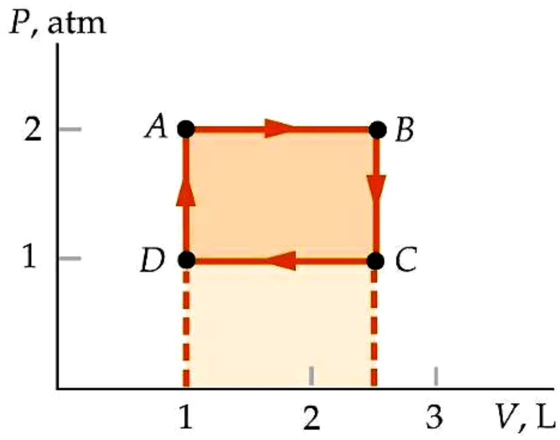
Physics 115

General Physics II

Session 13



Specific heats revisited
Entropy

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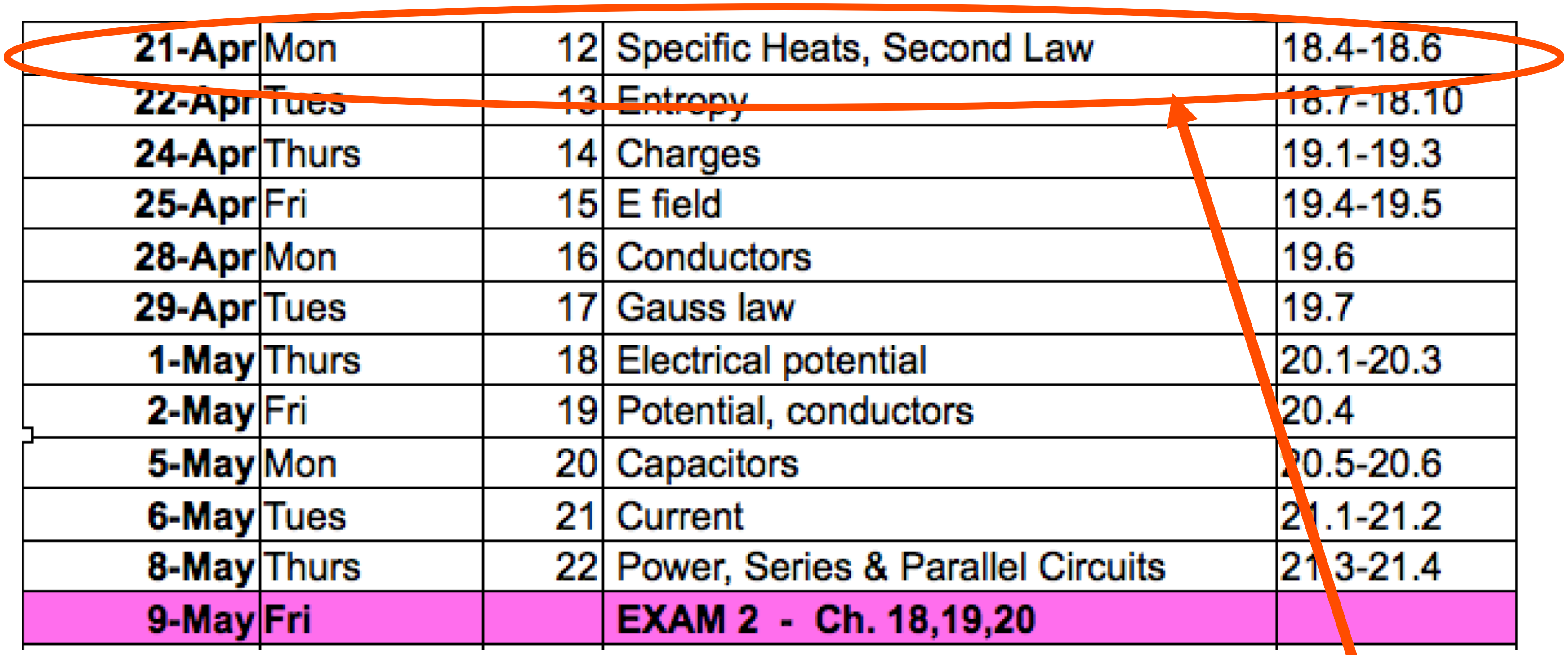
Lecture Schedule

