# Thursday April 20

Topics for this Lecture:

- *Heat Engines*
- *Review for final*

- Assignment 14 due Friday
- Pre-class due 15min before class

Study Tips:

- Look at old TopHat questions
- Try a problem before looking at the solution
- Focus on solution **processes**, not equations

The comprehensive final is Thursday April 27th 7:00-9:00pm in Walter Hall (room depends on your last name).

Date: 04/27/2017

Time: 7:00 pm – 9:00 pm

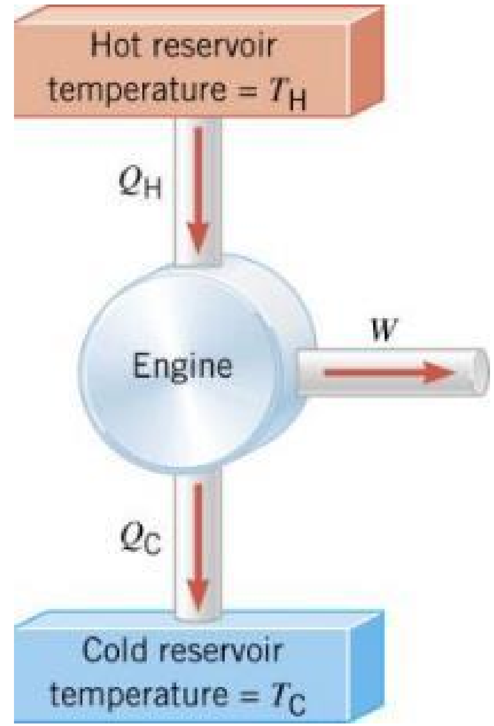
| Room : | | |
|---|---|---|
| Walter 135 | [Last Name: | A - G ] |
| Walter 145 | [Last Name: | H - N ] |
| Walter 235 | [Last Name: | O - Z ] |

If you have an exam-schedule conflict, **immediately** email Meisel@ohio.edu me know which of your other exams conflicts with this one.

**Heat engines:**

- $Q_H = W + Q_C$
- Efficiency, $e = W/Q_H = (Q_H - Q_C)/Q_H$
  $= (1 - Q_C/Q_H)/1$
- Max heat engine efficiency, is the Carnot efficiency, $e_{Carnot} = 1 - (T_C/T_H)$
- Coefficient of performance, COP, $COP = Q_H/W$

# Heat Engines




- *Heat Engine*: generating work from a temperature difference between a hot and a cold reservoir.
  - E.g. the High-T reservoir could be created by burning fuel & the Low-T reservoir could be the ambient air
- This is accomplished by heat transfer between the reservoirs and the engine.
- The heat engine can be reversed; where work is used to create a temperature difference.

- Heat engines operate in a cycle: $\Delta U = 0$
  - From the 1st law of thermodynamics: $\Delta U = Q - W$ ….so for the engine, $Q_{cycle} = W_{cycle}$
  - The high-T reservoir is adding heat for the cycle, whereas the low-T reservoir is removing heat, so $Q_{cycle} = Q_H - Q_C$
  - Therefore, $W = Q_H - Q_C$ (this is more commonly written as: $Q_H = W + Q_C$)
- Efficiency is what you get out over what you put in: $e = W/Q_H = (Q_H - Q_C)/Q_H = 1 - Q_C/Q_H$

What is the efficiency of a heat engine that pulls 8000J from the hot reservoir and expels 6000J in the form of exhaust?

