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CAT®

THE ARTHUR M. BLANK FAMILY FOUNDATION

2007 TE Sessions – Mechanical Energy and Fluid Power

Oct. 30, 2007

www.robojackets.org

MECH ENERGY STORAGE

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Energy

What is energy?

Energy

Units:

Foot-pounds; Newton-meters; Joules; BTU; Calories, etc

- **Energy is energy regardless of sign**
- **Non directional**

Sign significance

- **Energy can be stored in two ways**
- **Potential**
- **Kinetic**

Sign significance

- **Energy can be expended through work**
- **or dissipated (friction & heat)**

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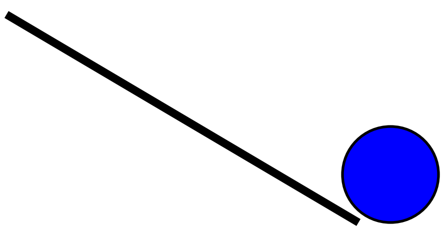
Energy

Potential Storage

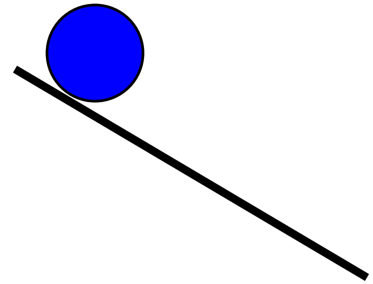
Potential

Energy can be stored as a force against gravity

- **Simplest way is a force at a distance (foot-pounds)**
- **Raising a mass against gravity**



No energy stored



E = mgh Joules stored

Energy stored = mass x gravity x height

E = mgh

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Energy

Potential Storage

Potential

Energy can be stored as inside mechanical devices through material deflection

- **Springs store energy**
- **Spring constant**

No energy stored **Energy stored by applying force**

Energy

Potential Storage

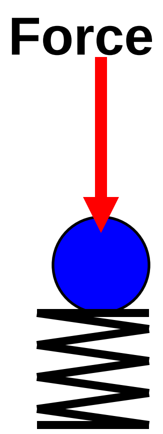
Springs

Energy stored is a function of two things:

- Spring constant k
- Distance of spring deflection x

Spring constant

- **k = Force/Displacement = F/x**
- **Amount of force needed to deflect spring one inch**



Force causes spring to deflect

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Energy

Potential Storage

Springs

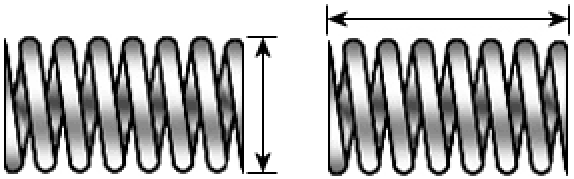
Other spring definitions, terms, and specs

Material

- Spring steel, music wire

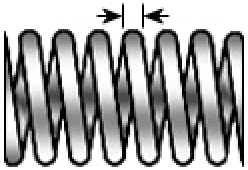
Specs

- Outside Diameter and length



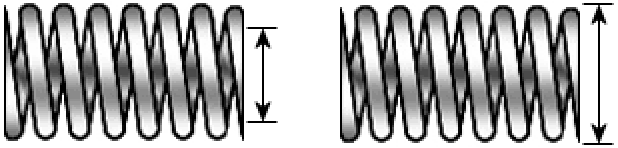
Specs

- Wire Size



Specs

- Rod and Hole Size



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Energy

Potential Storage

Springs

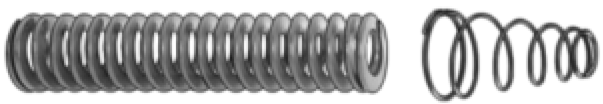
Other spring definitions, terms, and specs

Compressed Length

- Minimum length of spring under force

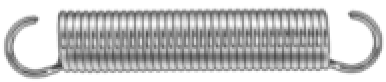
Compression springs

- Forces compress the spring



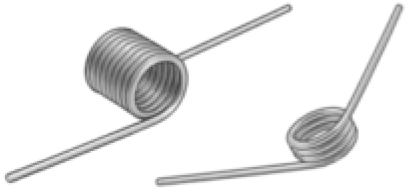
Tension

- Forces extend the spring



Torsion

- Torques compress the spring



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Energy

Potential Storage

Potential

Energy can be stored as inside mechanical devices through spring deflection

- **Energy stored = ½ k x^2**

No energy stored **Energy stored by applying force**

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Energy

Potential Storage

Example

- Energy stored = ½ k x^2
- k = 20 lbf/in
- Desired energy = 100 ft-lbf
- How far must spring be compressed?
    - 100 ft-lbf = ½ 20 lbf/in x^2
    - x = 3.16 inches

Energy storage is quadratic, not linear

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Energy

Potential Storage

Other Potential Storage Mechanisms

- **Compressed gas**
  - **Air compressors store air in large tanks**
  - **Stored air is used in large quantities by tools**
- **Fuel**
  - **Hydrocarbons (gasoline, propane, etc)**
  - **Fuel is chemically stored energy**
- **Batteries**
  - **Batteries store energy as chemical electricity**
  - **Batteries can be recharged by adding energy**

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Energy

Kinetic Energy

What is kinetic energy?