(up to exam 2)

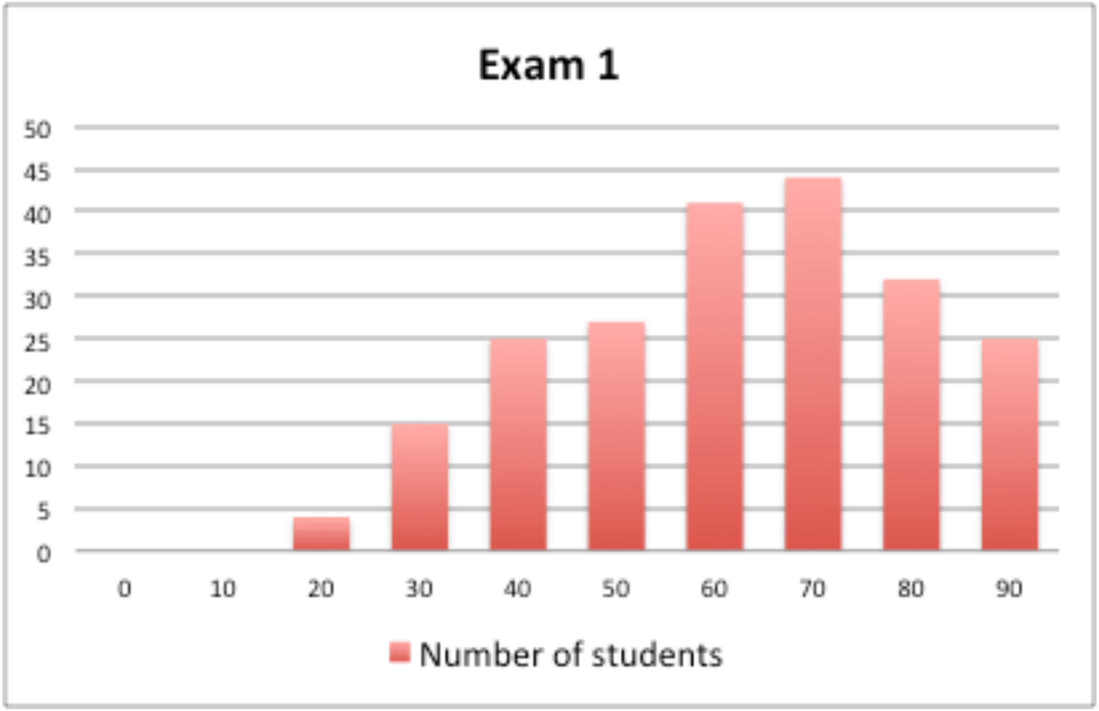


21-Apr	Mon	12	Specific Heats, Second Law	18.4-18.6
22-Apr	Tues	13	Entropy	18.7-18.10
24-Apr	Thurs	14	Charges	19.1-19.3
25-Apr	Fri	15	E field	19.4-19.5
28-Apr	Mon	16	Conductors	19.6
29-Apr	Tues	17	Gauss law	19.7
1-May	Thurs	18	Electrical potential	20.1-20.3
2-May	Fri	19	Potential, conductors	20.4
5-May	Mon	20	Capacitors	20.5-20.6
6-May	Tues	21	Current	21.1-21.2
8-May	Thurs	22	Power, Series & Parallel Circuits	21.3-21.4
9-May	**Fri**		**EXAM 2 - Ch. 18,19,20**	

Today

Exam 1 results

- Average = 68, standard deviation = 19



- "Statistic" = a single number *derived from data* that describes the whole data set in some way
  - "Average" = indication of *center* of data distribution
  - "standard deviation" = measure of *width* of data distribution

Announcements

- FYI: have you been watching ‘Cosmos’?