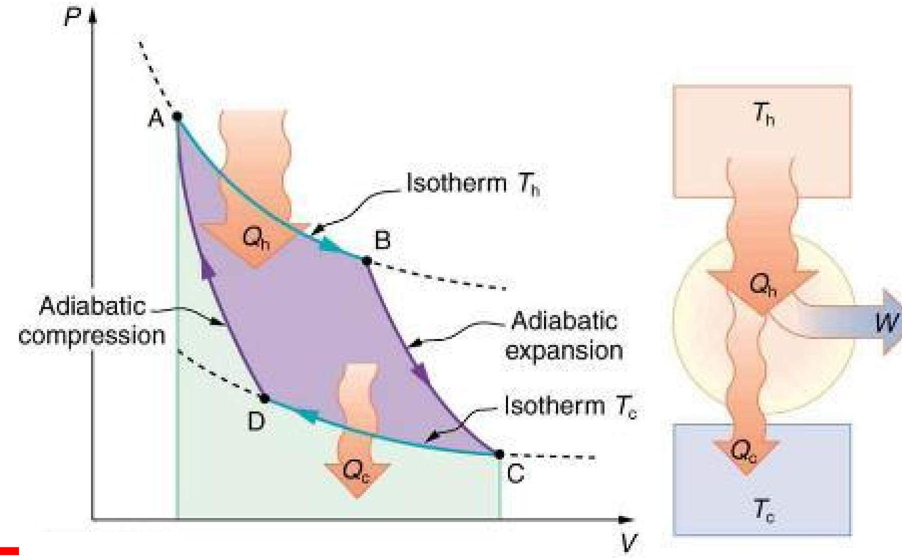
(A) 10%  (B) 25%  (C) 33%  (D) 125%

1. Efficiency = (What you get out)/(what you put in)
2. $e = W/Q_H$
3. Work you get out is the difference between head added & heat removed.
4. $W = Q_H - Q_C$
5. $e = (Q_H - Q_C)/Q_H = (8000J - 6000J)/(8000J) = 0.25 = 25\%$

Can see (also from the form: $e = 1 - Q_C/Q_H$) that minimizing the ratio of heat removed to heat added is required to maximize efficiency.
The amount of heat added & heat removed depends on the type of transition that's doing the adding/removing.

# **Carnot Engine**: Maximally efficient heat engine

- For the best-possible heat engine, the disorder of the system & surroundings doesn't increase when transferring heat. (This is practically impossible, but we can imagine it).
- Also, the hot & cold reservoirs are infinite and no amount of adding or removing heat changes the reservoirs' temperatures.
- For this case, the Carnot Engine,




$$\frac{Q_C}{Q_H} = \frac{T_C}{T_H} \qquad e_{Carnot} = 1 - \frac{T_C}{T_H}$$

- You can never have a larger efficiency than this for a heat engine!
- *Here **temperature must be in Kelvin**

Because of the 3rd law of thermodynamics, you can't make $T_C$=0, so you can't have a perfectly efficient engine.

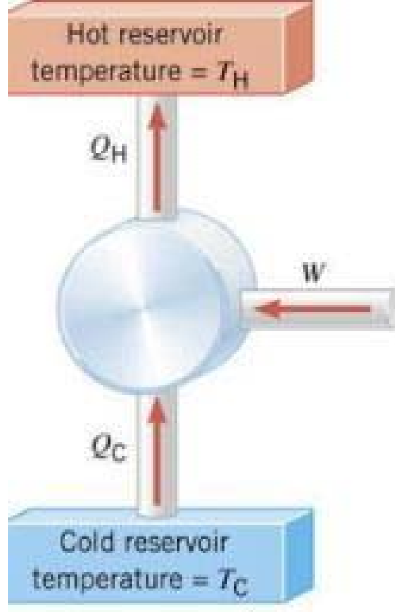
Your crazy uncle fancies himself an inventor and claims to have created an engine that draws heat from a reservoir at 375K, does 5000J of work per second and expels 4000J of work per second into a cold reservoir of 225K. Is this possible?

(A) yes (Invest!)

(B) no (Tell him to go away)

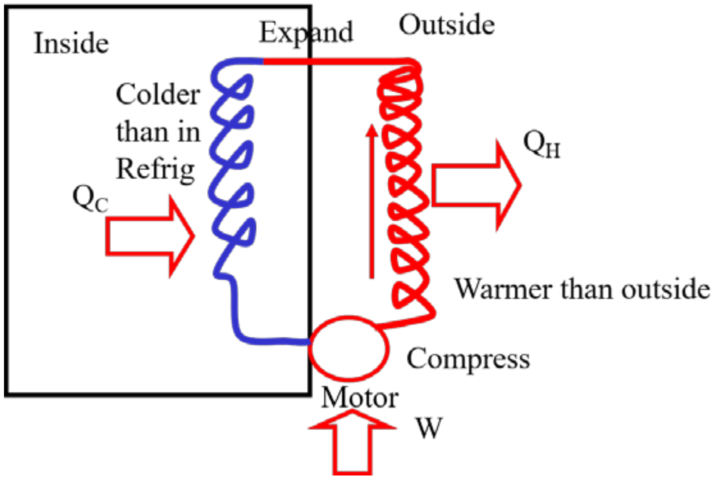
1. Claimed efficiency = $e = W/Q_H = W/(W+Q_C)$ = 5000J/(5000J+4000J) = 0.56
2. Carnot efficiency = $e_{Carnot} = 1 - T_C/T_H$ = 1 - 225K/375K = 0.4
3. The claimed efficiency is better than the theoretical maximum. It is not possible.

