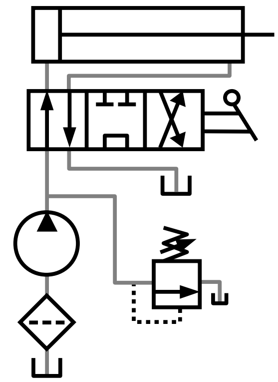
Hydraulic Cylinders

Purpose of Cylinders



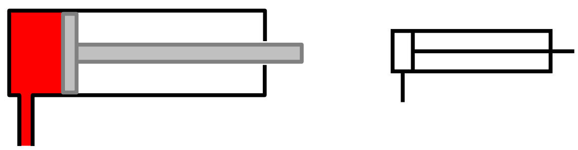
Here's the circuit diagram of lab #1 on the hydraulic stand. From an energy standpoint, the purpose of the pump is to add energy to the hydraulic fluid; the purpose of the cylinder is to extract energy from the hydraulic fluid, to do useful work.

This lecture is about different kinds of cylinders, how they work, and how we can use simple equations to figure out pressure, force, power, and velocity. In a manufacturing environment, these things matter. If you are installing a cylinder to move boxes of toothpicks on a high-speed packaging line, you would look for a cylinder that handles light loads at high speeds. If you are installing a cylinder in a garage to lift schoolbuses, you would look for a cylinder with a high load capacity that moves relatively slowly. If you are designing a hydraulic sheet metal stamping press, you want a high load cylinder that moves fast.

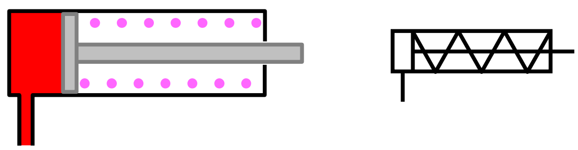
Types of Cylinders

Single-Acting Cylinder

The simplest type of cylinder has one port. Fluid flowing into the cap end of the cylinder pushes the piston and rod. The cylinder retracts under the force of a spring, the force of gravity (acting on a vertical load...like the weight of a car on a vehicle lift), or by pumping the fluid out.

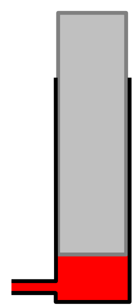


A squiggly line in the cylinder represents a compression spring in a spring-returned single-acting cylinder.



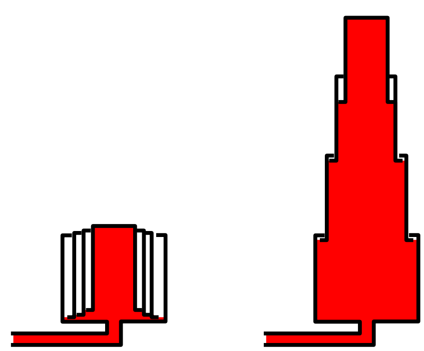
The simplest type of single-acting cylinder is the *ram*, where the rod and piston are the same diameter (or nearly the same)…indeed, often they are a single part. The ram extends as fluid flows into the cylinder. Typically, we use the load (often under gravity) to make the ram retract.

We can also use tension springs for retraction. Rams are used for elevators, jacks, and vehicle lifts.

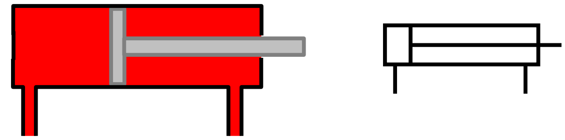


This single-acting hydraulic cylinder has a series of nested tubular shells called sleeves. You can have 4 to 5 sleeves in a typical telescoping cylinder. The load capacity will be based on the smallest diameter sleeve in the assembly. The advantage of this cylinder is its small size when unloaded.

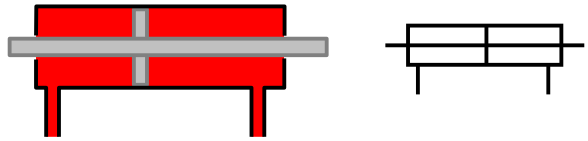
The maximum load that you can lift with a telescoping cylinder is the fluid pressure times the area of the *smallest* shell.