http://www.cosmosontv.com/

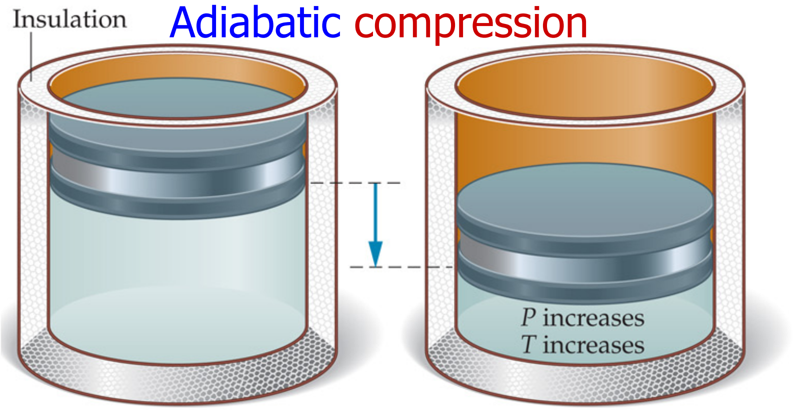
In *last* week’s episode (Sunday April 13) he visited the project I work on in Japan, Super-Kamiokande:

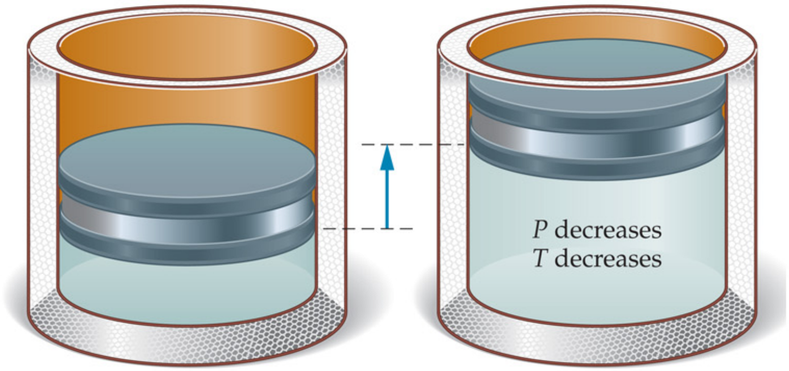
(See display case just outside this room for more info about Super-K)

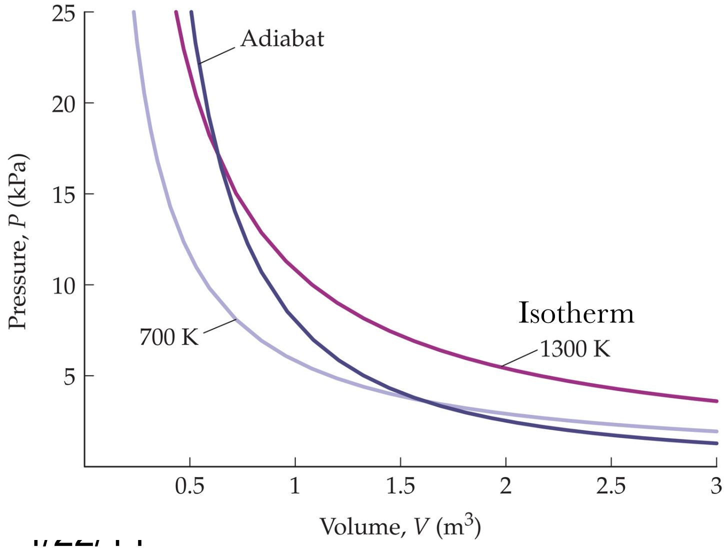
Adiabatic (Q=0) processes

- If ideal gas expands but no heat flows, work is done by gas (W>0) so U must drop: $\Delta U = Q - W \Rightarrow \Delta U = -W$

  U ~ T, so T must drop also


Adiabatic compression


Adiabatic expansion



Adiabatic expansion path on P vs V must be steeper than isotherm path: Temperature must drop →
State must move to a lower isotherm