# **Refrigerator**: Reversed heat engine (to cool) 📖 Sect 15.10



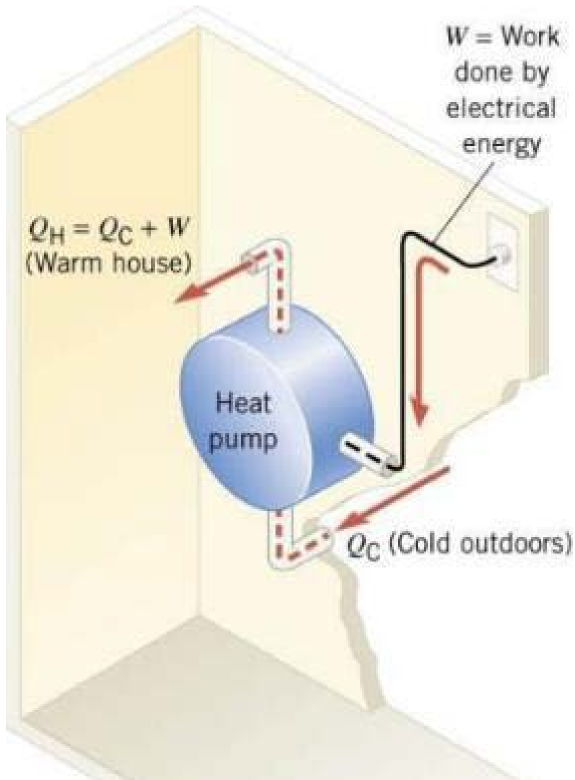
Refrigeration Process

- We can reverse our heat engine, putting work in to create a temperature difference. This can be a refrigerator.
  - This works by compressing a fluid (a.k.a. refrigerant), which heats it. That heat is given-off to the environment (on the back of your refrigerator). It is then allowed to expand, cooling it (just before it enters the fridge). Heat is then transferred from the stuff in the fridge to the cold tubes with the cold refrigerant.
- As before: $Q_H - Q_C = W$
- Now, how well your refrigerator is performing depends on how much it is cooling divided by how much work you put it:
  - Coefficient of performance = $COP_R = Q_C/W$
  - Rewritten: $COP_R = (Q_C/Q_H)/(1-Q_C/Q_H)$
- For a perfect (a.k.a. Carnot) refrigerator:
  - $COP_{R,Carnot} = (T_C/T_H)/(1-T_C/T_H)$



# **Heat Pump**: Reversed heat engine (to heat) 🕮 Sect 15.10

- We can reverse our heat engine, putting work in to create a temperature difference. This can be a heater.
- As before: $Q_H - Q_C = W$
- Your heat pump performance depends on how much heat you're getting out compared to how much work you're putting in
  - Coefficient of performance = $COP_H = Q_H/W$



# **Heat Engines, Heat Pumps, & Refrigerators**: Summary

| Device | Basic Concept | What it provides | What we pay for/put in | How well the device is doing its job |
|---|---|---|---|---|
| Heat Engine | A natural flow of heat (hot to cold) is used to do work on surroundings. | Net Work: $W_{net}$ | Heat from high-T reservoir: $Q_H$ | $0 < e = W_{net}/Q_H < 1$ <br><br> $(e_{Carnot} = 1 - T_C/T_H)$ |
| Heat Pump | An un-natural flow of heat (cold to hot) is created by work from surroundings. | Adds heat: $Q_H$ | Work from surroundings: $W_{net}$ | $COP_H = Q_H/W_{net}$ <br><br> $(COP_{H,Carnot} = 1/(1 - T_C/T_H)$ |
| Refrigerator | An un-natural flow of heat (cold to hot) is created by work from surroundings. | Removes heat: $Q_C$ | Work from surroundings: $W_{net}$ | $COP_R = Q_C/W_{net}$ <br><br> $(COP_{R,Carnot} = 1/(T_H/T_C - 1)$ |