- **Kinetic energy is in motion**
- **All mass in motion has kinetic energy**

- Falling/Moving mass

Mass in motion has energy proportional to its mass and speed

- Rotating mass

Spinning mass has energy proportional to its inertia and rpm

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Energy

Kinetic Energy

- **Kinetic energy is in motion**
- **All mass in motion has kinetic energy**

- Falling/Moving mass
Mass in motion has energy proportional to its mass and speed

- Rotating mass
Spinning mass has energy proportional to its inertia and rpm

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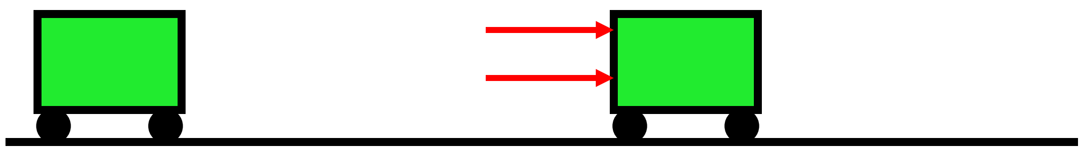
Energy

Kinetic Energy

Mass in motion

- **Energy = ½ mass x velocity^2**
- **$E = \frac{1}{2} mv^2$**



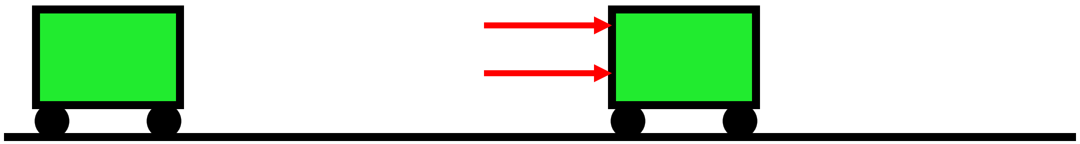
- **Energy increases quadratically with velocity**
- **Energy increases linearly with mass**

Energy

Kinetic Energy

Example

- **20kg mass moving at 10 m/s**
- **$E = \frac{1}{2} mv^2$**



Energy required = $\frac{1}{2} \times 20kg \times (10m/s)^2$
E = 1000 Joules (N-m)

Energy

Kinetic Energy

- **Flywheels**

  - **Flywheels store kinetic energy by spinning**
  - **Examples: engine flywheel, saw blade, governor**

  - **Rotating mass energy:**

  Energy = ½ I w^2

  I = moment of inertia

  w = angular velocity (rad/s)

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Energy

Kinetic Energy

- **Flywheels**

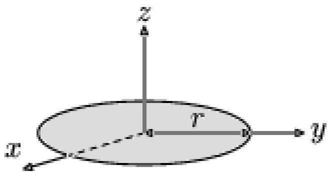
Example:

5kg, 0.2m diameter, thin disc spinning at 100 rad/s
How much energy is it storing?

First calculate its moment of inertia:

$I_z = ½ m r^2$

$I_z = ½ 5kg (0.1m)^2 = 0.025kg\text{-}m^2$



Calculate kinetic energy stored:

$E = ½ Iw^2$

$E = ½ (0.025kg\text{-}m)(100rad/s)^2$

$E = 125$ Joules

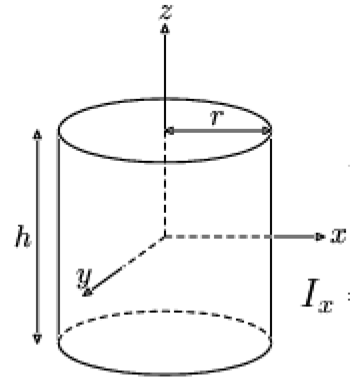
Energy

Kinetic Energy

- **Notes on spinning masses:**
  - **Energy increases quadratically with angular velocity (rpm)**
  - **Energy increases linearly with inertia**

  - **Inertia increases linearly with mass**
  - **Inertia increases quadratically with radius**

- **Greater inertia effects from having all mass at the edge of flywheel**



$$I_z = \frac{mr^2}{2}$$

$$I_x = I_y = \frac{1}{12}m\left(3r^2 + h^2\right)$$

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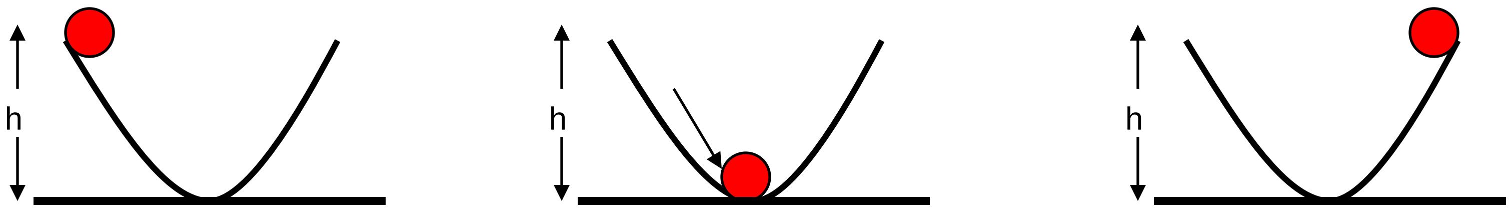
Energy

Dissipation

Where does energy go???

First an example on ideal energy conversion:



PE = mgh
KE = 0 (v = 0)

PE = 0 (h = 0)
KE = ½ mv^2

PE = mgh
KE = 0 (v = 0)

Ideally, mgh = ½ mv^2 and potential is fully converted into kinetic, then back to potential, infinitely

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Energy

Dissipation

Conservation Of Energy

FOUNDING PRINCIPLE OF THE UNIVERSE!!!

Energy in = Energy out ALWAYS!!!

- **Energy is never perfectly converted though**
- **Efficiency % = mechanical energy output / mechanical energy input**

$$\text{Efficiency \%} = \frac{\text{mechanical energy output}}{\text{mechanical energy input}}$$

Sources of loss:

- **Friction**
- **Heat loss**
- **Noise**

Most energy is lost through friction and heat generation

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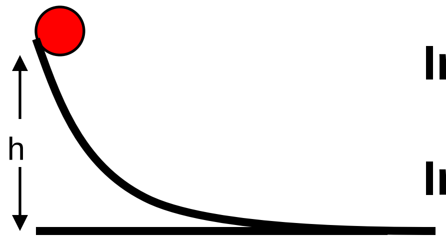
Energy

Dissipation

Efficiency Example

A mass slides down a slope, reaching a final velocity

$m = 10\ kg$, $h = 2m$, $v_f = 5\ m/s$



$PE = mgh$

$KE = \frac{1}{2} mv^2$

Initial potential energy:

$PE_0 = mgh = (10kg)(9.81m/s^2)(2m) = 196.2\ J$

Initial kinetic energy:

$KE_0 = \frac{1}{2} mv^2 = (1/2)(10kg)(0m/s) = 0J$

Final potential energy:

$PE_f = mgh = (10kg)(9.81m/s^2)(0m) = 0\ J$

Final kinetic energy:

$KE_f = \frac{1}{2} mv^2 = (1/2)(10kg)(5m/s)^2 = 125\ J$

Efficiency = Final total energy / Initial total energy:

eff% = (125 J)/(196.2 J) = 63.7%

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Energy

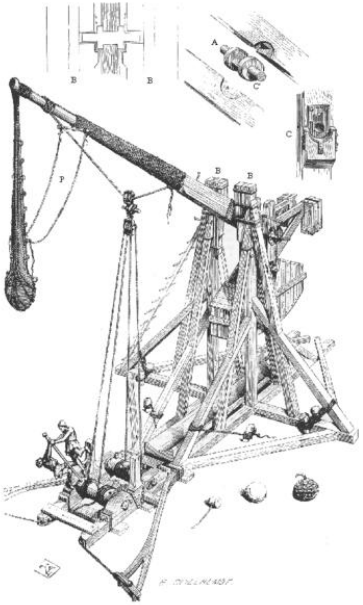
Storage and Conversion

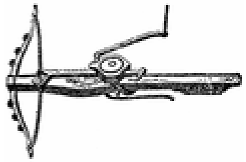
DEMO

Energy is stored in a spring, then released
Converting its potential energy to kinetic energy of a smaller body

Other energy converters:

- **Trebuchet, catapult (potential → kinetic)**
- **Generator (kinetic → electric potential)**
- **Engine (chemical potential → kinetic)**
- **Motor (electric potential → kinetic)**
- **Air compressor (kinetic → potential)**





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Activity # 1

30 minutes

CATAPULT!!!

Store some potential energy and convert it to kinetic energy!

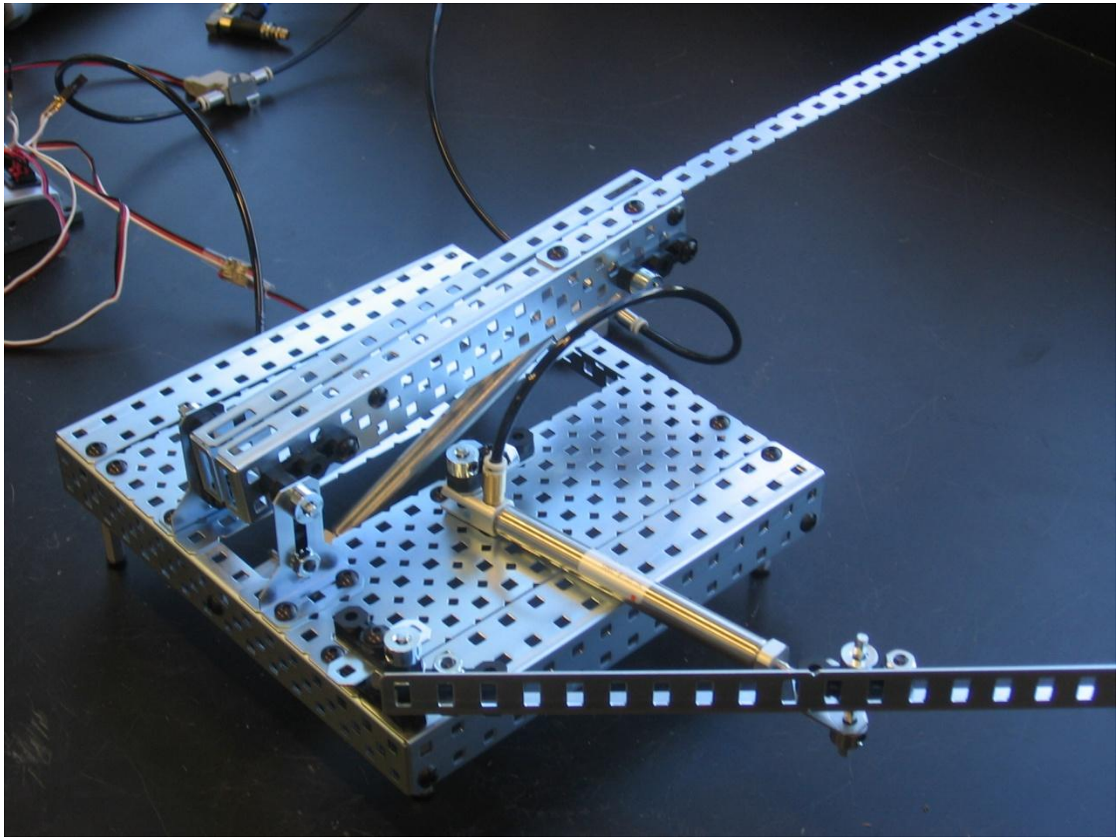
Ammo: Vex gear (36 tooth)

Build a catapult using gravity to fling a Vex gear

Distance will be judged from where the gear first hits ground

Be quick though! You have 25 MINUTES starting NOW

Demo of example



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FLUID POWER

What is Fluid Power?

- Pressurized fluid does the work
- Hydraulics
  - Oil
  - Water
  - Other fluids
- Pneumatics
  - Air
  - Nitrogen
  - Hot gases
  - Other gases

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When to use fluid power

- Electric
  - High speed but low torque (force) → requires gears
  - Control is often more precise and rapid and less expensive
- Hydraulic and pneumatic
  - Speed/torque combo is well suited to many motion applications
  - Well suited to high forces
  - Can be delivered “around the corner”
  - Control is usually by throttling, hence wastes energy
- Center for Compact Efficient Fluid Power
  - A brazen commercial