Summary of processes considered

- W and Q for each type of process in an ideal gas

$$\boxed{\Delta U = Q - W}$$

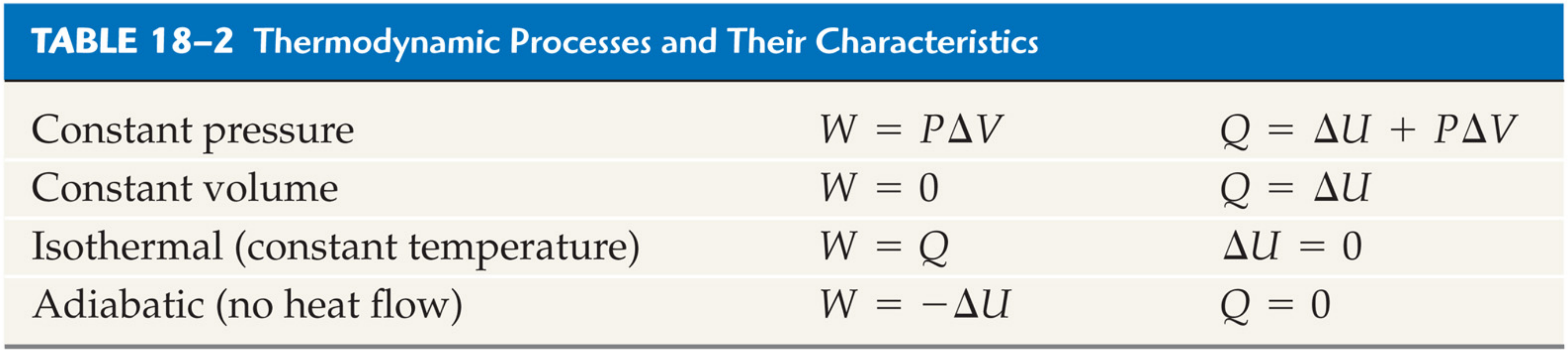


TABLE 18–2 Thermodynamic Processes and Their Characteristics

Constant pressure	$W = P\Delta V$	$Q = \Delta U + P\Delta V$
Constant volume	$W = 0$	$Q = \Delta U$
Isothermal (constant temperature)	$W = Q$	$\Delta U = 0$
Adiabatic (no heat flow)	$W = -\Delta U$	$Q = 0$

For adiabatic:

work **by**/**on** gas → W is **+**/**–** → ΔU is **–**/**+**

Quiz 7

- Which of the following is **not** true for an isothermal compression ($V_{final} < V_{initial}$) process in an ideal gas?

A. Temperature remains constant
B. Internal energy U remains constant
C. No work is done by or on the gas

Quiz 7

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A. Temperature remains constant
B. Internal energy U remains constant
C. No work is done by or on the gas

work must be done on gas to compress it: $W \sim \ln(V_f / V_i)$

Heat capacity at constant volume

- Previously discussed: heat capacities for P=1 atm
  - Assumed constant P environment: so c was actually c_P
- Heat required to change T with V=constant is c_V
- Specific heat per mole at constant V = C_V :

$$Q_V = mc_V \Delta T = nC_V \Delta T, \quad c_V = J/kg/K, \quad C_V = J/mol/K$$

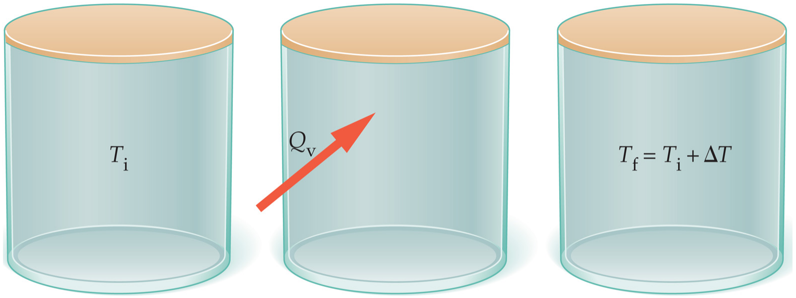
Heat capacity at constant P

- Heat required to change T with P=constant is c_P
- Specific heat per mole at constant P = C_P :

$$Q_P = mc_P \Delta T = nC_P \Delta T, \quad c_P = J/kg/K, \quad C_P = J/mol/K$$

C_P vs C_V

- In constant V process, Q is added, T (and U) increases, but no work is done
  - Since T rises, P must increase: P=nRT/V

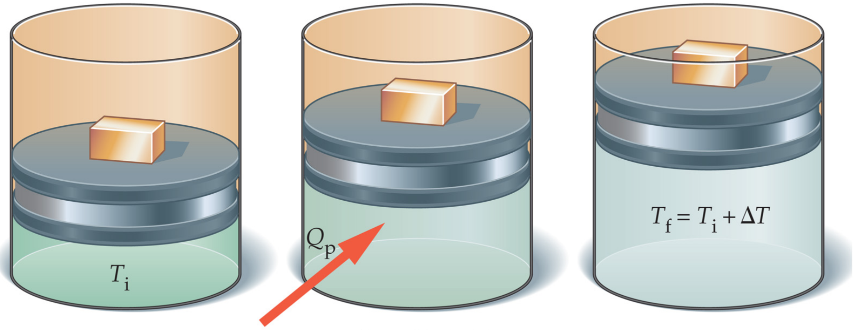


$C_V = Q_V / n\Delta T$

$$\text{1st Law:} \quad Q_V = \Delta U$$

$$\Rightarrow nC_V\Delta T = \frac{3}{2}nR\Delta T \rightarrow \boxed{C_V = \frac{3}{2}R}$$