# **Class Review**: Whirlwind tour of PHYS 2001

- Topics: (Section 1, Section 2, Section 3. Final is ~1/2 Section 3, ~1/2 Sections 1&2.) — In OpenStax
  - Kinematics (Ex.: soccer ball trajectory, free-fall, braking time) — Ch. 2-3
  - Forces (Ex.: tension of rope holding weight, free-body diagram) — Ch. 4-5
  - Torque (Ex.: person on a bridge, weight hanging from a beam) — Ch. 9
  - Energy & Work (Ex.: speed of dropped thing just above ground) — Ch. 7
  - Momentum conservation (Ex.: collisions, bullet & block) — Ch. 8
  - Circular Motion (Ex.: linear speed of rotating object, ice skater) — Ch. 6
  - Simple Harmonic Motion (Ex.: mass & spring, pendulum) — Ch. 16
  - Fluids (Ex.: buoyancy, water speed in an expanding pipe) — Ch. 11,12
  - Thermal Physics (Ex.: expansion of rod, equilibrium temp.) — Ch. 13,14
  - Thermodynamics (Ex.: engine efficiency, cycles) — Ch. 15

*Anything covered in the lecture notes is fair game.
*TopHat questions, practice exams, homework problems, & pre-class assignments all contain the types of questions that could be on the exam.

# Study Tips


***Recommended study procedure*:**

1. Review notes
2. Try typical practice problems (a couple per topic, e.g. TopHat Q's)
3. Look at lecture notes for the questions you struggled on & possibly consult the relevant section of the book
4. Go back to step 1 until you feel at least ok about most topics
5. Try the practice exam in a realistic setting.
6. Zero-in on the topics you're still struggling on, trying practice problems, reviewing the notes & repeating.

***General comments:***

- At least 8 hours of studying is probably necessary to do well. Likely more.
- Making an equation sheet doesn't really count as studying.
  Just like copy-pasting isn't the same as reading & comprehending.
- Try practice problems without looking at the solutions.
  The solution will almost always look clear/obvious when reading it,
  but that won't mean you can actually reproduce it!
- <u>Focus on the relevant process for solving a class of problems.</u>

# Exam Taking Tips


- Stay calm.
- Work on the problems that are easy for you first.
- Work your way through progressively tougher ones.
- If you get stuck on a problem, move to a different one and revisit it later.
- Read over your exam carefully once you're finished to make sure you didn't miss anything, read a problem wrong, or make a small mistake.
- Write something down for every question.
  You'll get partial credit, e.g. for the correct equation.

# *NOTE:*

# The following are general tips for major items related to a given topic, but they are by no means are comprehensive.

# Anything presented in class this semester is fair game.

## The following information will be on the cover of your exam sheet:

**Numerical Constants and Conversions:**

femto $10^{-15}$; pico $10^{-12}$; nano $10^{-9}$; micro(μ) $10^{-6}$; milli $10^{-3}$; centi $10^{-2}$; kilo $10^{3}$; Mega $10^{6}$; Giga $10^{9}$;

$g = 9.80\ m/s^2$; $G = 6.673\times10^{-11} N\cdot m^2/kg^2$

1 mi = 1.609 km; 1 in = 2.54 cm; 1m = 39.4 in; 12 in = 1 ft; 1 m = 3.28 ft;

1 mi = 5280 ft; 3.16 × 107 s = 1 year; 1 rev = 360° = 2π rad.

$I_{point}=MR^2$; $I_{hoop}=MR^2$; $I_{sphere}=\frac{2}{5}MR^2$; $I_{solidcyl}(disk)=\frac{1}{2}MR^2$

$\rho_{water}$ = 1000. kg/m3; $\rho_{air} = 1.29\ kg/m^3$; 1 atm = $1.013\times10^5$Pa;