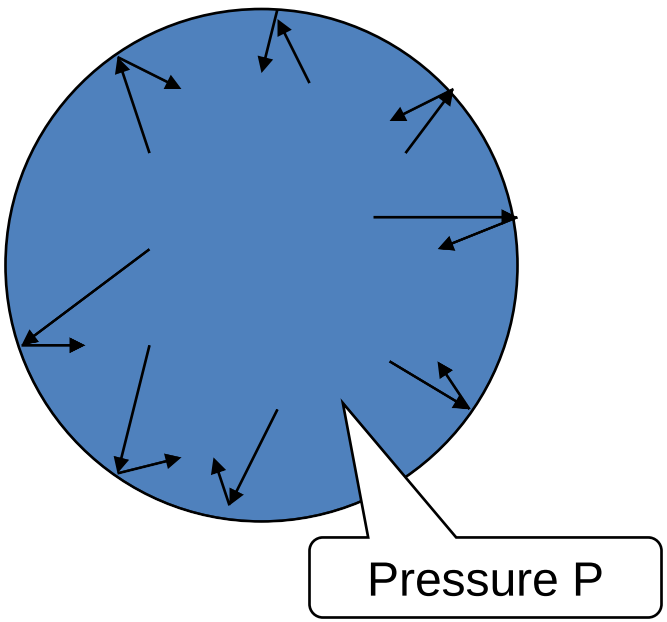
Hydraulics is Especially critical to the Mobile Equipment Industry

Mobile equipment (construction)

Pneumatics compared to hydraulics

- No problems of a spills
- Compressibility stores energy
  - Available for your use
  - Dangerous if excessive volumes or pressures
- Difficult to control precisely
- Fluid is readily available
  - Should be filtered, dry
- Usually lower forces

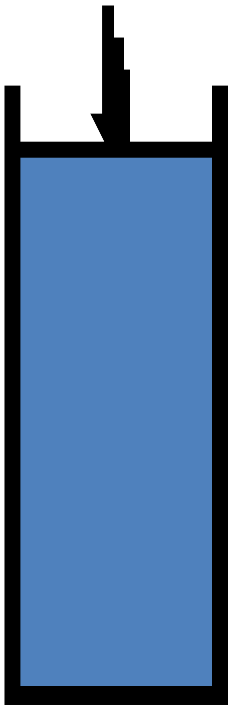
Pressure of an “ideal” Gas



$$P \times V = mR \times T$$

- Pressure of a gas is due to the force of gas molecules bouncing off the walls.
- Pressure increases when molecules are moving faster, heavier, or if there are more molecules.
- Molecules move faster when they are hot.
- mR depends on molecule.

Getting Work out of Air



- Work is force acting over a distance of motion, e.g. Newton x meters
- Put air in a container under pressure
- Allow part of the container to expand
- The expanding part does work

How much energy is in your tank?

- Tank Volume = 150 ml or 9.154 in^3
- Pressure = 413,700 Pa or 60 psi
- Atmospheric pressure = 101,325 Pa or 14.7 psi

- Answer:
  - Assume constant temperature:
    PV = mRT = constant
  - Work = $PV \ln(P/P_{atm})$
    $= 0.15 \times 413{,}700 \times \ln(4.083) = 87.3$ kJ

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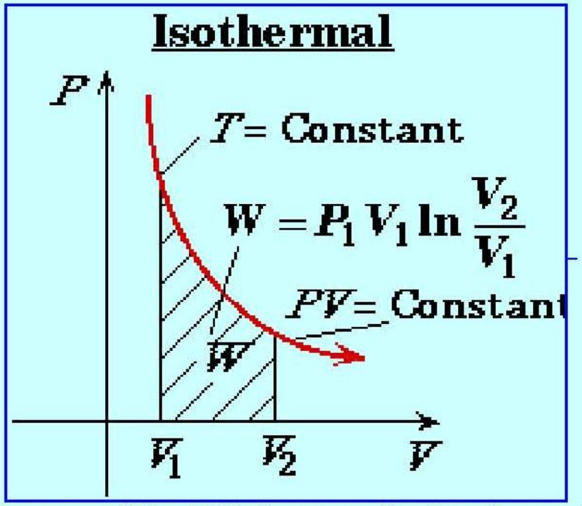
Alternative Work Possibilities