- In constant P process, Q is added, T increases, but work is done by gas
  - To keep P const, V must increase



$C_P = Q_P / n\Delta T$

$$\text{1st Law:} \quad \Delta U = Q_P - W \rightarrow Q_P = \Delta U + W$$

$$W = P\Delta V = nR\Delta T, \quad \Delta U = \frac{3}{2}nR\Delta T$$

$$\Rightarrow nC_V\Delta T = \left(1 + \frac{3}{2}\right)nR\Delta T \rightarrow \boxed{C_P = \frac{5}{2}R} \Rightarrow \boxed{C_P - C_V = R}$$

Molar Heat Capacities: Ideal gas is good approx

$$\boxed{U = \tfrac{3}{2}nRT}$$

$$\boxed{C_V = \frac{\Delta U}{mol \bullet K} = \tfrac{3}{2}R}$$

$$\boxed{C_P = C_V + R = \tfrac{5}{2}R}$$

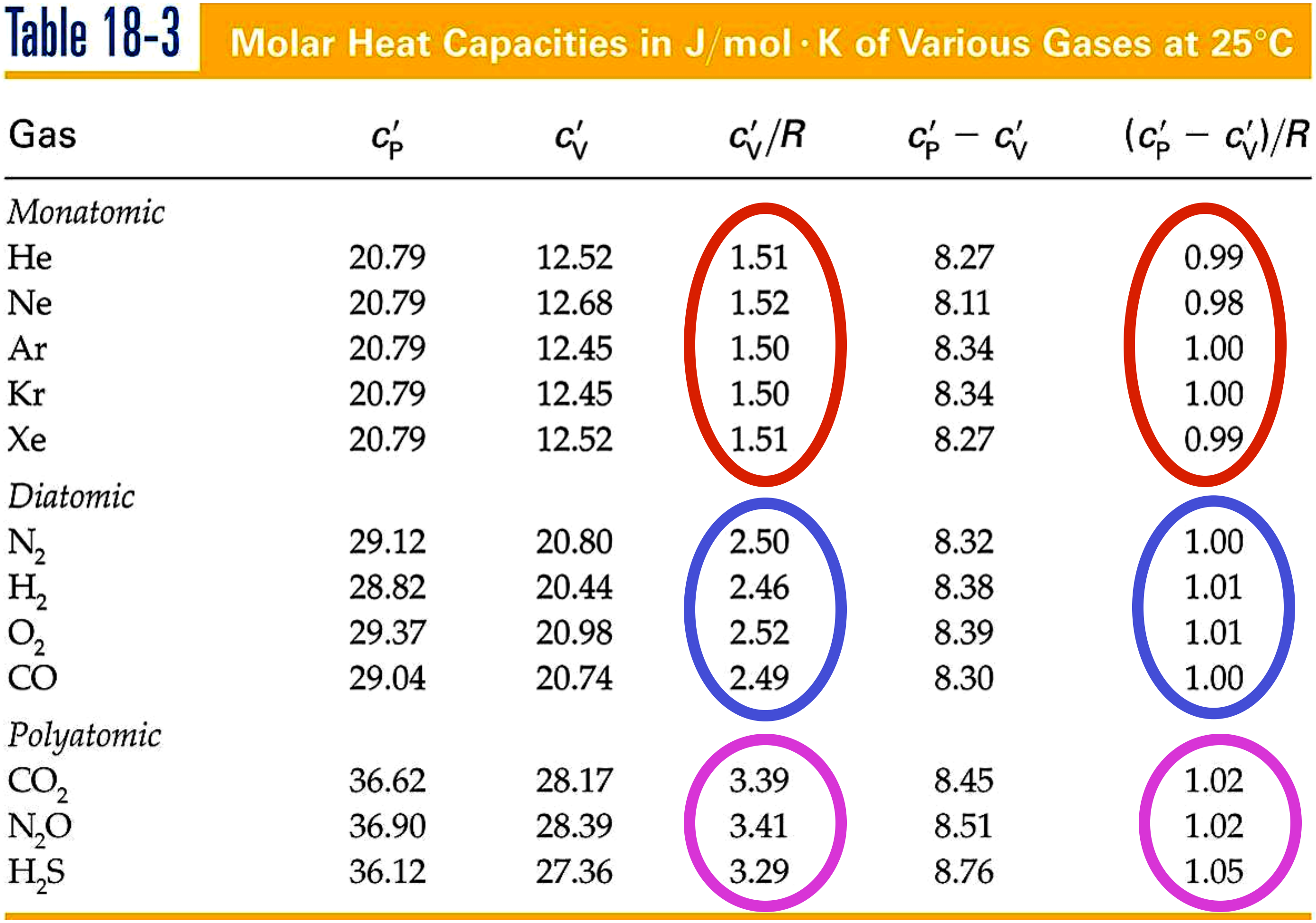


Table 18-3 Molar Heat Capacities in J/mol·K of Various Gases at 25°C

Gas	c'_P	c'_V	c'_V/R	$c'_P - c'_V$	$(c'_P - c'_V)/R$
Monatomic					
He	20.79	12.52	1.51	8.27	0.99
Ne	20.79	12.68	1.52	8.11	0.98
Ar	20.79	12.45	1.50	8.34	1.00
Kr	20.79	12.45	1.50	8.34	1.00
Xe	20.79	12.52	1.51	8.27	0.99
Diatomic					
N_2	29.12	20.80	2.50	8.32	1.00
H_2	28.82	20.44	2.46	8.38	1.01
O_2	29.37	20.98	2.52	8.39	1.01
CO	29.04	20.74	2.49	8.30	1.00
Polyatomic					
CO_2	36.62	28.17	3.39	8.45	1.02