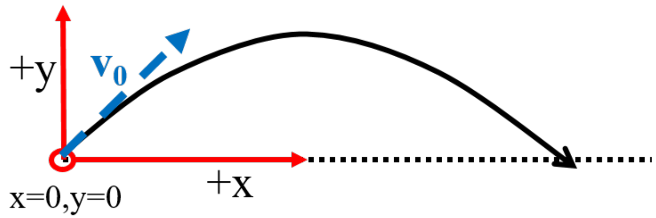
T(K) = T(C) + 273.15

Water: Specific Heat = 4186 J/kg °C ; $L_{vaporization} = 2.26\times10^6$ J/kg ; $L_{fusion} = 3.33\times10^5$ J/kg

Specific Heat(Ice) = 2090 J/kg °C; Specific Heat(Steam) = 2010 J/kg °C

$A_{SQUARE} = l^2$; $A_{CIRCLE} = \pi r^2$; $V_{CYL} = \pi r^2 h$

# Kinematics



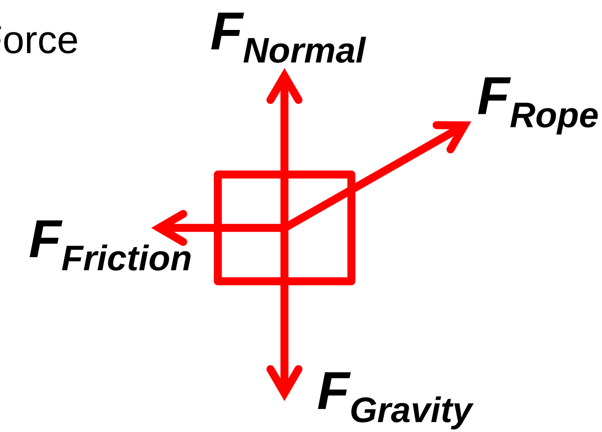

- How to recognize:
  - Trajectories, motion with linear acceleration
- Tips for solving:
  1. Draw (if not drawn already)
  2. What information do you know?
  3. What do you want to know?
  4. Which of your equations will get you (2) from (1)?
  5. Work through algebra of that equation.
  6. If it doesn’t work-out, go back to (4) and try another equation.
- Notes:
  - Horizontal & vertical motion in a 2D-kinematics problem can both be solved like separate 1D-kinematics problems. They are only linked in time.
  - Be sure to cancel-out irrelevant variables in your equations when you can. For example, if the initial velocity is zero.

2D Projectile motion eqns.

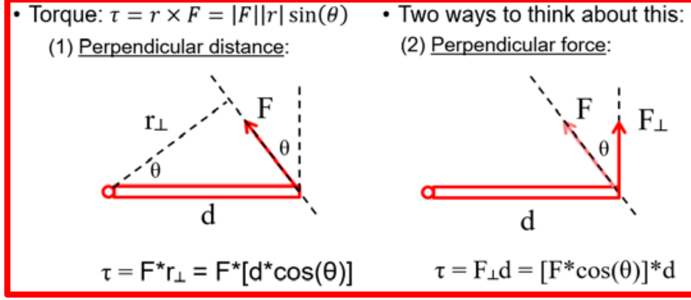
1. $v_x = v_{x,0}$
2. $x = x_0 + v_{x,0}t$
3. $v_y = v_{y,0} + a_y t$
4. $y = y_0 + v_{y,0}t + \frac{1}{2}a_y t^2$
5. $y = y_0 + \frac{1}{2}(v_{y,0} + v_y)t$
6. $v_y^2 = v_{y,0}^2 + 2a_y(y - y_0)$

# Forces & Equilibrium

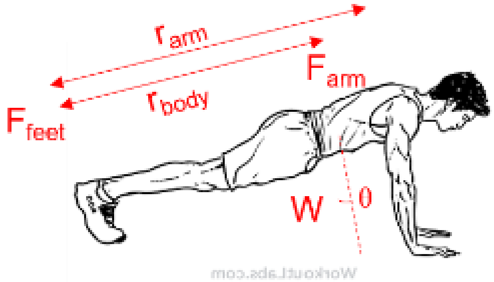
- How to recognize:
  - Free-body diagram, pushing and/or pulling happening (not about an axis), acceleration due to pushing/pulling is being asked for.
- Tips for solving:
  1. Draw a free-body diagram (i.e. labeled arrows for each force)
  2. Apply newton's 1st law: $\Sigma F = ma$.
  3. Do the algebra to find the missing force or the acceleration.
- Notes:
  - If an object is not accelerating, the forces must be balanced.
  - Should know formulae for:
    - Gravity, Buoyancy, Friction, Normal Force, Centripetal Force

