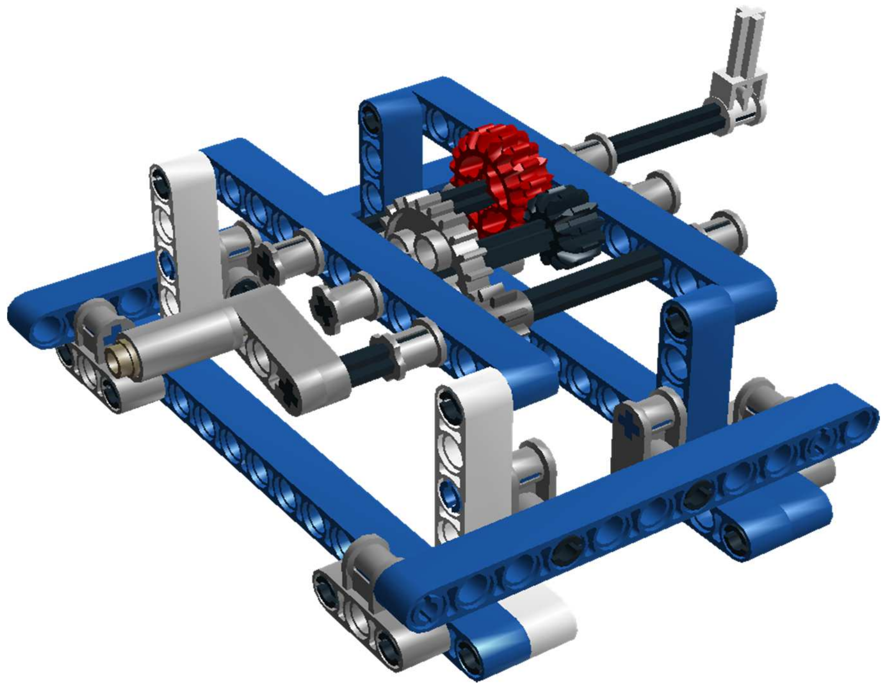


Note also how the directions change. We will assume in this book that we always turn the crank clockwise (from our point fo view), we will denote it by "+". The output shaft then turns anti-clockwise, denoted by "-". The essential information about our first gearbox can be therefore expressed by this diagram.

The energy we put into one revolution is used up on three revolutions on the output. Thus every revolution on the output is less powerful than revolutions on the input. When it comes to the power of a turning mechanism, engineers talk of torque, and there is a general law: the ratio of gears when flipped around tells us the ratio of torque. Thus the more we increase the revolutions, the less powerful each revolution will be. This is important when we actually expect to get some work done. If we are not careful, we may get our mechanism spinning so fast that it would not be powerful enough to do its task. Conversely, when we have a task that requires a lot of torque, we need to slow down the spinning.

We talked at the beginning about the need to slow down the revolutions when our car is taking off. Our simple gearbox is actually speeding things up. We chose to do so because it makes it easier to see what is happening. In our next gearbox we will switch the two gears, which will slow down the revolutions three times.

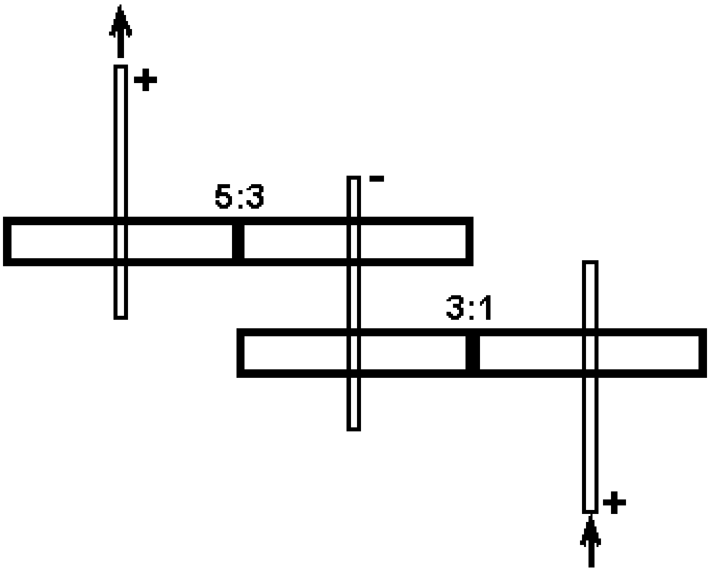
Project 5b. More gears.



Now we have two pairs of gears in contact, two of the four gears are connected by a common shaft. What does this gearbox do? First we look at the first two shafts from the right. The only gears that matter are the smallest and the largest that we already met in the previous project, so we know that the middle shaft will now spin three times slower than the input shaft, the gear ratio is 3:1. We can cancel in this ratio (imagine that it is a fraction) so that the first number becomes one, we get 1:(1/3), so every time we turn the crank a whole circle, the middle shaft does one third of a revolution. On the other hand, each rotation of the middle shaft will be three times as powerful, which comes handy, because it takes a lot of power to get a car moving. Actually, it will only be **almost** three times as poweful, because some energy is always lost when transmitting power through gears.

Now we imagine that the middle shaft is the source shaft for the third one. It has a black 12 tooth gear that connects with a red 20 tooth gear on the output shaft. Thus, just taking these two shafts, we see the gear ratio 20:12, that is, 5:3. When we rewrite it as 1:(3/5), that is, 1:0.6, we see that for every turn of the middle shaft, the third one makes slightly over half a turn.

Now we need to put it all together. We will use the following fact: When gear transmissions are put one after another like we have them here, then the gear ratios multiply. This means that the whole gearbox we have here has gear ratio (3:1)*(5:3). This gives 15:3, that is, 5:1 (you can write the ratios as fractions and see that the three cancels). So it seems that for every five turns of our crank, the output shaft is going to turn once. We easily check that it is, indeed, true.



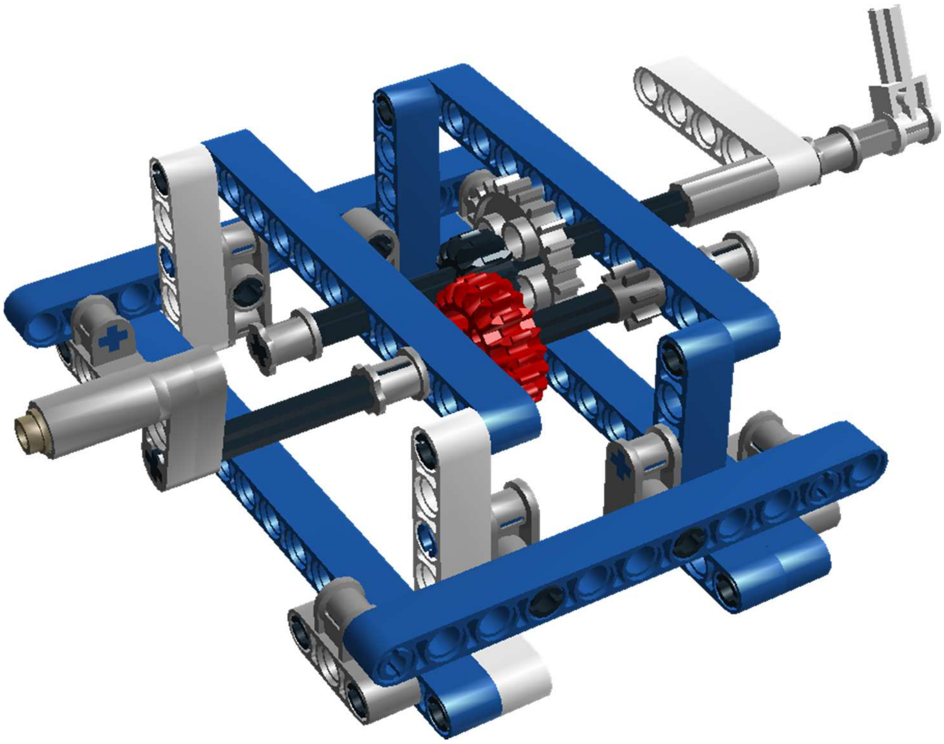
Note also how the direction of the spinning changes from shaft to shaft. We easily capture the whole situation in a diagram.

Let's revisit our car. We used a gear ratio that makes the wheels spin slower to get the car moving. Now we increase speed and suddenly we find ourself zipping along a highway. When a car goes fast, its wheels spin really quickly, a typical car wheel can make 1800rpm (revolutions per minute). If we still kept the gear ratio from the time we were starting, it would force the engine to spin even faster, too fast for our liking. First, going in high revs strains the engine, and second, it would guzzle the fuel like a thirsty elephant.

Note also that when we geared for take off, we were decreasing revolutions and thus increasing the force of each wheel spin. However, now that the car is going, we do not really need to push it with much force, it is enough to just nudge it along. This means that we can actually afford to use a gearing that does not produce that much torque.

For a passenger car, the gear ratio used for making the car move, called the first gear, is typically between 3:1 and 2.5:1. When a car goes very fast, it would use a gear ratio close to 1:1, sometimes even gearing in the opposite way, that is, making the wheels actually spin faster than the engine. The gearbox in a car thus has to be able to offer more gear ratios to choose from. How is that possible?