$$W = \int_{V_1}^{V_2} P(V)\, dV$$

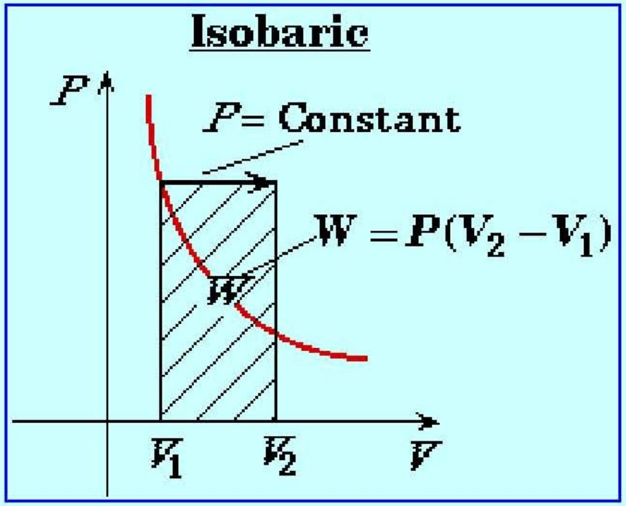


Blowup of the PV diagram for Isothermals

$$P = \frac{nRT}{V}$$

$$W = \int_{V_1}^{V_2} P\, dV = \int_{V_1}^{V_2} \frac{nRT}{V} dV$$

$$= nRT \int_{V_1}^{V_2} \frac{dV}{V} = nRT \ln \frac{V_2}{V_1}$$

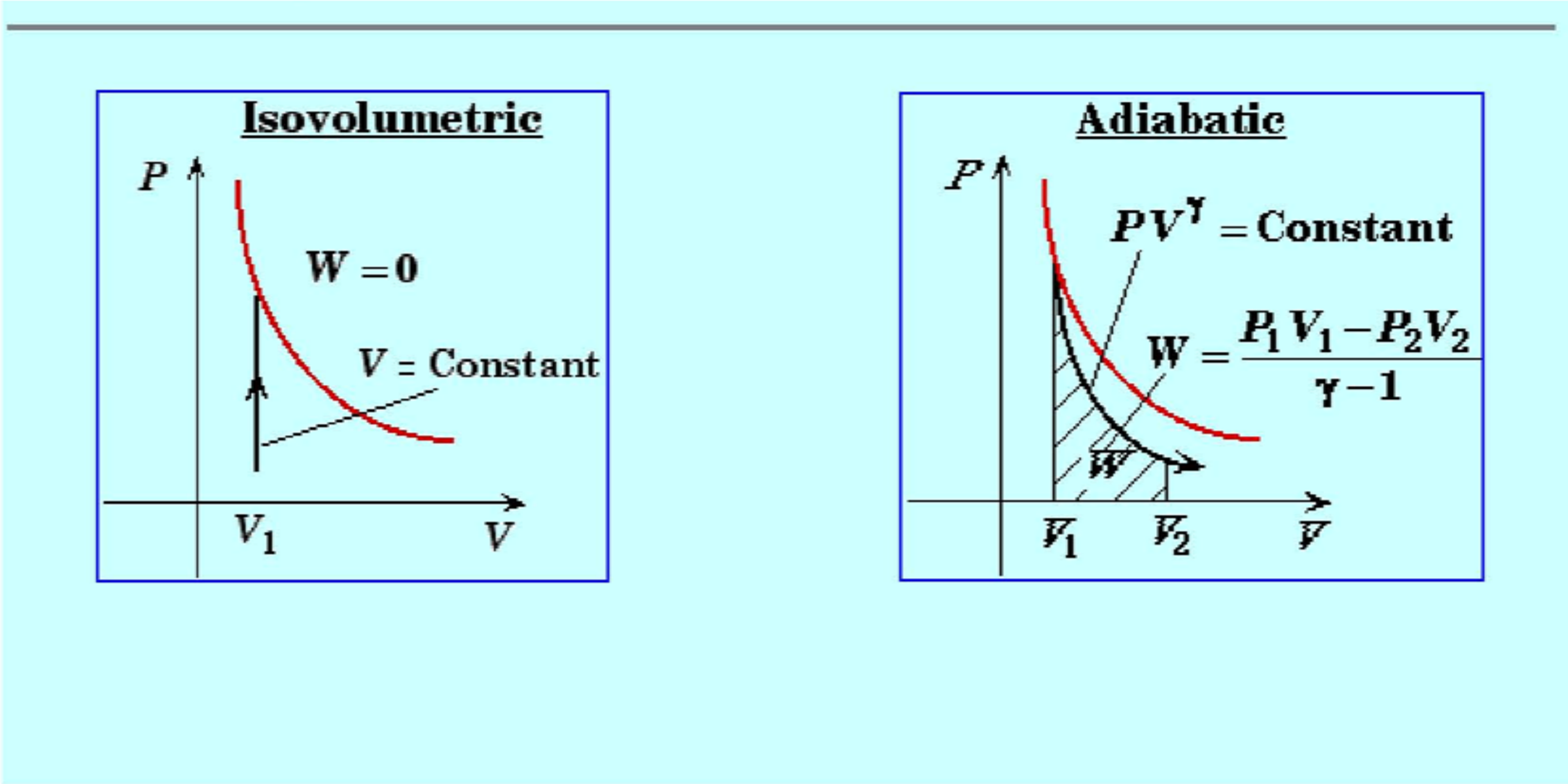


$$P = \text{Constant}$$

$$W = \int_{V_1}^{V_2} P\, dV = P \int_{V_1}^{V_2} dV$$

$$= P\, \Delta V$$

More work possibilities



http://www.ac.wwu.edu/~vawter/PhysicsNet/Topics/Thermal/PV_WorkDiag.html (1 of 2)10/23/2006 1:07:17 PM

How much energy in your tank can you use?

- Line losses:
  Pressure drop proportional to flow

- Throttling losses:
  Pressure drop proportional to flow squared

- Cylinder friction:
  Coulomb plus viscous friction, depends on seals

Force available

- Pressure x Area = Force
- Area = pi x Bore^2 / 4

- For Vex cylinder:
  - Bore = 10 mm → Area = 78.5 mm^2
  - Force = 413,700 x 78.5 x 10^{-6} = 32.48 N
  - at 100 psi: F = 54 N