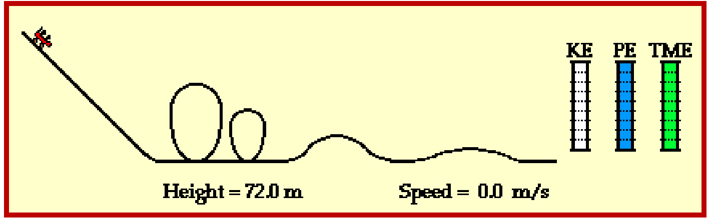
# Torque & Static Equilibrium




- How to recognize:
  - A force or forces are acting on an object, but aren't applied directly to the center of an object.
- Tips for solving:
  1. If it's not rotating or accelerating, use static equilibrium: $\Sigma F_x=0$ & $\Sigma F_y=0$ & $\Sigma\tau=0$.
     If it is, then you're probably just being asked for torque.
     Or for the angular acceleration due to torque: $\tau=I\alpha$.
  2. Draw a free-body diagram.
  3. Pick an axis of rotation.
     If you want to ignore a force, put the axis of rotation where it is applied.
     If you want to find a force, put the axis of rotation in a place so that the other force(s) create a net torque.
  4. Do the algebra for the static equilibrium equations.
- Notes:
  - The weight of an object pulls down from its center of gravity.
    For a uniform object, this is its geometric center.

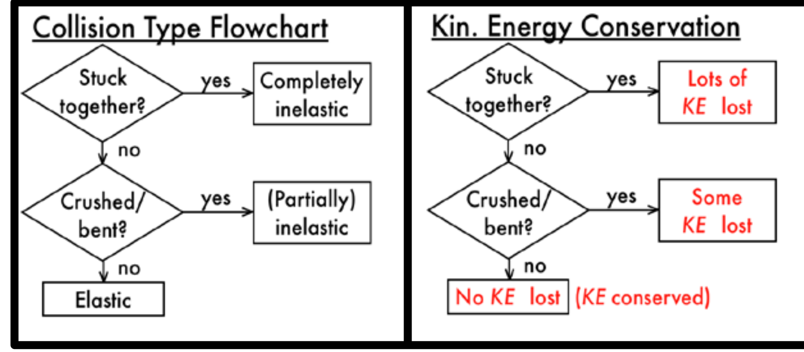


# Energy & Work




- How to recognize:
  - You're given a height of an object at one location, but asked for the speed at another (or vice versa). You know a non-conservative force and are asked for an energy change (or vice versa).
- Tips for solving:
  1. Employ energy conservation, minus energy removed by non-conserving forces.
  2. $\Sigma PE_i + \Sigma KE_i = \Sigma PE_f + \Sigma KE_f + W_{NC}$
  3. If you know the non-conserving force, $W=Fd\cos(\theta)$
  4. Work through the algebra.
- Notes:
  - Potential energy is with respect to some reference height, which you choose.
  - Typical non-conserving forces are friction or the force of an object being indented as it is impacted (e.g. a landing pad for a stunt person).
  - If you're asked for information regarding a trajectory (e.g. max height, velocity before impact), but you don't need time information, this can be easier than using 1D kinematics.

# Momentum Conservation

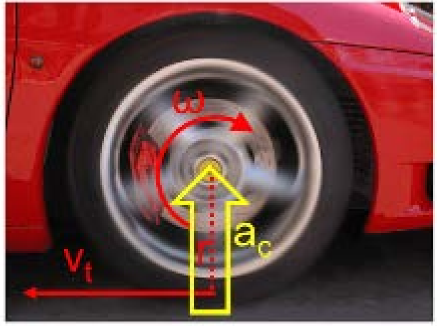



Patrick M. Len

- How to recognize:
  - Objects are colliding.
- Tips for solving:
  1. Draw your initial & final situations. Label all object(s)' velocities.
  2. Employ momentum conservation.
  3. $\Sigma p_i = \Sigma p_f$
  4. Work through the algebra to find the missing information.
- Notes:
  - Impulse is equal to the change in momentum.
  - If no kinetic energy is lost, the collision is elastic.
  - If some kinetic energy is lost, the collision is inelastic.
  - If the objects stick together, a lot of kinetic energy is lost, and the collision is completely inelastic