Project 5c. Simple linear gearbox.



When gears are in the position as in the picture, we can spin the crank and the output shaft does not move. This is the neutral position. To get some action, pull the left shaft forward (you can use the lever), so that two gears get in contact. It may happen that it will not go, because teeth of one gear will be bumping against teeth of another. If that happens, crank the input shaft a bit so that teeth align and then try again. Spin the handle and notice that the output shaft spins really slowly. This is not surprising, we engaged gears that we are familiar with and we know from the previous projects that we now have gear ratio 3:1.

Note that the other two gears also turn, but they do not contribute to the transmission of power from the input shaft to the output shaft. Thus we can ignore them.

Now pull the left shaft closer to the crank. Again, this may require some cranking to align gears properly. Try what happens. You should see that now the output shaft actually turns faster than the crank. Look at the gears and try to figure out the gear ratio.

Now only the black and red gears transmit power, we ignore the grey gears and see that the gear ratio 3:5, that is, for three revolutions of the crank we get five revolutions of the output shaft. This ratio is approximately 1:1.67, so it is smaller than one. This tells us that this gearbox setting makes revolutions get faster, but each has lower torque (less power).

We just saw the core functionality of a gearbox. There are two gear ratios ready, one for slow start and the other for fast driving, and we choose one using a handle. While technical details may differ, this choosing of prepared ratios is what drivers do when they move the stick about.

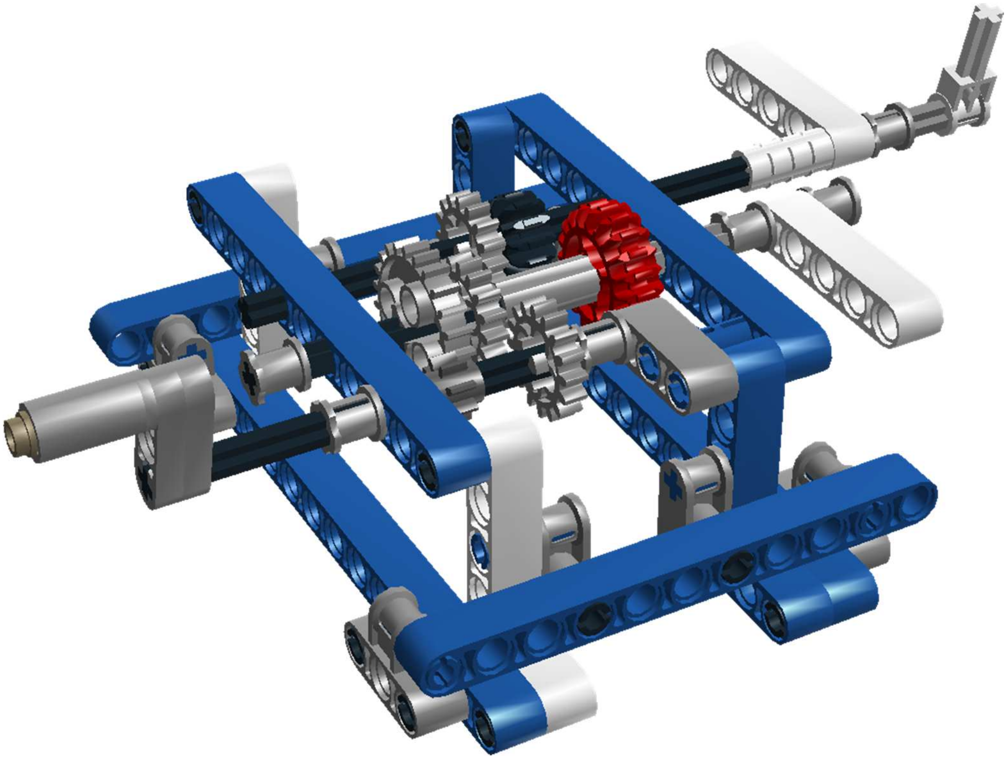
This kind of a gearbox is called a linear gearbox or a linear transmission. It's main advantage is simplicity. You most likely also encountered the biggest disadvantage: When you shift the shaft and teeth are not aligned properly, the wheels bump against each other and proper shifting is not possible. Early gearboxes worked like this and they had to be repaired frequently as the teeth did not like being grated against each other.

Many years ago, cars started to use a different kind of a gearbox that dooes not have this problem. But before we get there, we will look at another example of a linear transmission.

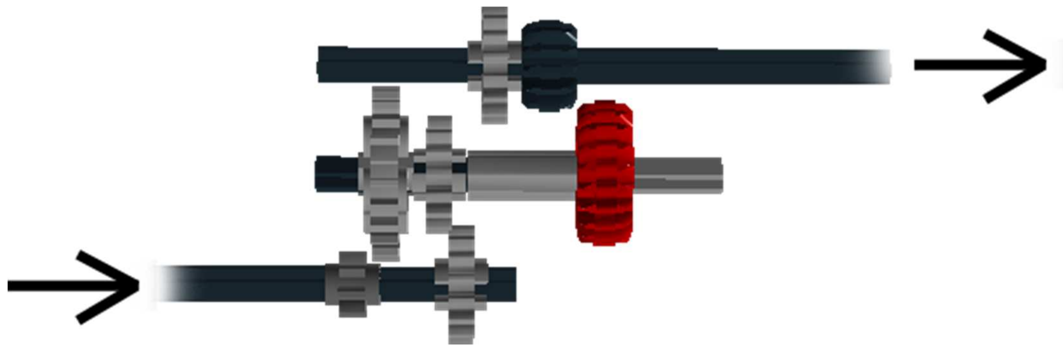
Project 5d. Four speed linear gearbox.

Having just two gear settings, one for extra slow drive and one for very fast drive, would not be practical. It is preferable to change gear ratios by smaller steps, that is, we also need some gear ratios between the two extremes. That's why gearboxes in cars offer four or more gear ratios for going forward. We will construct such a gearbox here.

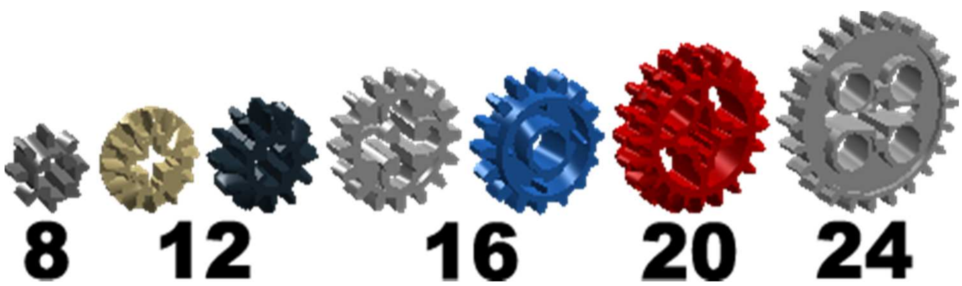
It would be possible to arrange more couples of gears along two long shafts, but axles in Lego are not that long. Instead we will get more ratios by using two shifing shafts.



There are two possible connecting position between the first and the second shaft (counting from the right). Once we position the middle shaft (we will say that it is forward or back), there are again two possible connecting positions between the middle and the left shaft. This means that there are four situations to investigate. Try to figure out gear ratios for each of them. We will see better how this works when we disregard the rig and just focus on shafts and gears.



We also offer an overview of common Lego gears so that you do not have to count the number of teeth for them.



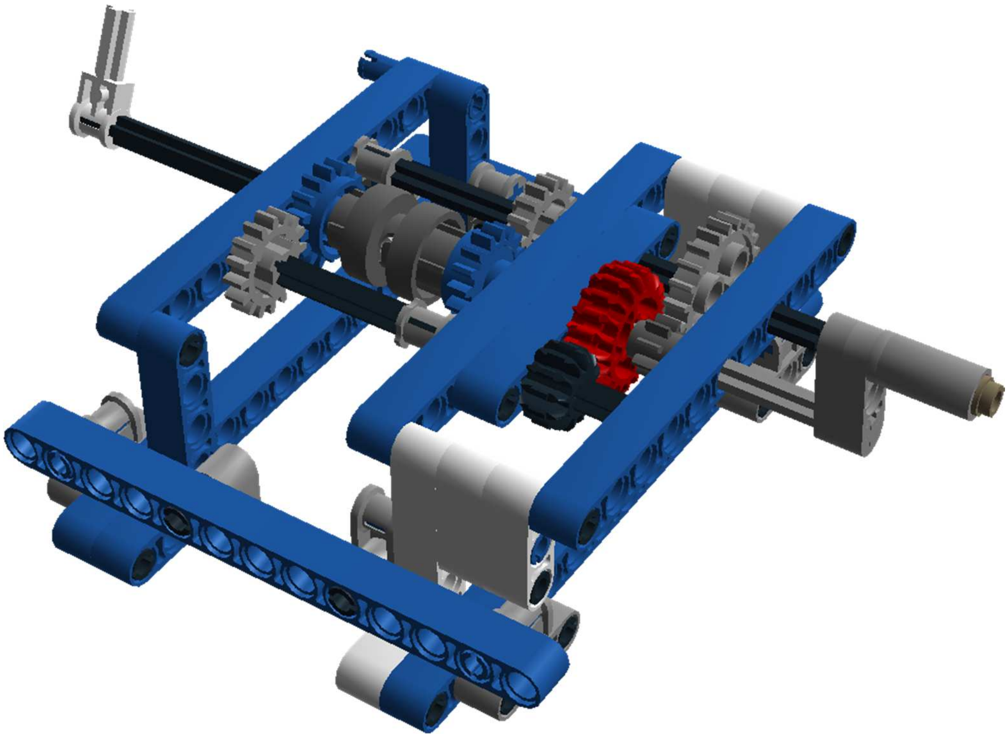
Our task is made easier by the fact that in every working position of shafts, only four gears actually do some work, the others are irrelevant.