Double-Acting Cylinder

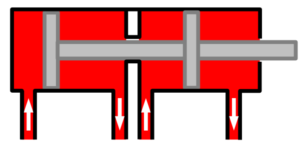


Most hydraulic cylinders are *double-acting cylinders*. They are also called *differential cylinders* because the area that the fluid pushes on is different on each side of the piston – therefore the extension force is greater than the retraction force. On the left side, it's the cross-sectional area of the piston. On the right side, it's the cross-sectional area of the piston minus the cross-sectional area of the rod.



If you let the rod extend out both ends of the cylinder, then you have a *double-rod cylinder*. They are also called *nondifferential cylinders* because the area that the fluid pushes on is the same on each side of the piston: the cross-sectional area of the piston minus the cross-sectional area of the rod. Now the extension and retraction forces are equal.

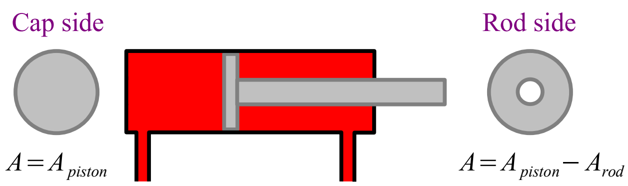
Tandem Cylinder



We can increase the force output from a cylinder by splitting it in two, and installing a second piston. Now the pressure pushed against a greater area, so the output is bigger. Typically, a tandem cylinder is built out of two shorter cylinders.

Pressure, Force, Velocity, & Power

Force



Consider a double-acting hydraulic cylinder, plumbed so that one side of the piston is pressurized, while the other side drains to tank. Force generated by the cylinder is equal to the pressure times the area it acts on: $F = pA$. On the cap side, the area is the piston area, therefore $F_{ext} = pA_{piston}$. On the rod side, the area is the piston area minus the rod area, therefore $F_{ret} = p(A_{piston} - A_{rod})$. Since the area for extension is larger, force during extension is larger than force during retraction.

Velocity

In general, velocity $v = \frac{Q}{A}$, therefore $v_{ext} = \frac{Q}{A_{piston}}$ and $v_{ret} = \frac{Q}{A_{piston} - A_{rod}}$. Retraction is faster than extension because the denominator in the retraction equation is smaller.

Power

We use upper-case *P* for power, defined as the rate of doing work. Since work is force times the distance it act through, we can write $P = \frac{FS}{t}$ where *S* is distance and *t* is time. Since $v = \frac{S}{t}$, $P = Fv$.

In a hydraulic system, $F = pA$ and $v = \frac{Q}{A}$, so $P = Fv = \frac{pA\,Q}{A} = pQ$.

The US Customary units for power are lb.ft./s, which you can convert to horsepower because $\text{hp} = \frac{550\,\text{ft.lb.}}{\text{s}}$.

The SI unit for power is the watt, where $\text{W} = \frac{\text{N m}}{\text{s}}$.

Pressure/Force/Velocity/Power Example #1

A hydraulic pump delivers 0.003m³/s of oil to a double-acting cylinder having a 6 cm piston diameter and a 2 cm rod diameter. The cylinder supports a load of 5000N in both directions; it shifts a heavy weight horizontally across a floor. Calculate pressure, velocity, and power for extension and for retraction.