# Circular Motion

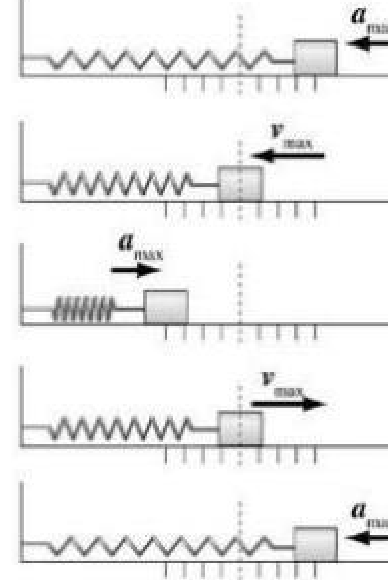
- How to recognize:
  - Something is moving, but not in a straight line.
- Tips for solving:
  1. Convert linear variables to angular variables when necessary. Or convert the other way when necessary.
  2. If something is spinning, but changing its mass distribution, employ angular momentum conservation: $I_i\omega_i=I_f\omega_f$
  3. If a torque is applied, use the analogy to Newton's 1st law: $\tau=I\alpha$
- Notes:
  - Newton's law still applies for centripetal force: $F_c = ma_c = mr\omega^2$




*Equations for kinematics in 1D & Newton's Laws apply to rotational motion as well, by subsituting the appropriate quantities:*

| **Linear Quantity** | | | **Corresponding Rotational Quantity** | | |
|---|---|---|---|---|---|
| ***Quantity*** | ***Variable*** | ***SI units*** | ***Quantity*** | ***Variable*** | ***SI units*** |
| length | x | m | angle | $\theta = s/r$ | rad |
| velocity | $v = \Delta x/\Delta t$ | m/s | angular velocity | $\omega = \Delta\theta/\Delta t$ | rad/s |
| acceleration | $a = \Delta v/\Delta t$ | $m/s^2$ | angular acceleration | $\alpha = \Delta\omega/\Delta t$ | $rad/s^2$ |
| mass | m | kg | moment of inertia | I (formula depends on object shape) | $kg*m^2$ |
| force | $F = ma$ | N | torque | $\tau = I\alpha$ | N*m |
| momentum | $p = mv$ | kg*m/s | angular momentum | $L = I\omega$ | $kg*m^2/s$ |

# Simple Harmonic Motion




- How to recognize:
  - Something is repeating, e.g. in circles or moving back & forth.
- Tips for solving:
  1. What do you know?
  2. What do you want to know?
  3. Look at your list of relevant equations to figure out how to get to (1) from (2).
- Notes:
  - Newton's laws still apply, i.e. F=ma.
  - A cycle is anything that repeats: oscillations, circles, …
  - Position, velocity, and acceleration are related as they are in 1D kinematics.

Spring:

$F_{applied} = kx \qquad \omega_{spring} = \sqrt{\frac{k_{spring}}{m_{weight}}} = \sqrt{\frac{k}{m}}$

Note: T, f, ω are ***independent of amplitude!***

$x = A\cos(\omega t) \qquad x_{max} = A$

$v = -A\omega\sin(\omega t) \qquad v_{max} = A\omega$

$a = -A\omega^2\cos(\omega t) \qquad a_{max} = A\omega^2$

Note: $f = 1/T$

$\omega = 2\pi f$

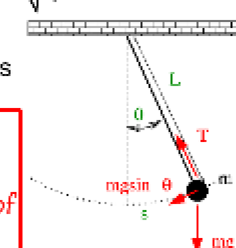
T, f, ω independent of oscillation amplitude.