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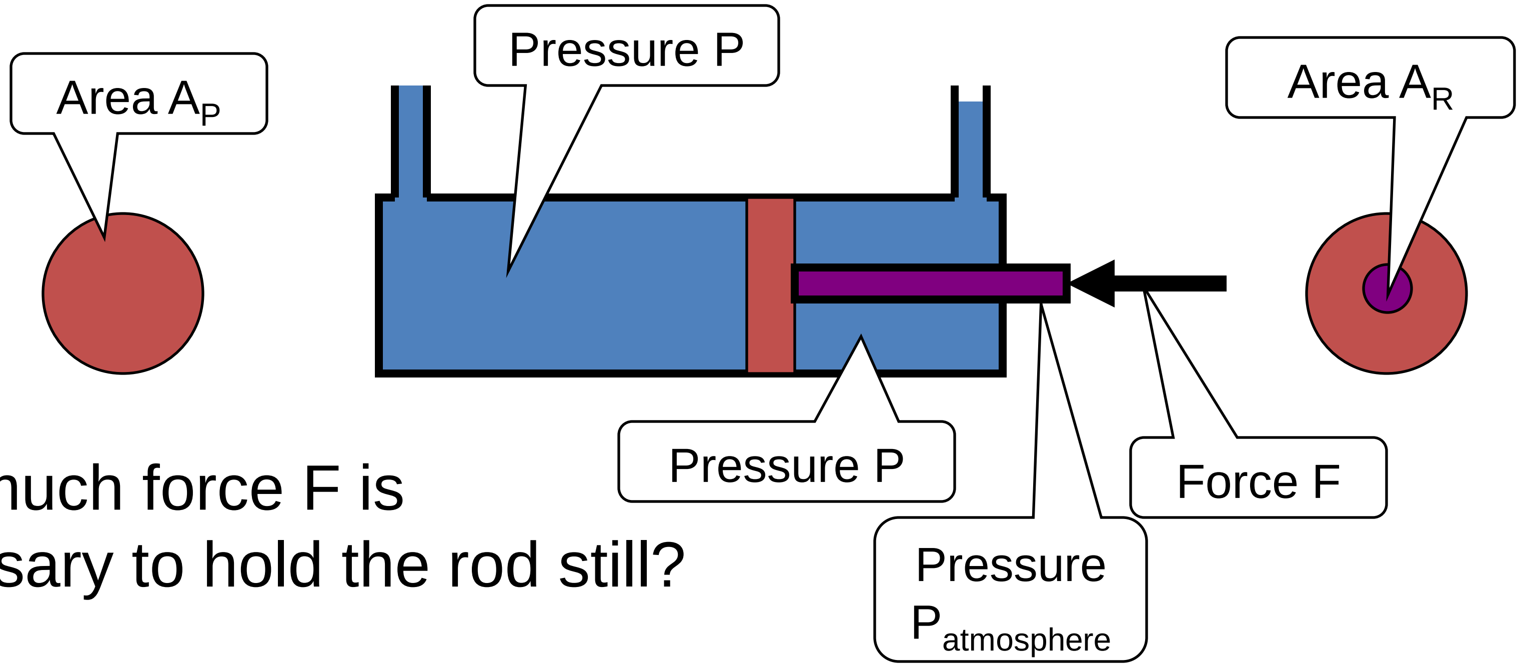
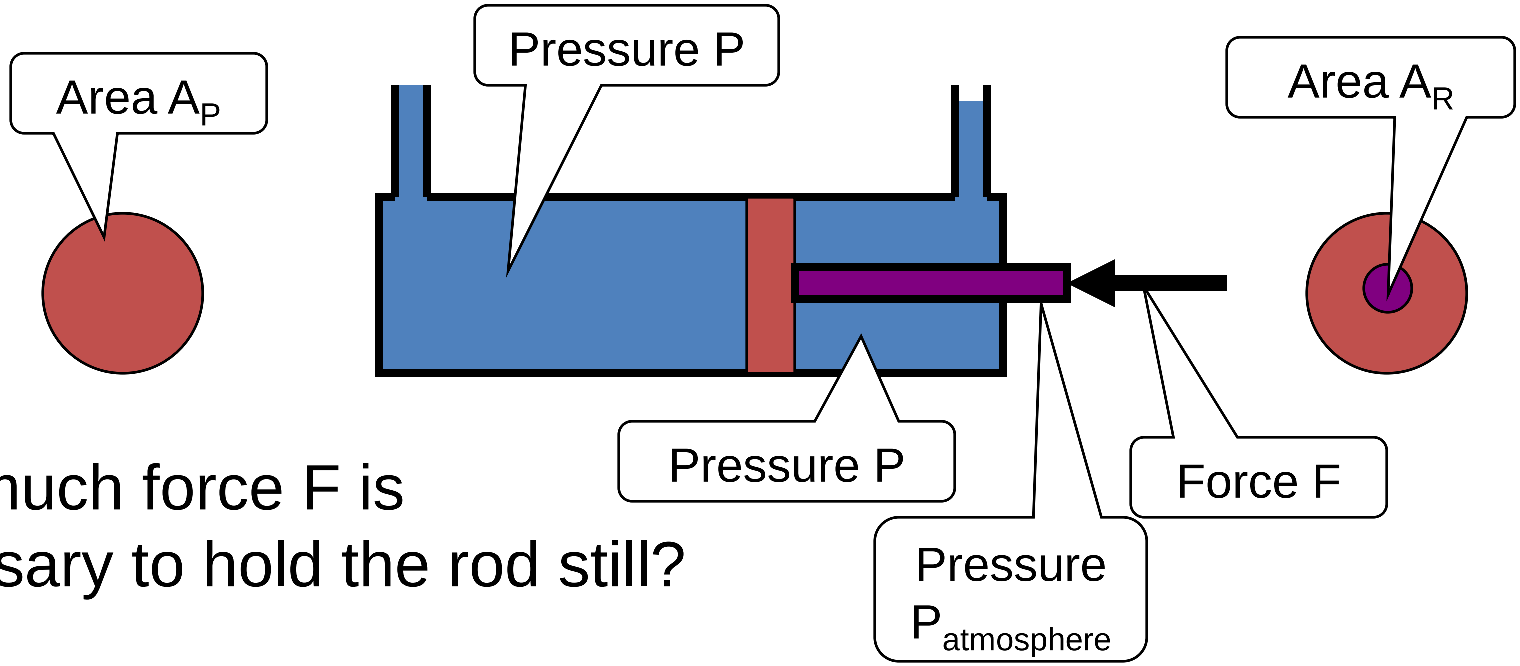
The Effect of Different Areas



How much force F is necessary to hold the rod still?

The Effect of Different Areas



How much force F is necessary to hold the rod still?

Answer: Force to the right = Force to the left

$$P \times A_P = P \times (A_P - A_R) + P_{atm} \times A_R + F$$

$$F = A_R \times (P - P_{atm})$$

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Basic Operation of the Servo Valve (single stage)