Here we go:
Middle shaft forward: gear ratio 1:1. Left shaft forward: gear ratio 12:20, that is, 3:5. The gearbox: 3:5 (which is approximately 1:1.67 or 0.6:1), this speeds up, for every turn of the crank we get almost two turns of the output shaft.
Middle shaft forward: gear ratio 1:1. Left shaft back: gear ratio 1:1. The gearbox: 1:1. So the gearbox does not change anything in this setting (but some energy is lost in those gears).
Middle shaft back: gear ratio 3:1. Left shaft forward: gear ratio 12:20, that is, 3:5. The gearbox: 9:5 (which is approximately 1:0.56 or also 1.8:1), so this gearbox setting slows down approximately to half.
Middle shaft back: gear ratio 3:1. Left shaft back: gear ratio 1:1. The gearbox: 3:1. So this gearbox setting makes the wheels spin three times slower.

Summary: Our gearbox offers ratios (from the slowest to fastest) 3:1, 1.8:1, 1:1, 0.6:1. All spin the output shaft in the same direction. In a car, these would be called the first gear, the second gear, the third and the fourth gear. These gear ratios are not entirely realistic, but they are not too far off either. For comparison (and to satisfy our curiosity) we show actual gear ratios from a 5-speed gearbox in a certain passenger car.
1st gear: 3:1
2nd gear: 1.9:1
3rd gear: 1.3:1
4th gear: 1:1
5th gear: 0.8:1
So if we added another gear ratio between the second and third gear in our gearbox, we would be pretty close.

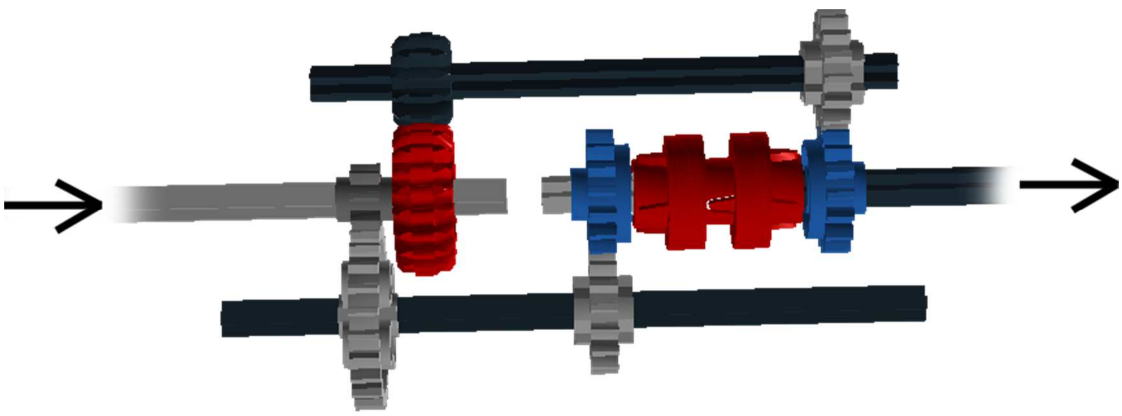
It is very likely that while experimenting with this geabox, you again encountered the problem of crashing teeth. Engineers found a way to solve this problem. In gearboxes used in modern cars the teeth are aligned at all times, we say that they are meshed. Obviously, we cannot have several different gears driving the same axle at one time, so the gears are meshed, but disconnected from the shaft they are supposed to drive. A special device is used to connect and disconnect these spinning gears from shafts.

Project 5e. Mesh gearbox.



In this model we will explore the substance of a mesh gearbox. Indeed, note that all gears are connected in this gearbox. What happens when we turn the crank? This input motion is split into the two side shafts using different gearing. We already met these gears before, so we easily determine that the left shaft spins a bit faster than we crank, the gear ratio is 12:20, that is, 3:5, which is about 1:1.67. For every spin of the crank, the left shaft does about one and half spins. On the other hand, the right shaft spins three times slower.

These two rotations are then fed to the blue gears on the middle shaft. Since the blue gears and the grey gears that feed them have the same number of teeth, the spin rates stay the same. That is, the blue wheel closer to the crank spins three times slower, while the blue wheel further from the crank spins somewhat faster compared to our cranking. We can see it well in the picture that focuses just on the gears and shafts.



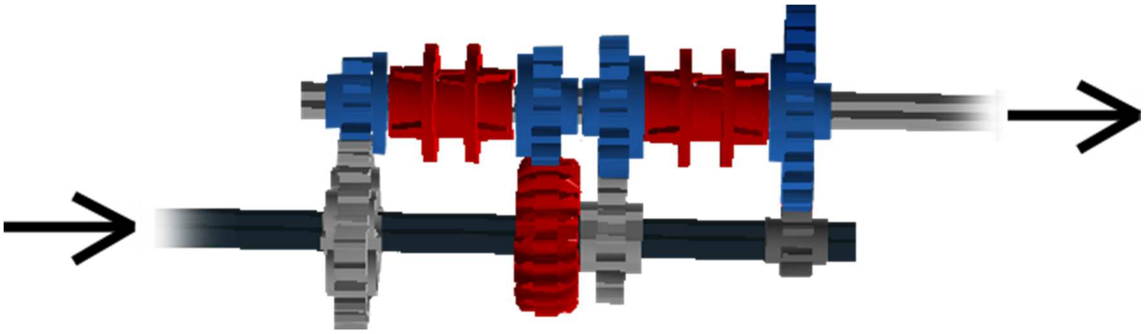
The central output shaft is not connected to the blue gears, which makes it possible for them to spin at different speeds. Those blue gears are called clutch gears. If we want to send power to the output shaft (and wheels), we have to connect it with one of the blue clutch gears. We do this by moving the large thing between them called the driving ring toward one or the other clutch gear, until they click together. Try it and see what happens. Note how the ridges on the driving ring engage the ridges on a clutch gear to transmit rotation.

Here's a good question: In our linear gearboxes we had a problem with clashing teeth when aligning gears. Is it not happening here? Well, it actually is, but not that much, because the ridges are far apart. This kind of a connection is called dog gear and one can find it in other places than just car gearboxes. For instance, if you have a microwave oven, it is very likely that the spinning dish is powered by a dog gear.

The fact that those ridges/teeth are far apart makes a tooth collision less likely, but it still happens once in a while, so a transmission like we have here is mainly used in racers and sports cars, where they appreciate its quick performance and do not worry much about having to replace it frequently. In passenger cars - where the users prefer not having to get repair bills often - gearboxes are more complicated. They are called synchronized mesh gearboxes. When we want to connect a dog gear with a clutch gear, a special device called synchronizer makes sure that before they engage, their rotation is adjusted so that they spin at the same speed and teeth align well.

Back to our project. By moving the driving ring forward or backward you can choose between two different speeds for the output shaft. Each time it spins in the same direction, so these would be different gears for forward travel. Our gearbox needs 8 gears to achieve this. This is an important concern, because in a mesh gearbox all gears are spinning at all times, so the more gears there are, the more energy we waste on those that are not needed for the actual chosen gear ratio. We will see below that much better designs are possible. This was just a practice model to see how the clutch gears and the driving ring work.

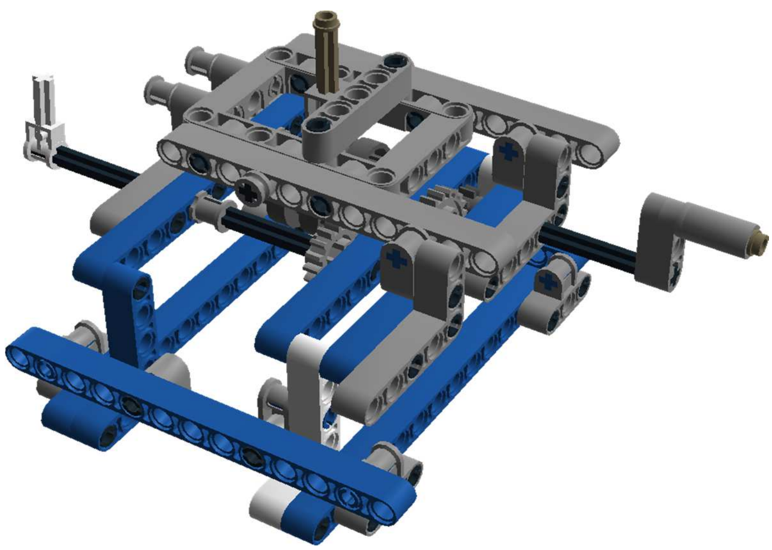
The clutch gears and driving rings are at the heart of gearboxes in modern cars. They actually use just one shaft to offer all the needed ratios to the output shaft, using clutch gears of different sizes. A four speed gearbox might look look like this.