N_2O	36.90	28.39	3.41	8.51	1.02
H_2S	36.12	27.36	3.29	8.76	1.05

Quasi-Static Adiabatic Compression

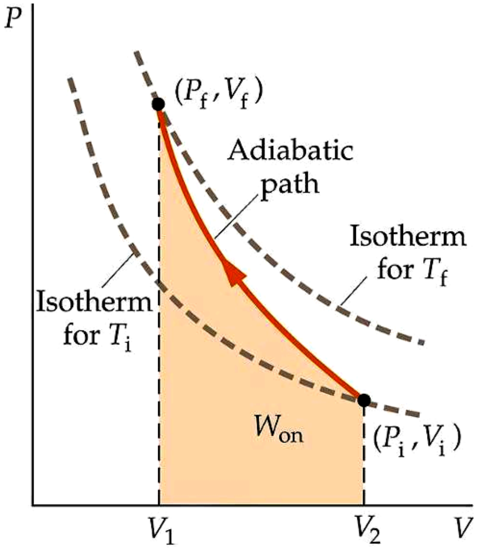
- Process can be adiabatic if
  - It occurs very rapidly (no time to lose heat), or
  - Container is insulated

Example: Slow (quasi-static) compression in an insulated container

- Work is done on gas (W<0), but Q=0, so

$$\Delta U = Q_{\text{in}} + W_{\text{on}} = W_{\text{on}}$$

- U increases so T must rise



Result obtained using calculus:

$$adiabatic: PV^{\gamma} = const, \quad \gamma = \frac{C_P}{C_V} = \frac{(5/2)R}{(3/2)R} = \frac{5}{3}$$

for ideal monatomic gases (different values for others)

Example: $V_i = 0.0625 m^3, V_f = 0.0350 m^3, T_i = 315 K, 2.5 mol$

Find initial P: $P_i = nRT_i / V_i = 2.5 mol(8.31 \text{ J/mol K})315K / 0.0625 m^3 = 104.7 kPa$

Find final P: $adiabatic: PV^{\gamma} = const, \quad \gamma = 5/3 \Rightarrow P_i V_i^{5/3} = P_f V_f^{5/3}$

$$\rightarrow P_f = P_i (V_i / V_f)^{5/3} = (104.7 kPa) 2.62 = 274 kPa$$

Cyclic Processes

An ideal gas undergoes a cyclic process when it goes through a closed path in P-V space and returns to its original {P,V} state.