Rewrite $F_{ext}=pA_{piston}$ as $p_{ext}=\frac{F_{ext}}{A_{piston}}=\frac{4F_{ext}}{\pi d_{piston}^2}=\frac{4\cdot 5000\,\text{N}}{\pi(6\text{cm})^2}\left|\frac{\text{kPa m}^2}{10^3\,\text{N}}\right|\frac{(100\,\text{cm})^2}{\text{m}^2}=1770\,\text{kPa}$

$$v_{ext}=\frac{4Q}{\pi d_{piston}^2}=\frac{4\cdot 0.003\,\text{m}^3}{\text{s}}\frac{}{\pi(6\,\text{cm})^2}\left|\frac{(100\,\text{cm})^2}{\text{m}^2}\right.=1.06\,\text{m/s}$$

$$P_{ext}=F\,v_{ext}=\frac{5000\,\text{N}\ 1.06\,\text{m}}{\text{s}}\left|\frac{\text{kW s}}{10^3\,\text{N m}}\right.=5.3\,\text{kW} \quad \text{or} \quad P_{ext}=pQ_{ext}=\frac{1770\,\text{kPa}\ 0.003\,\text{m}^3}{\text{s}}\left|\frac{\text{kN}}{\text{kPa m}^2}\right|\frac{\text{kW s}}{\text{kN m}}=5.3\,\text{kW}$$

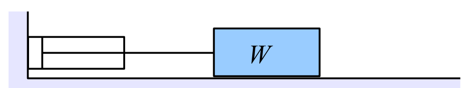
For retraction, $p_{ret}=\frac{F_{ext}}{A_{piston}-A_{rod}}=\frac{4F_{ext}}{\pi[d_{piston}^2-d_{rod}^2]}=\frac{4\cdot 5000\,\text{N}}{\pi[(6\text{cm})^2-(2\text{cm})^2]}\left|\frac{\text{kPa m}^2}{10^3\,\text{N}}\right|\frac{(100\text{cm})^2}{\text{m}^2}=1990\,\text{kPa}$

$$v_{ret}=\frac{4Q}{\pi[d_{piston}^2-d_{rod}^2]}=\frac{4\cdot 0.003\,\text{m}^3}{\text{s}}\frac{}{\pi[(6\,\text{cm})^2-(2\,\text{cm})^2]}\left|\frac{(100\,\text{cm})^2}{\text{m}^2}\right.=1.19\,\text{m/s}$$

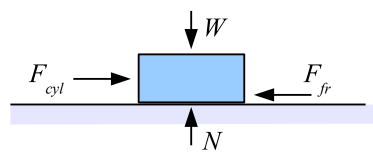
$$P_{ret}=F\,v_{ret}=\frac{5000\,\text{N}\ 1.19\,\text{m}}{\text{s}}\left|\frac{\text{kW s}}{10^3\,\text{N m}}\right.=6.0\,\text{kW}$$

In summary, we need more pressure to retract because the fluid acts on a smaller area. We get a higher velocity on retraction because the fluid fills a smaller volume. We consume more power on retraction because power is force times velocity.

Pressure/Force/Velocity/Power Example #2



Consider a 1000 lb. weight pushed by a cylinder across a floor at a constant velocity. The friction coefficient $\mu=0.2$. How much force is required?



The first step is to draw a Free-Body Diagram of the block, showing all forces acting on the block. These forces include the weight *W* of the block due to the acceleration of gravity, the normal force *N* acting perpendicular to the surface that the block is sitting on, cylinder force F_{cyl}, and frictional force $F_{fr}=\mu N$.

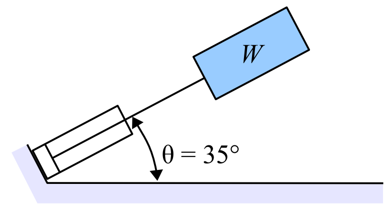
To solve the problem, use the principle of Sum of the Forces from *Statics* and *Physics I* classes. The sum of forces acting in one direction must equal zero if the body is still or is moving at a constant speed.

In the vertical direction, the only two forces are *W* and *N*, acting in opposite directions, therefore $N=W=1000\,\text{lb}$.

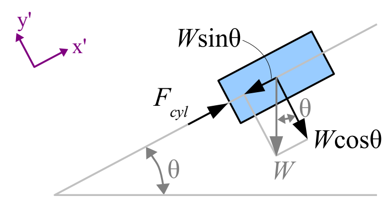
In the horizontal direction, the only two forces are F_{cyl} and F_{fr}, acting in opposite directions, therefore $F_{cyl}=F_{fr}=\mu N=0.2\cdot 1000\,\text{lb.}=200\,\text{lb.}$

Pressure/Force/Velocity/Power Example #3

Consider a 1000 lb. weight elevated into the air by a cylinder at a constant velocity. How much force is required?