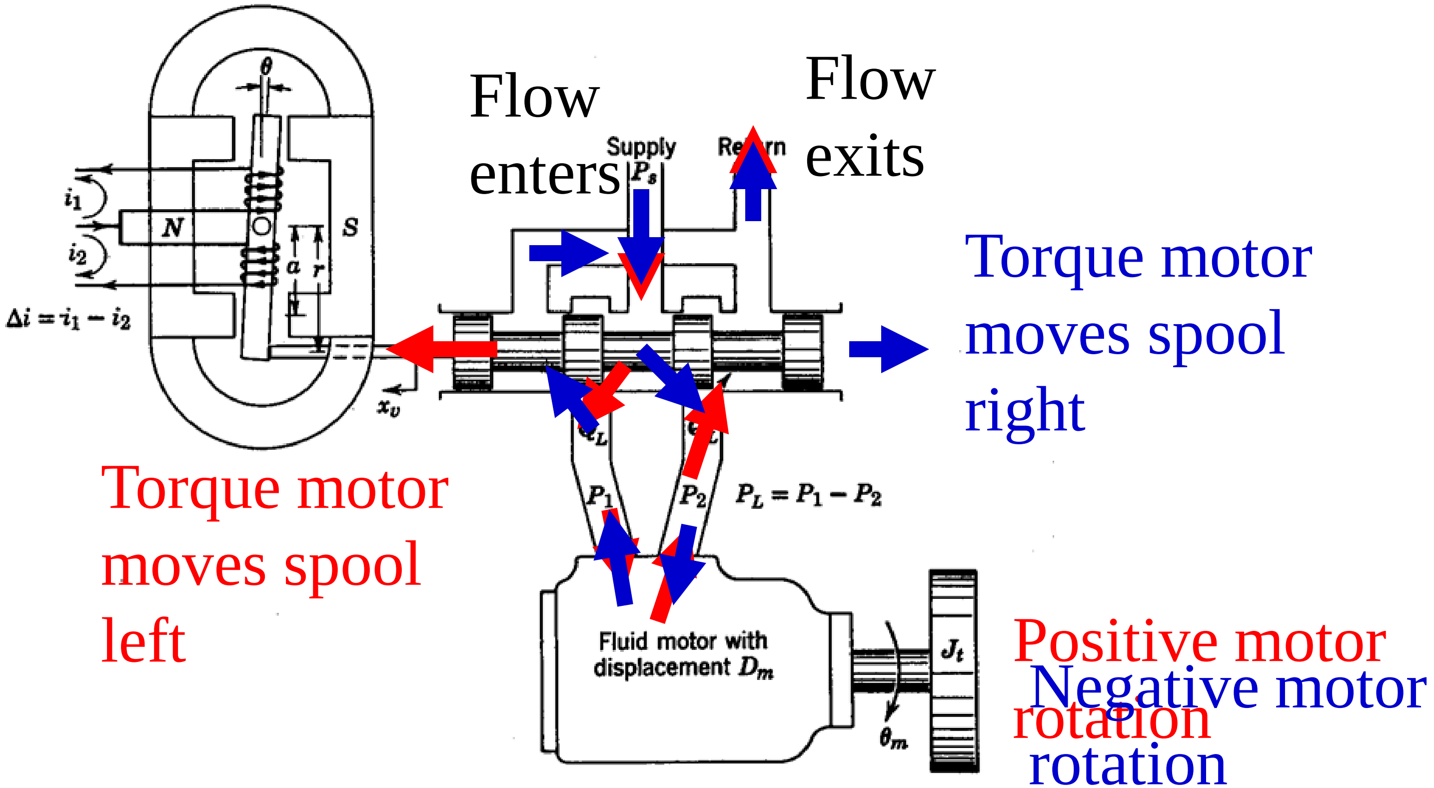

Figure 7-11 Schematic of a single stage electrohydraulic servovalve connected to a motor with inertia load.

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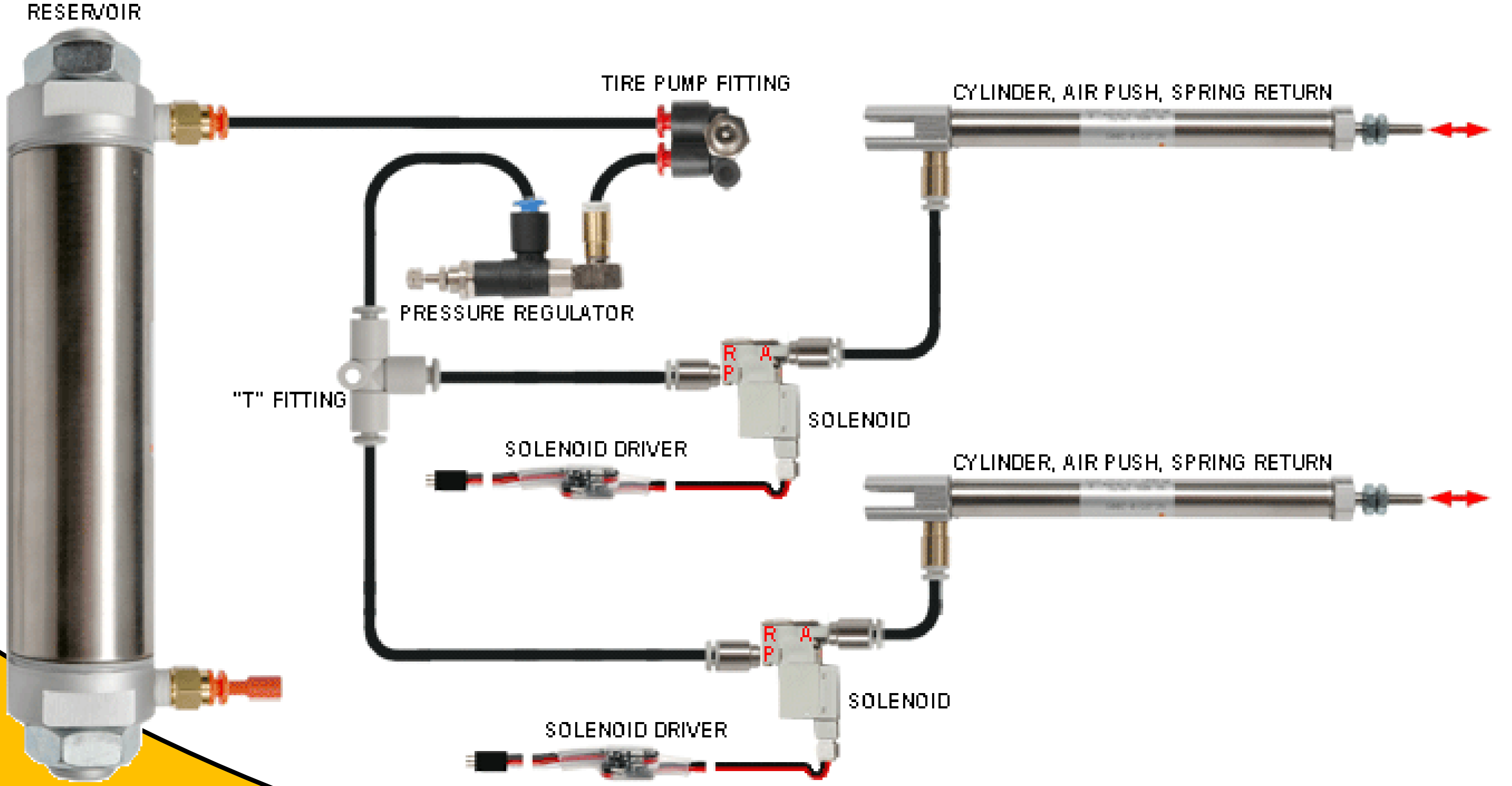
Components for hands on task