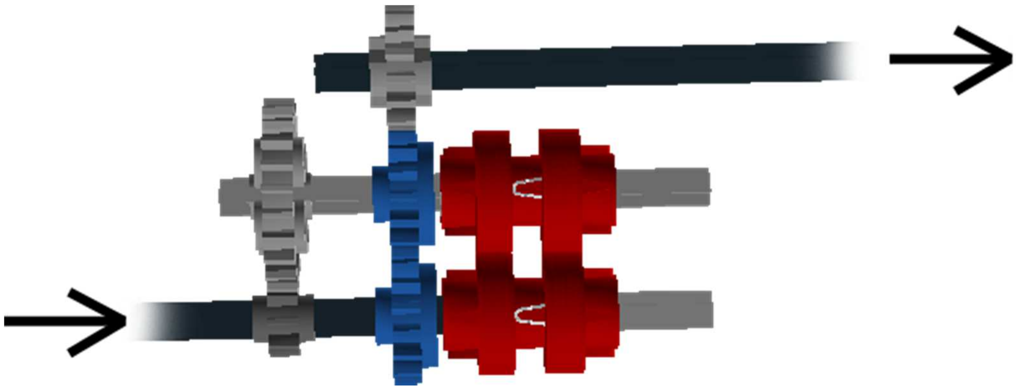
Unfortunately, we do not have such clutch gears available, in Lego there is just one size, so different approach must be used in the Lego world. We will explore it below. Before we dismantle our curent gearbox, we would like to point out some features that we will see in all gearboxes here. There is an important area - we will call it the selector area - where we choose which path the input should take through our gearbox. It is the part with driving ring(s) and blue clutch gears. This selector area is fed by two shafts (left and right) that offer power (they spin) to choose from. We will call them the source shatfs for the selector area.

It is worth noting that in many Lego sets you would see a design like our current model, but working "in reverse". Turn our rig around and imagine that instead of the crank you actually spin the shaft that originally served as output. Now your energy powers the middle shaft with the driving ring, but nothing else is moving. Using the driving ring you can choose whether to send the power to the left or to the right and then move it on to whatever place you need it. So this works as a switcher and Lego sets use such designs when they want to power several functions with just one engine.

Project 5f. Flat gearbox - 2 speeds with split input.



This project shows one of the two basic Lego strategies for creating more gear ratios in one gearbox. We offer the selector area two different speeds of rotation by splitting the power from the source (crank), just like in the previous model. However, this time we use just one extra shaft for that and the other source will be the input shaft itself. Another novelty is that now the selector area is two shafts wide.



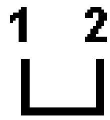
When we move the stick left and forward, the left driving ring moves back and the left blue gear picks up the revolutions of the left source shaft that spins three times slower than the input shaft. This movement is then taken through the grey gear with the same number of teeth (so no further chaneg) to the output shaft. In this case the gear ratio is 3:1, power goes through 4 gears and two connections, hence two changes in direction of spin.

When we move the stick right and forward, the right blue clutch gear picks up the original input shaft, so the gear ratio is 1:1. This is then transferred through the left blue gear (which is now free to spin) and the grey gear to the output. So here the gear ratio is 1:1, this gear selection uses 3 gears and two connections, so two changes in direction again.

We see that for both gear selections the output shaft spins in the same directions, so we can imagine that we have two different gears ratios for going forward. The position on the left slows down, so that would be the first gear. The position on the right is faster, we can call it the second gear.

This gearbox does the same job as the previous project (2 speeds), but it is much more efficient. Indeed, there are altogether five gears, compared to the eight gears we had earlier. I do not know of a more efficient design for a two-speed Lego mesh gearbox.

It often happens that one pays for good things with some disadvantages. What is not to like in this design? An important part in evaluating a gearbox is played by user friendliness. How easy or difficult is to go from one gear to another? We can see it from a picture that captures how the gear ratios are chosen using the stick, it is called the shift pattern. In this gearbox the shift pattern is

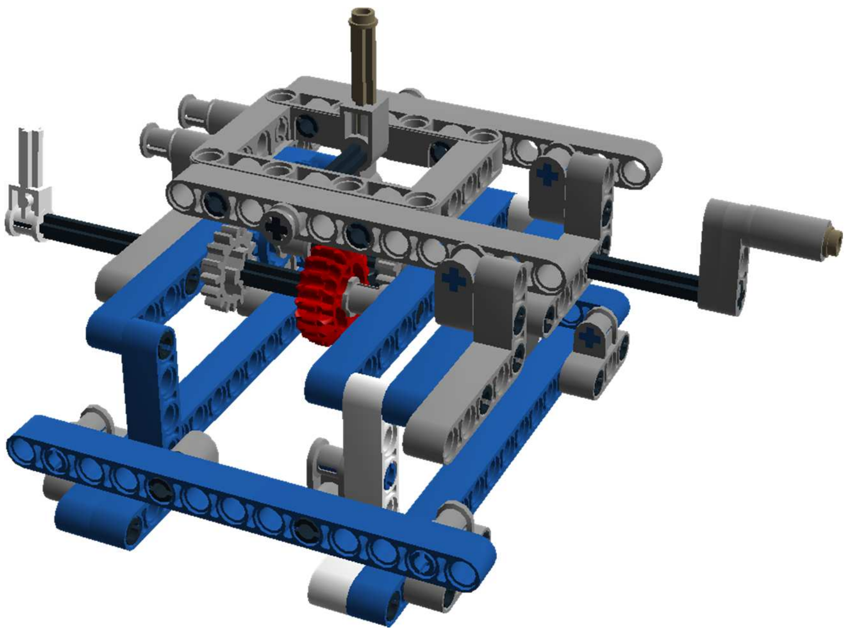


To change gears, one has to move the stick around, changing the direction twice. This is not very convenient. Such trade-offs are fairly common in engineering, usually one needs to weigh advantages and disadvantages of various designs. Perhaps we do not need to change gears too often, then we would be happy with such an efficient gearbox.

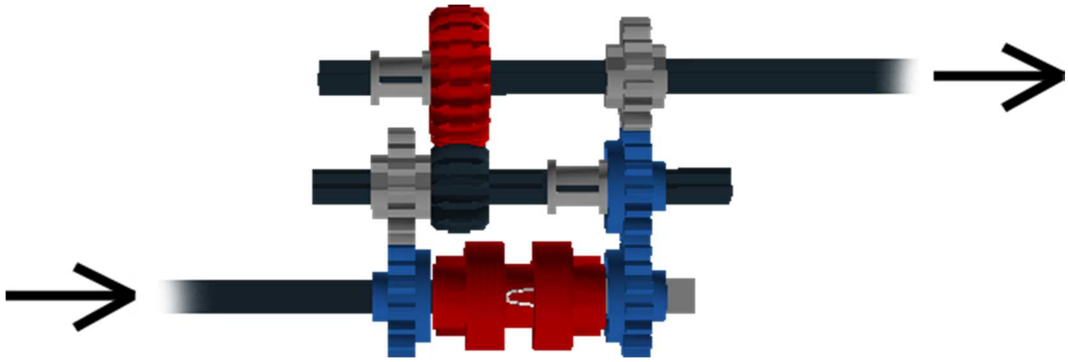
Some of the savings in number of gears can be traced to the blue clutch gear on the middle shaft. It actually does two jobs. When engaged, it serves as a selector gear. When it is not engaged, it is free to spin and serves as one of those gears that transmit power from one place to another. This is a typical feature of Lego gearboxes.

Note that the two source shafts spin in opposite directions, but things worked out in the end so that the output shaft always goes in the same direction. We can easily figure out which way various shafts go, since each connection between two gears means that we change the direction of spinning. What really matters is parity, whether there is an even or odd number of such changes.

Project 5g. Flat gearbox - 2 speeds with split output.



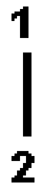
In this project we introduce the other possibility how to create different gear ratios. We have two clutch gears here on the same shaft, so when engaged, they will both rotate at the same speed. Only after selecting one or the other we start creating our rear ratios. Look at the gear arrangement and try to work out how this gearbox works.



When we push the stick forward, the clutch gear that is closer to the crank engages. Its action is first transferred to the second (middle) shaft using a gear with the same number of teeth, so this shaft now spins as fast as the input shaft. But then we transfer this rotation to the output shaft using unequal gears. Their gear ratio is the familiar 20:12, that is, 5:3, so the output shaft will spin slower. This gear slows down and uses 4 gears, there are 2 working connections and therefore two changes of direction.