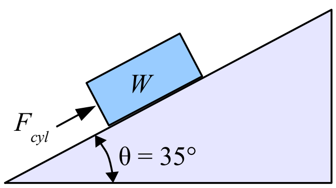
Again we draw a Free-Body Diagram. Now there are only two forces acting on the block: W and F_{cyl}. We'll define axes x' and y', parallel and perpendicular to the direction of movement, to make the math easier.



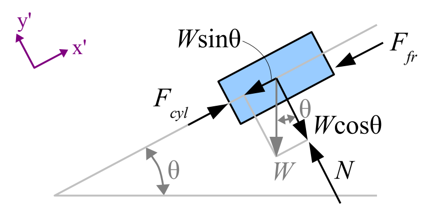
Break the weight into two components acting in the x' and y' directions, so there are two forces acting along the line of direction: F_{cyl} and $W\sin\theta$. Cylinder force $F_{cyl} = W\sin\theta = 1000\,\text{lb.}\sin 35° = 573\,\text{lb.}$

Pressure/Force/Velocity/Power Example #4

Consider a 1000 lb. weight pushed up a 35° slope by a cylinder at a constant velocity. How much force is required?



The Free-Body Diagram has four forces acting on the block. Again we break the weight into two components acting in the x' and y' directions.



First, solve for the forces in the y' direction: $N = W\cos\theta$.

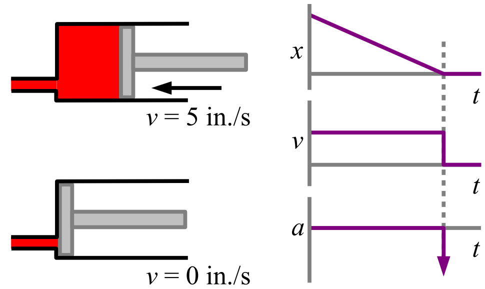
Next, solve for the forces in the x' direction. There are three forces: cylinder force, friction force, and the component of the weight that acts along the slope.

$$\begin{aligned} F_{cyl} &= F_{friction} + W\sin\theta \\ &= \mu N + W\sin\theta \\ &= \mu W\cos\theta + W\sin\theta \\ &= 0.2(1000\,\text{lb.})\cos 35° + (1000\,\text{lb.})\sin 35° \\ &= 164\,\text{lb.} + 574\,\text{lb.} = 737\,\text{lb.} \end{aligned}$$

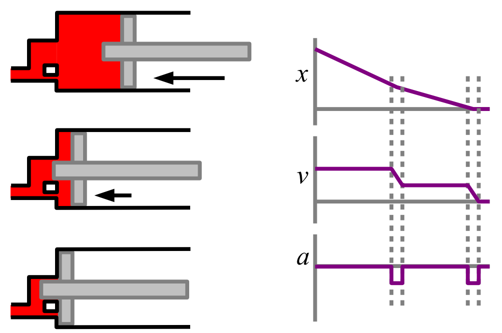
Friction accounts for 22% of the cylinder load; weight accounts for 78%. If you want to reduce the cylinder force, either lubricate the slope or install rollers on the ramp.