Pendulum:

$\omega_{pendulum} = \sqrt{\frac{g}{l_{pendulum}}} = \sqrt{\frac{g}{l}}$

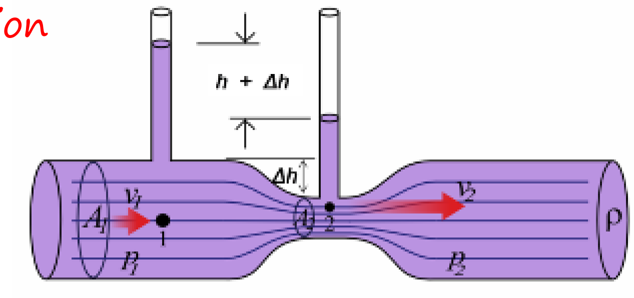
F ≈ -mg θ

F ≈ -(mg/L)s



# Fluids

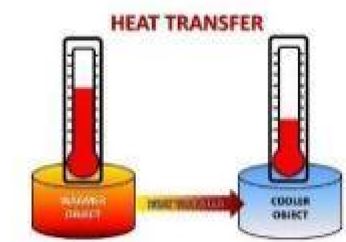
*The Hagen-Poiseuille equation will not be on the exam.

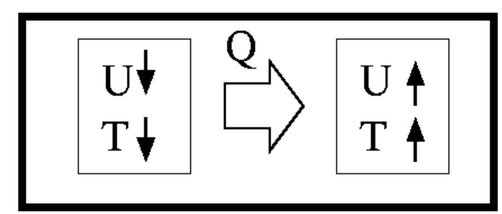


- How to recognize:
  - Something is floating or flowing.
- Tips for solving:
  1. If floating, draw a free-body diagram including the buoyancy force: $F_{buoyancy}=\rho_{fluid}V_{displaced}g$.
  2. Solve for the missing piece of information with algebra.
  3. If flowing, use Bernoulli's equation and the continuity equation to relate things you know at one point in the system to things you know at a later point.
  4. If looking for pressure with depth: $P=\rho gh$
- Notes:
  - Continuity says that if you squeeze a flowing fluid into a smaller diameter pipe, it will speed up.
  - Bernoulli says that if you slow-down a fluid, the pressure will increase.
  - Pressure in a fluid is height-dependent.
  - The pressure above atmospheric pressure is the gauge pressure. The pressure including the atmospheric pressure is the absolute pressure.

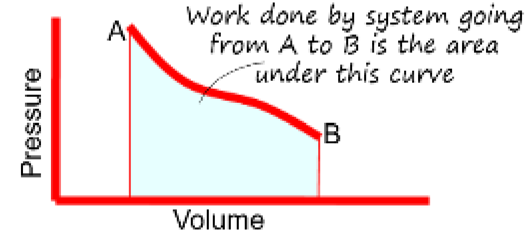
## Thermal Physics

- How to recognize:
  - Some object is responding to being heated/cooled by some other object or heat source.
- Tips for solving:
  1. Convert temperature information into favorable units (if it isn't already). These will be the units that match whatever constants you're provided.
  2. If heat is being transferred, use the heat-transfer equation: $Q=mc\Delta T$.
  3. If a hot object is touching a cold object, note that the cold object will gain some heat and the hot object will lose some heat. $Q_{gained}=Q_{lost}$.
  4. If a phase transition is occurring, take into account the heat required: $Q=mL$.
  5. If an object is expanding, are you asked for a linear or volumetric quantity? Be sure to use the correct formula.
- Notes:
  - Stick to Kelvin (or Celcius), but make sure all the units are consistent.
  - An object with a higher heat capacity takes more heat-input raise its temperature



# Thermodynamics




- How to recognize:
  - An ideal gas is undergoing some change or a heat engine/heat pump/refrigerator is being discussed.
- Tips for solving:
  1. For an ideal gas: PV=nRT.
  2. Work through the algebra to find-out how the variable you're asked for changes when all of the other variables change in the way described.
  3. For cycles of transitions: There is no net internal energy change: $\Delta U=0$.
  4. Apply the first law of thermodynamics if need be: $\Delta U = Q-W$.
  5. If a heat engine, or pump, or refrigerator, the amount of work put-in or generated depends on the difference between the heat transfer to/from the hot reservoir and the heat transfer to/from the cold reservoir: $Q_H-Q_C = W$.
  6. Efficiency/performance is how much stuff you get-out over how much stuff you get in: Engine: $e=W/Q_H$, Pump: $COP=Q_H/W$, Refrigerator: $COP =Q_C/W$.
- Notes:
  - The Carnot efficiency is the maximum theoretically possible efficiency.
  - The direction of the transition on the PV-diagram matters.

Thanks for a solid semester.

Best of luck on the exam.

Feel free to contact me in the future with any physics/astrophysics questions that may cross your mind.