- Cylinder: single acting, spring return
  - Max force: 54 N or 12 lbf
  - Stroke: 50 mm or 1.987 in
  - Bore: 10 mm or 0.394 in
- Valve: normally closed vents to atmosphere
- Tank:
  - Size: 150 ml or 9.154 in^3
  - Max pressure: 6.895 bar (10^5 bar) or 100 psi
- Mechanical parts

VEX Pneumatic Kit 1



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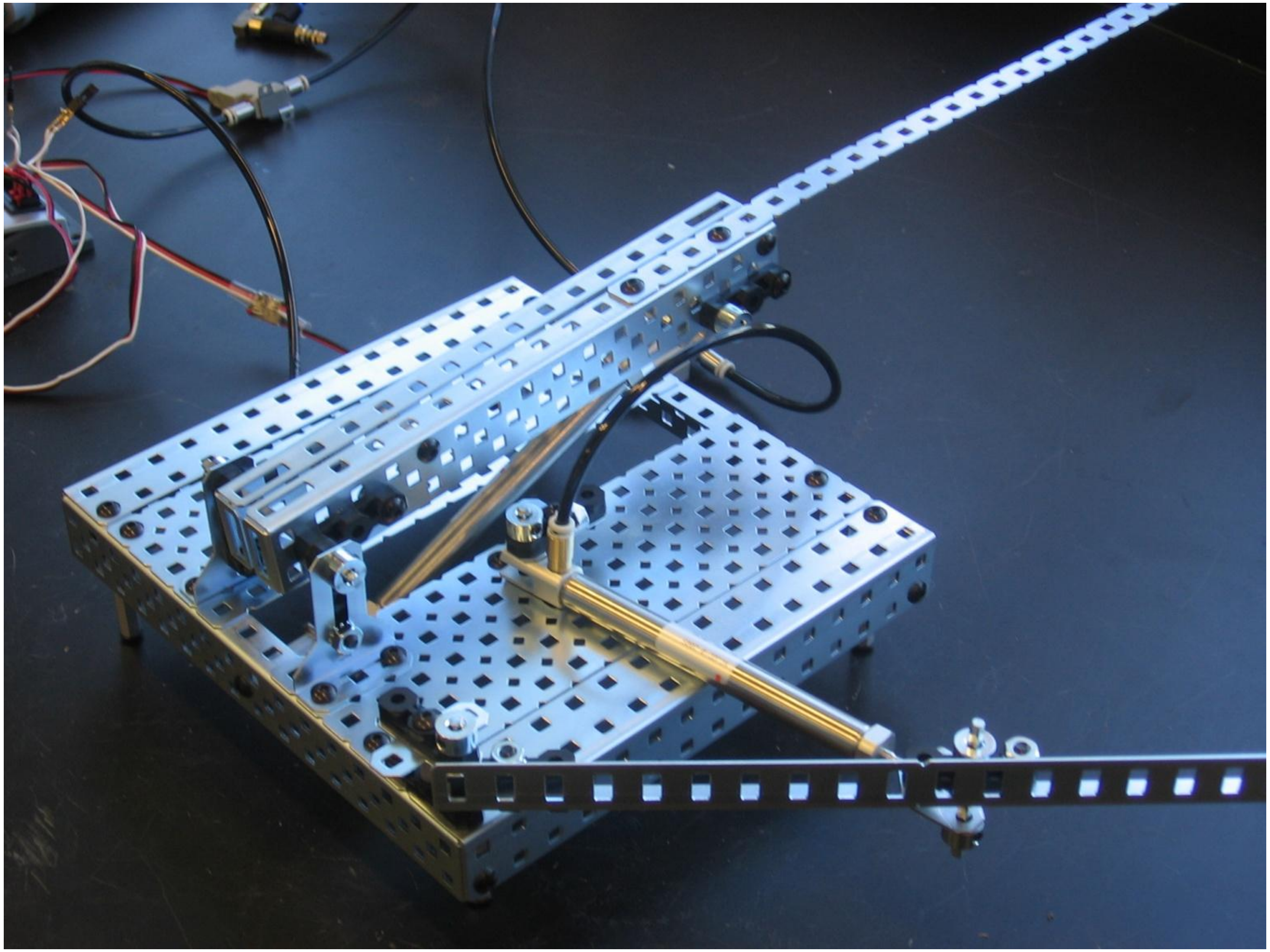
Today's Challenge

- Maximum distance launch of 1 Vex gear
- Rules
  - The reservoir shall be charged at 60 psi
  - The base shall remain immobile
  - Only fluid power actuators (pistons) shall be used
  - The best out of three launches shall be considered



An example design

- Consider different configurations than the one shown?
  - two cylinders in parallel or in series
  - different linkage configurations to achieve higher speeds
  - making the lever as light as possible
  - taking advantage of flexibility to achieve higher release speeds…

Today's Challenge # 2

- Maximum distance launch of 1 Vex gear
- Rules
  - – The reservoir shall be charged at 60 psi
  - – The base shall remain immobile
  - – Only fluid power actuators (pistons) shall be used
  - – The best out of three launches shall be considered

Some YouTube Videos

- http://www.youtube.com/watch?v=jkft2qaKv_o
- http://www.youtube.com/watch?v=0gk-yQ1H3M8
- http://www.youtube.com/watch?v=7l0qIO7y6Cc
- http://www.youtube.com/watch?v=2cIuuplWRIQ

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