Cylinder & Circuit Design Issues

End-of-Stroke Conditions

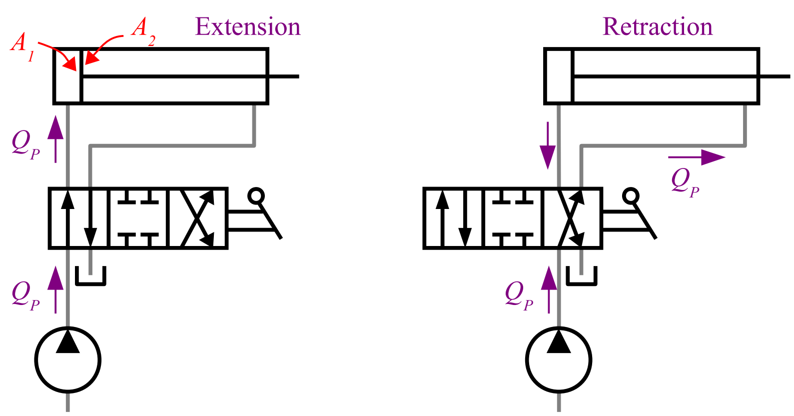


Here's another issue that comes up with cylinders, whether they're hydraulic or pneumatic. Let's say we're retracting a piston at a constant velocity, $v = 5\,\text{in./s}$. At the end of the stroke, $v = 0\,\text{in./s}$. Acceleration is defined as the change in velocity per unit of time…it's how fast the velocity changes. In theory, the acceleration at the end of the stroke is infinite. In practice, it's finite, but very large…we get impact. Over time, the hardware will break down. Keep in mind Newton's First Law: $F = ma$. If a is infinite (or extremely high), then F is infinite (or extremely high), no matter what the mass.



The way to prevent cylinders from shaking themselves apart is to install a *cushion* at the end of the cylinder. In a pneumatic cylinder, the cushion can be a piece of soft material. Another solution is to design the piston with an extra smaller diameter piston on the end, which fits into a cavity in the end of the cylinder. In the cartoon, the piston is moving pretty fast at the top, at a constant velocity. Next, the piston slows down, because all the flow has to go through a small hole. Motion of the piston is cushioned. Finally, the piston stops.

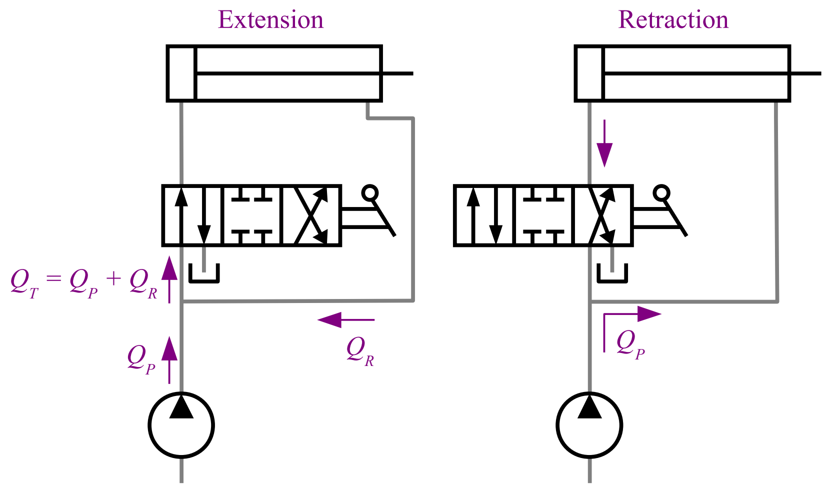
Regenerative Circuit



One way to change the velocity of a cylinder is to change the plumbing. Consider the hydraulic circuit from Lab #1: we have pump flow Q_P going from the pump, through the directional control valve (DCV), and to the cap side of the cylinder. We'll define the area of the piston as A_1 and the area of the piston minus the area of the rod as A_2. The velocity of the piston on extension is $v_{ext} = \frac{Q_P}{A_1}$, the pump flow rate divided by area A_1. The force exerted by the piston on extension is $F_{ext} = p\,A_1$. The velocity of the piston on retraction is $v_{ret} = \frac{Q_P}{A_2}$ and the force exerted by the piston on retraction is $F_{ret} = p\,A_2$.