When we pull the stick backward (towards us), we engage the clutch gear further from the crank. Its rotation is then transferred using two gears with equal number of teeth to the output shaft, so there will be no change in gear ratio. This selection has gear ratio 1:1, uses 3 gears and two connections.

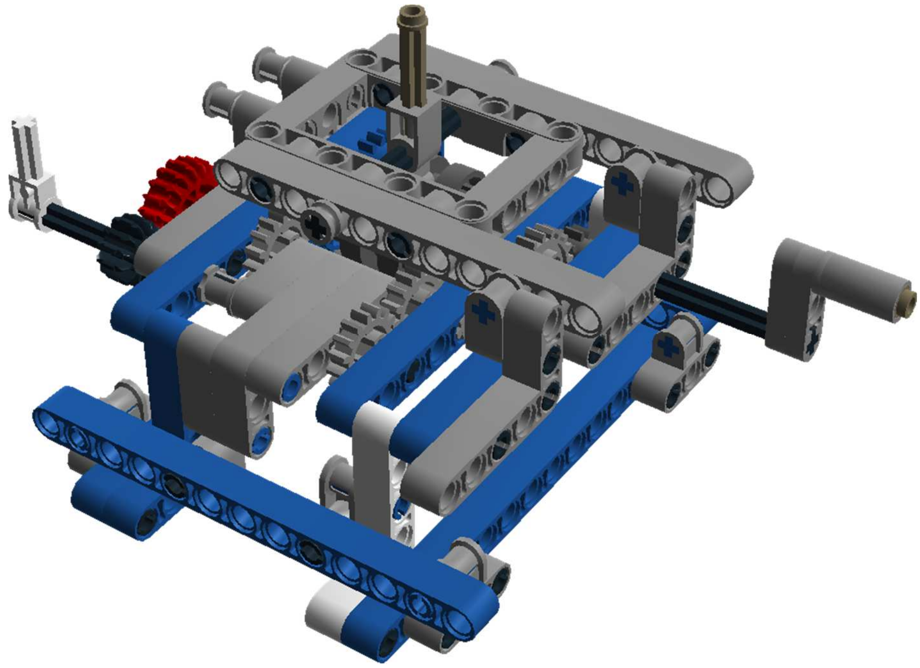
Since both gear selections have the same parity of connections (both even), they spin the wheels in the same direction. We conclude that we again have a first and second gear for forward travel arranged in the following shift pattern:



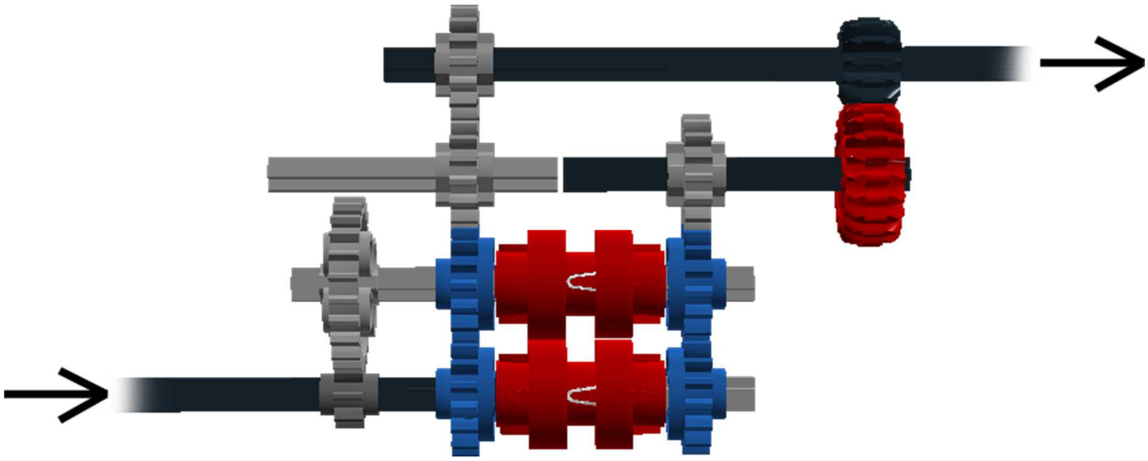
This is a nice intuitive pattern, very simple to use, we just move the stick forward and back. How did we pay for this? This gearbox uses 7 gears, two more than the previous project. Note that all these gears start moving once we engage some clutch gear, which is something that we expect from mesh gearboxes. In this particular case, only half the gears (3 or 4) do any useful work.

Note that the blue clutch gear on the middle shaft is not used for selecting anything. We put it there because of its ability to spin freely on its shaft. If we used a regular gear instead, then the middle shaft would be connected to the output shaft in two different ways, with two different gear ratios. In effect, the closer end of the output shaft would be forced to spin slower that its middle. The most likely outcome is that the whole gearbox would lock up. If we used more force, then some part would break.

Project 5h. Flat gearbox - 4 speeds.



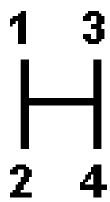
In this project we combined the two basic ideas from the previous projects: We create gear ratios before we get to the selection area and also after we select a path. Four speed transmissions are quite popular with Lego enthusiasts. However, they usually look different from the one we have here, because people generally prefer more compact arrangements that can fit into tight places. We will go that way eventually, but for now we stay with our flat rig, it has the advantage that all is laid before our eyes nicely.



The selector area is again two shafts wide, each source shaft offering different speed of rotation. There are four positions for our stick. Trace how the power moves each time and try to work out the ratios.

Summary:
Left forward (engages closer left clutch gear): gear ratio 3:1 (we slow down three times, the slowest gear). 5 gears, 3 connections (changes of direction).
Left back (engages far left clutch gear): gear ratio 9:5 (we slow down almost twice). 6 gears, 3 connections (changes of direction).
Right forward (engages closer right clutch gear): gear ratio 1:1. 4 gears, 3 connections (changes of direction).
Right back (engages far right clutch gear): gear ratio 3:5 (about 1:1.67, speeds up by two thirds). 5 gears, 3 connections (changes of direction).

All gear selections have odd number of connections when selected, so the output shaft always spins in the same direction. Thus these would be ordinary gears for forward travel, we listed them in order of the gear ratios, so these would be the 1st, 2nd, 3rd and 4th gear. We obtain the following shift pattern that should be familiar to any driver:

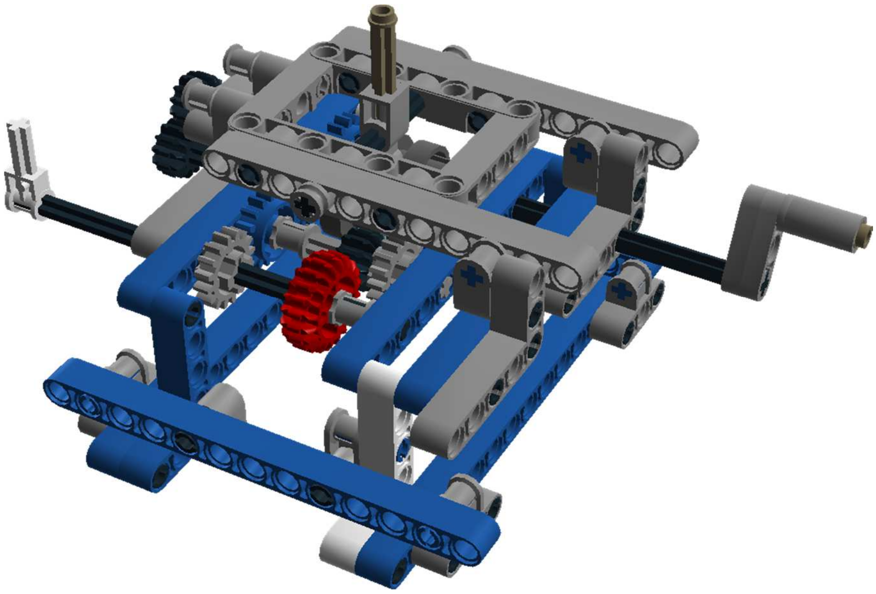


These are the same gear ratios as in Project 5d, so it's a fairly realistic gearbox. We needed 11 gears, which is not bad for a 4-speed gearbox, although a small improvement is still possible (see Project 5k).