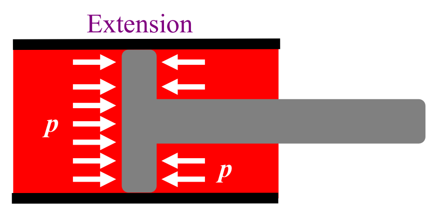
Now let's change the plumbing, so the fluid coming out of the rod end of the cylinder joins the fluid coming from the pump. The flow from the rod end is called *regenerative* flow, or Q_R. The total flow to the cap end of the cylinder is $Q_T = Q_P + Q_R$.

In general, we can say that $Q = A v$, so total flow rate $Q_T = A_1 v_{ext}$ and the regenerative flow rate $Q_R = A_2 v_{ext}$. Rewrite these equations to solve for the pump flow rate: $Q_P = A_1 v_{ext} - A_2 v_{ext} = (A_1 - A_2) v_{ext}$.

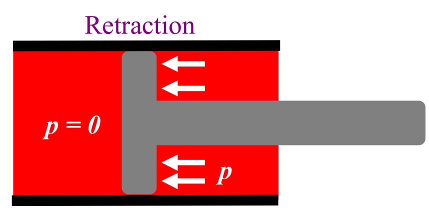


Since $A_1 - A_2 = A_{Rod}$, we can write $Q_P = A_{rod} v_{ext}$, or $v_{ext} = \frac{Q_P}{A_{rod}}$. We have a simple equation for extension velocity as a function of pump flow rate and rod area. The cylinder diameter doesn't matter…it's just the rod diameter and pump flow rate that determine extension velocity. If you use a smaller rod diameter, you can increase the extension velocity.

Consider a free-body diagram of the piston during extension. The pressure on both sides of the piston is the same, so the force is the pressure times A_1 minus the pressure times A_2. $F_{ext} = p A_1 - p A_2 = p(A_1 - A_2) = p A_{rod}$. The extension force is *less* than the force we got in Lab #1, because there was no pressure on the rod side of the cylinder in that circuit...it went to drain. Since $F_{ext} = p A_{rod}$, we can increase the force by increasing the rod diameter.



Now let's consider retraction. The pump sends its flow directly to the rod end of the cylinder, while the cap end drains to tank. There is no regenerative flow adding to the pump flow. Now $Q_P = A_2 v_{ret}$. Rewrite to solve for velocity: $v_{ret} = \frac{Q_P}{(A_{piston} - A_{rod})}$. If we take the ratio of extension velocity over retraction velocity, we get $\frac{v_{ext}}{v_{ret}} = \frac{Q_P}{A_{rod}} \frac{A_{piston} - A_{rod}}{Q_P} = \frac{A_{piston}}{A_{rod}} - 1$. What does this mean?



If $A_{piston} = 2 A_{rod}$: $\frac{v_{ext}}{v_{ret}} = \frac{2}{1} - 1 = 1$

If $A_{piston} > 2 A_{rod}$: $v_{ext} > v_{ret}$

If $A_{piston} < 2 A_{rod}$: $v_{ext} < v_{ret}$

In an industrial process, if we need a cylinder to extend or retract at specific speeds, we can select a cylinder based on its piston and rod diameters to do the job. This is a design issue.

Consider a free-body diagram of the piston during retraction. Pressure is only on the rod side, so the force is $F_{ret} = p A_2 = p(A_{piston} - A_{rod})$. The retraction force is *the same* as the force we got in Lab #1. The ratio of the retraction and extension forces is $\frac{F_{ret}}{F_{ext}} = \frac{p(A_{piston} - A_{rod})}{p A_{rod}} = \frac{A_{piston}}{A_{rod}} - 1$ ...a familiar ratio. What does this mean?

If $A_{piston} = 2 A_{rod}$: $F_{ext} = F_{ret}$

If $A_{piston} > 2 A_{rod}$: $F_{ext} < F_{ret}$

If $A_{piston} < 2 A_{rod}$: $F_{ext} > F_{ret}$

Again, this is a design issue. You can design a system with identical, greater, or less force in one direction vs. another using a regenerative circuit.

Dr. Barry Dupen, Indiana University-Purdue University Fort Wayne. Revised August 2016. This document was created with Apache Software Foundation's OpenOffice software v.4.1.2.

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