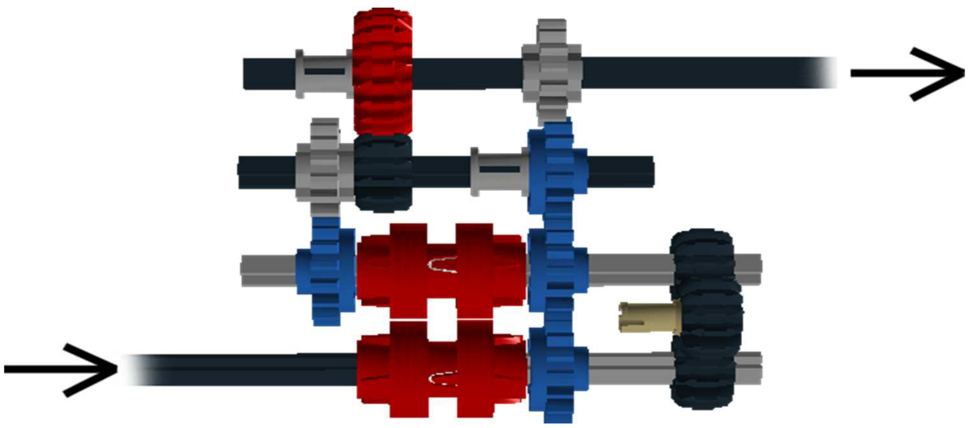
Recall our remark about the free spinning clutch gear at the end of the previous project. Here we have a similar situation, the output shaft is connected to the second last shaft in two different ways. But we did not have a fifth clutch gear, so we had to split that second shaft from the left so that its front part and the rear part can spin independently. If you happen to have an extra clutch gear in your spares box, you can build a significantly simplified version of this gearbox.

There is still one thing missing, the reverse.

Project 5i. Flat gearbox - 2 speeds and reverse.

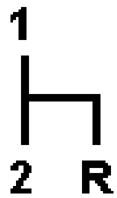


Just like the gearboxes from Project 5f and Project 5h, this one also has selector area with two shafts, but now there is a significant change. In those two projects, the source shafts rotated in opposite directions, which in the end worked out to the same direction for all speeds. This time we used the three black wheels (in the back) instead of two when connecting them to make sure that the two source shafts rotate in the same direction. Consequently, when we select the right one, it will eventually create the reverse. Try to work out what happens for the three engaged positions of the driving rings.



Summary:
Left forward: gear ratio 5:3, this is about 1.67:1 (slows down). Uses 7 gears, 4 connections (changes of direction).
Left back: gear ratio 1:1, uses 6 gears, 4 connections (changes of direction).
Right back: gear ratio 1:1, uses 4 gears, 3 connections (changes of direction).

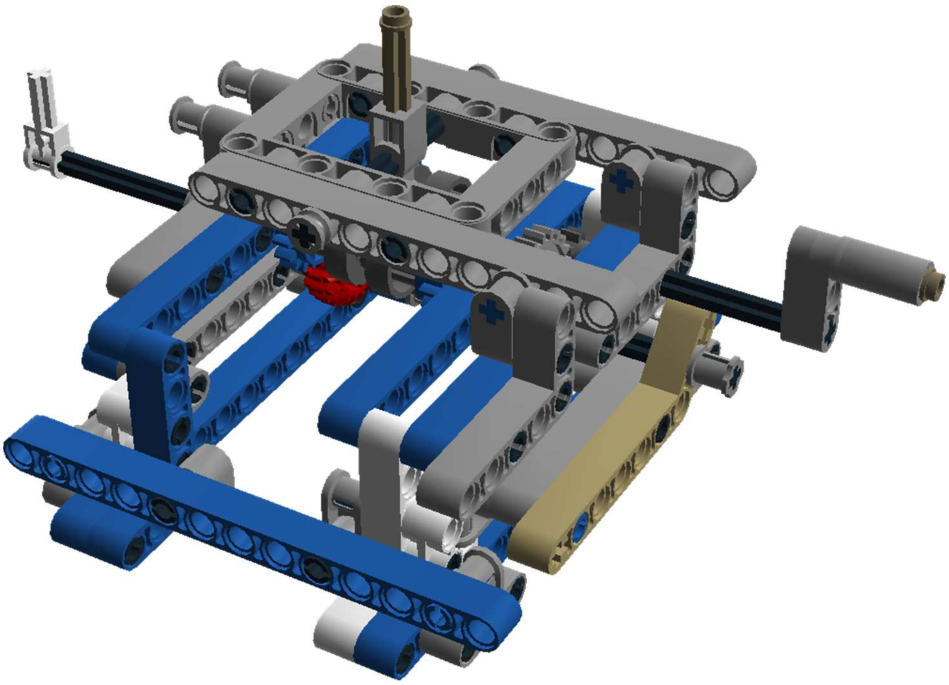
The first two spin in the same direction, these are the first and second gear. The last one spins in the opposite direction, that would be the reverse. We get the following shift pattern:



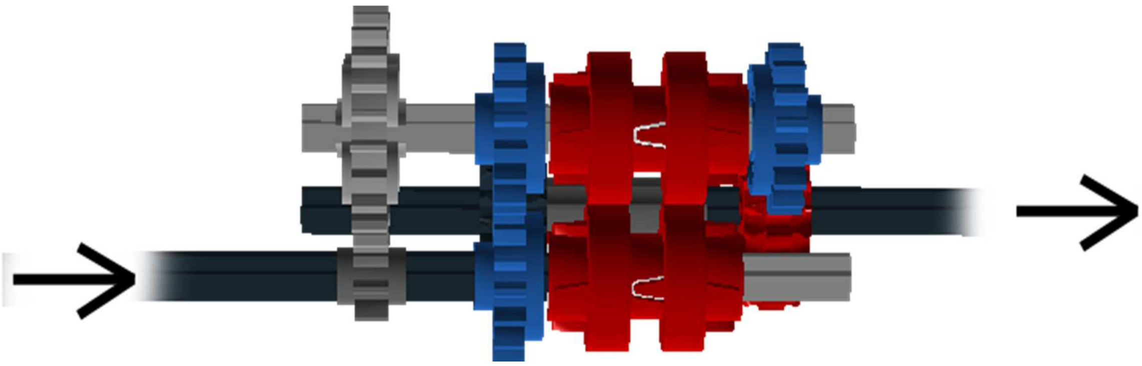
So this gearbox has a natural shift pattern. In total there are 11 gears, this is not completely bad but more efficient 2+R designs can be done. Another bad point is that the reverse is too fast, typically it should have gear ratio about the same as the first gear. This can be fixed by not using three identical gears when connecting the source shafts, but gears of different sizes. However, that would require a significant rebuild of our test rig.

Normally we use two gears when connecting the two source shafts for the selector area. This time we used three, so one can say that the extra gear created the reverse. This is a relatively simple way to get it, but it has one disadvantage: We cannot use that shaft for another gear, in particular we would not be able to make a 3+R gearbox like that. Sometimes this is not a problem, for instance if we want to make a 4+R gearbox, we could make a wider selector area with three shafts and reserve one of them for the reverse. However, sometimes we do want to use the same source shaft for the reverse and one of the forward gears. Then we have to change the direction of spin later, after the selector area.

Project 5j. Flat gearbox - 2 speeds and reverse.



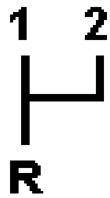
This time we will create one gear that spins in the opposite way after the selector area, that is, in the part where the motion from the selected clutch gear travels to the output shaft. While it is possible to do such a thing in flat gearbox, it would be very complicated and thus it would defeat the main purpose of our flat rig, that is, to have things nicely laid out for us. The easiest way to reverse the direction for one selection is to use more levels for shafts. To this end we added a basement level. The shaft below is now able to interact with both shafts above it, which is the core idea of this arrangement.



Analyze the three available selections.

Summary:
Left forward: 3:1 and 12:16 give 9:4, that is, 2.25:1. 5 gears, 3 connections.
Left back: 3:1 and 20:16 give 15:4, that is, 3.75:1. 4 gears, 2 connections.
Right forward: 3:4, that is, 0.75:1. 2 gears, 1 connection.

We have two gear settings with odd number of direction changes, these are the gears for going forward, and the one with 2 connections is reverse. We have the following shift pattern:

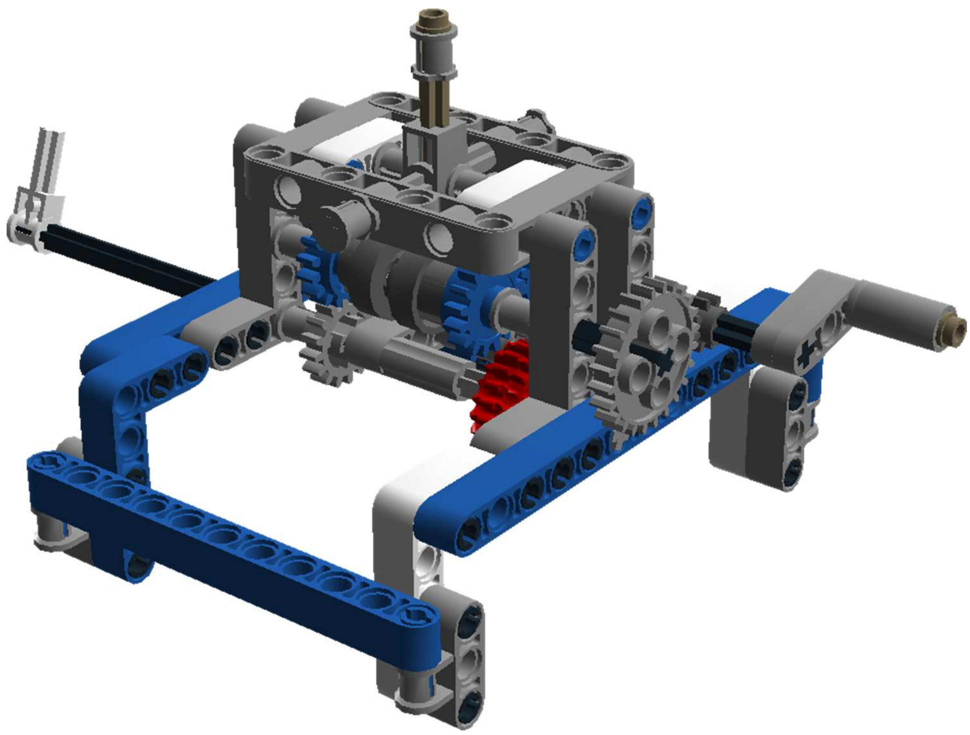


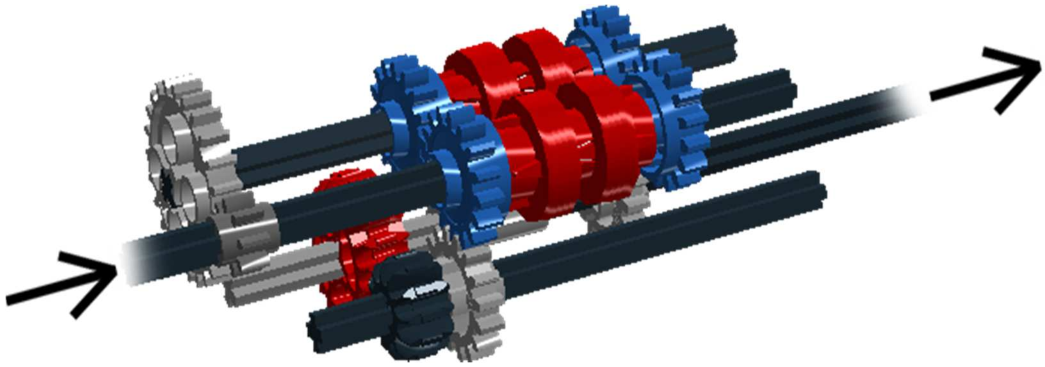
This gearbox uses only 7 gears. This is super efficient, I know of no other design for a Lego gearbox with reverse that would use this few gears. It is also fairly compact, in particular it is very narrow, we could make a rig that would be just five holes wide.

So what are the drawbacks? One is the unnatural shift pattern, another complaint might be that the reverse is too slow.

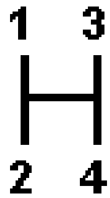
This was the last flat rig gearbox. We will now look at gearboxes composed of more levels, which is the traditional way to go with Lego.

Project 5k. Compact gearbox - 4 speeds.



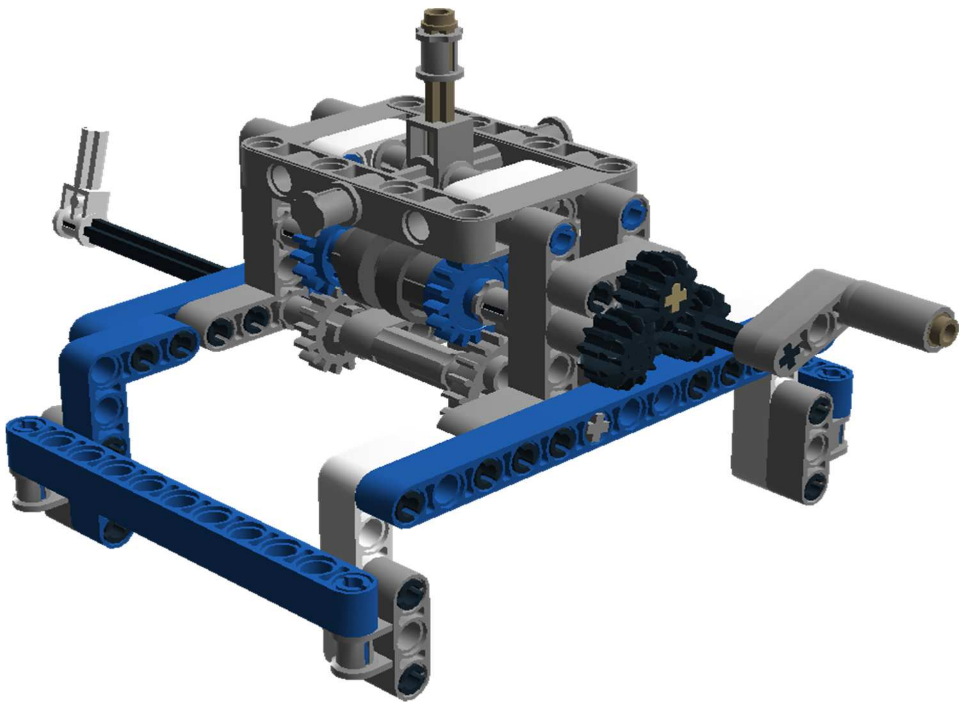


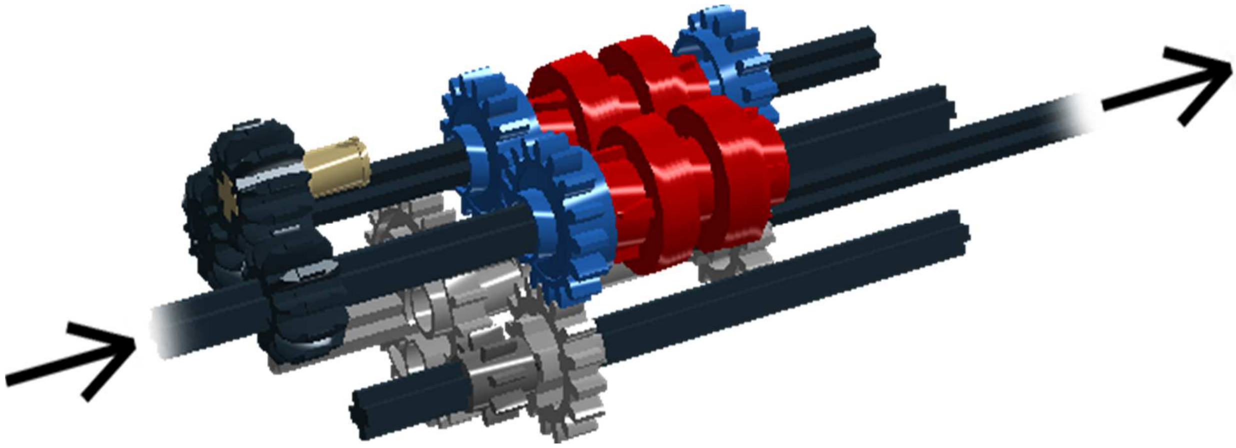
This gearbox has exactly the same shift pattern and gear ratios as Project 5h: 1st gear: gear ratio 3:1; 2nd gear: gear ratio 9:5; 3rd gear: gear ratio 1:1; 4th gear: gear ratio 3:5 (about 1:1.67).



So this is a gearbox with a natural shift pattern that would have fairly realistic gear ratios if we added one more between the second and third. Moreover, by going to two levels we saved one gear. This gearbox has 10 gears, which is probably the most efficient type of a 4 speed gearbox one can get in Lego. Given that it is also nicely compact so that is easy to place inside a machine, one can hardly do any better.

Project 5l. Compact gearbox - 2 speeds & reverse.

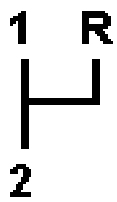




Summary:
Left forward: 3:1, 5 connections.
Left back: 1:1, 3 connection.
Right forward: 3:1, 2 connections.

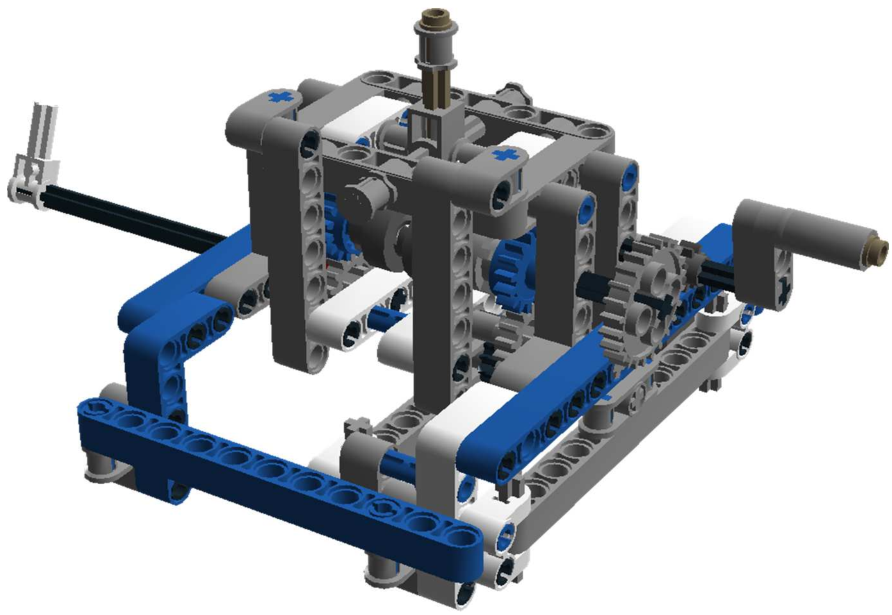
We see that we have a 2+R gearbox with reasonable gear ratios, in particular the reverse has the same gear ratio as the first gear. There are a lot of connections for the first gear. Since the reverse is used less often, we prefer to optimize the grear for going forward. Thus it would make sense to attach the crank (engine) to the left upper shaft, then the 1st gear would go through 3 connections and the 2nd gear through one connection.

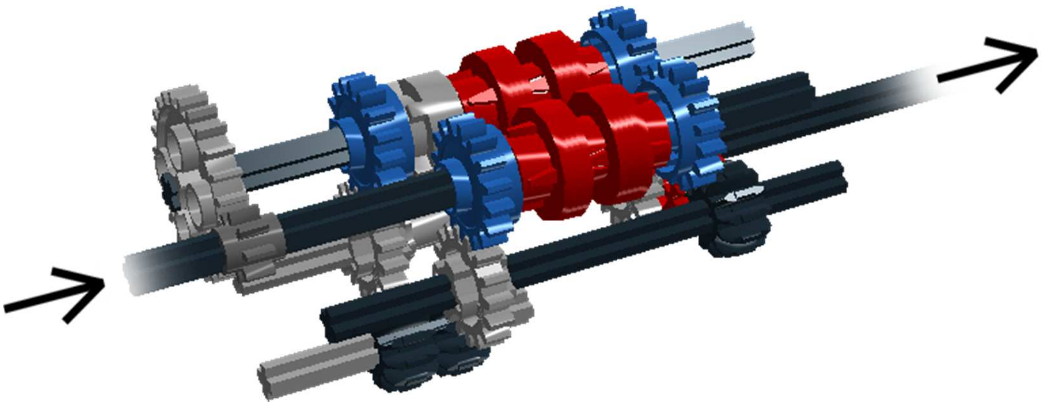
We have 10 gears, which is more (by 3) than in Project 5j, but we have a better gear ratio for the reverse and a nicer shift pattern.



This is the basis of the design we will use in our final car. We will use one more gear there to make the shift pattern even better, the reverse will be chosen by going right and back, which is more natural than going forward like we do here.

Project 5m. Compact gearbox - 3 speeds and reverse.

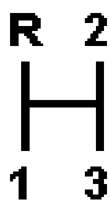




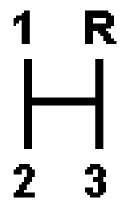
To get 3+R with just two source shafts for selection, we have to place one forward gear on the same shaft as the reverse. Thus we have to use a similar trick as in Project 5j, that is, we add one basement level.

The gearbox is still nicely compact and has the following gear ratios:
Left forward: 5:1, uses 10 gears, 5 connections.
Left back: 3:1, uses 4 gears, 2 connections.
Right forward: 5:3, approximately 1.67:1, uses 4 gears, 2 connections.
Right back: 1:1, uses 3 gears, 2 connections.

Looking at the number of connections, we see that the first gear in this list is the reverse and the last three are the first, second and third gears. We have the following shift pattern:

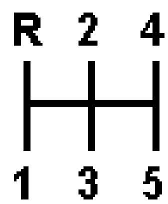


Total number of gears in this gearbox is 13, which seems quite a lot but one can hardy do better. I know of one design that uses just 12 gears, but it is three shafts wide, has a very fast reverse and uses an unusual shift pattern.

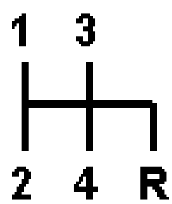


Actually, our shift pattern may also look weird to many people, as most drivers are used to have the first two gears in the left position. But the fact is that the pattern that we have here is actually used in some cars. When driving high performance cars (racers, sports cars), the driver has to shift between the 2nd and 3rd gear very often, so it makes sense to put them in one line where the driver just moves the stick forward and back. It is called the dog leg shift pattern, but most people never met it.

The same can be said about a typical Lego enthusiast designing a gearbox, but they also often put the reverse and the first gear on the same shaft. For them it is simply an optimal choice that makes life markedly easier. This explains why one can see the dog leg shift pattern in many transmissions built by fans and also in Lego official sets, be it 2+R, 3+R, or 5+R transmissions.

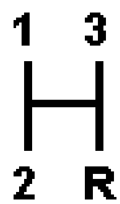


However, in a typical passenger car we tend to shift more between the 3rd and 4th gear, so the traditional pattern



makes more sense then. It would be reasonably easy to make such a gearbox with Lego, since the reverse has its own source shaft. However, it would require a design that is three shafts wide, which is something that we did now want in our final car.

Given that we want to stick with two shafts, it is very tempting to consider a gearbox like this and with the reverse with gear ratio comparable to the first gear. However, this is exactly the situation where requirements clash so badly that we would have to make a really complicated construction. This is the reason why we decided to stick with 2+R in our final model.

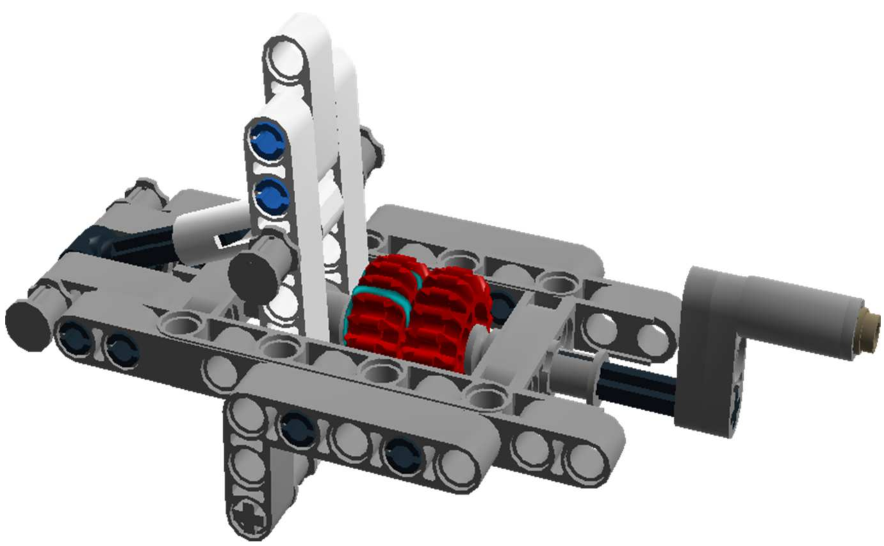


Project 6 - Clutch

In Project 5 we saw how gears are engaged in a gearbox and how they need to adjust their rotations so that their teeth align properly. However, in a typical case one of those gears is powered by the engine, while the other is spinning along with wheels. This makes it hard for them to align. To fix this problem, engineers put in a special device called clutch that connects and disconnects gearbox from the engine. When we need to change gears, we apply the clutch and gears that were powered by engine are now free to spin at their will and adjust.

A car clutch is in principle a fairly simple device. Imagine two disc, one connected to the engine shaft, the other to the input shaft of the gearbox, and faces of these two discs are pushed against each other. When one spins, the other has to spin as well due to friction. This is helped by a special coating that reduces slippage (and handles heat created by friction). When we want to disconnect the engine from the gearbox, we simply move the discs apart.

However, we do not have discs in our set and even if we had, they would not be coated with the special stuff. So we will improvise in the best Lego tradition. We will use two red gears (they have relatively flat faces) and instead of the special coating we will put a rubber band on one of those wheels.



Try turning the crank. If everything goes well, the other shaft should spin as well. Now push at the lever. You should see the two red gears coming apart and the output shaft cannot be spun using the crank any more. When you release the lever, the spring pushes the gears back together.

A clutch is different from gearbox in one important aspect. In a gearbox, wheels have to adjust their speeds before they come together and their teeth engage. On the other hand, with a clutch it is expected that the two disc do not spin at the same rate when they come together, which is why there are no teeth or ridges or any other solid handles by which the two discs would grab each other. As they move closer, their flat faces engage gradually, just gently touching at first and then increasing the pressure. Thus it does not matter that they spin at different rates at the start, because at first they can slide without much trouble. The increasing friction makes the connection gradually stronger and stronger, which forces the disc to synchronize their speeds and eventually they connect firmly.

This is actually exactly what we want. If we applied the engine power all at once, the car would lurch. It does happen occasionally, when the clutch is released too quickly. When done properly, the power is fed into wheels gradually and the car reaches the required speed smoothly.

In a Lego gearbox, the driving rings and clutch gears have just a few ridges far apart, so it is easier for them to come together. This is helped by the fact that in lego, shafts tend to run relatively slowly and without too much power behind them, so if one does not rush them, Lego gearboxes work reasonably well without a clutch. This explains why Lego cars do not feature a clutch.