Example: Process A-B-C-D, back to point A,

Here, steps are all either constant P or constant V

Example: Initial state A = {2 atm, 1 L}

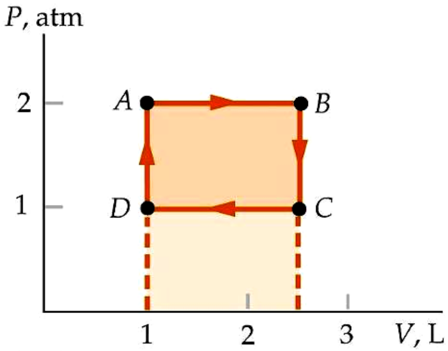
A-B: Expand at constant P to V_B= 2.5 L,

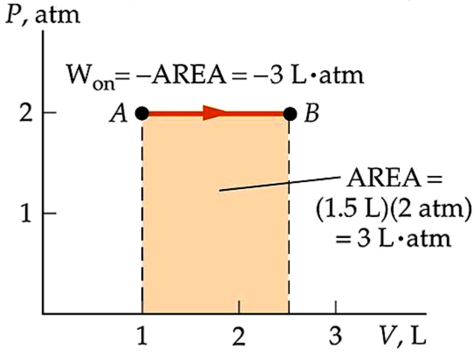
B-C: cool at constant V to P_C=1.00 atm.

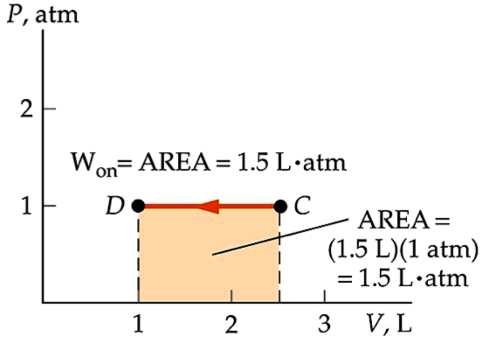
C-D: compress at constant P to V_D= 1 L,

D-A: heat at constant V, back to {2 atm,1 L}

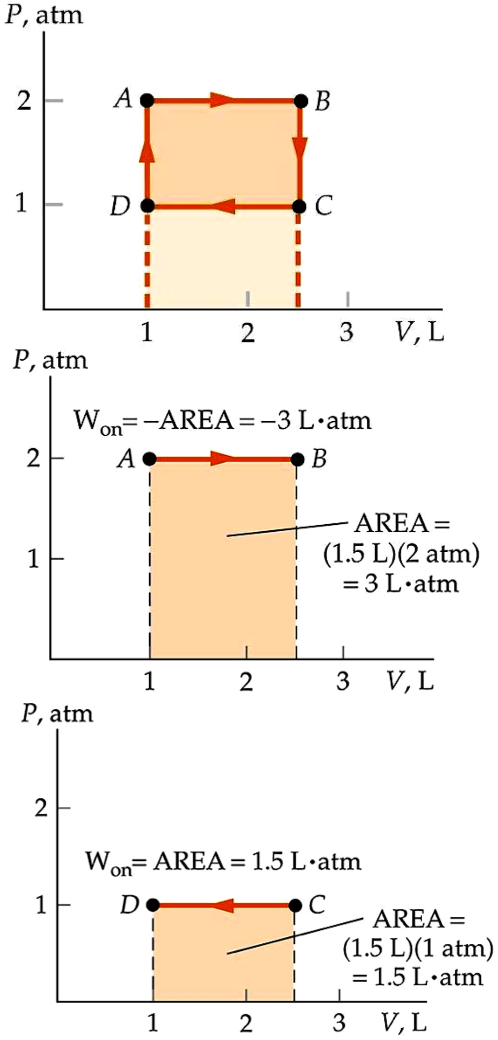
What is the total work done on the gas, and the total amount of heat transfer into it, in one complete cycle?







Cyclic Process example:



A-B: Expand at constant P : W by gas

B-C: cool at constant V : Q out of gas

C-D: compress at constant P : W on gas

D-A: heat at constant V : Q into gas

What is the net work done on the gas, and the total amount of heat transfer into it, in one complete cycle?

$$W_{AB} = P\Delta V = (2.00\ \text{atm})(2.5\ \text{L} - 1.0\ \text{L}) = 3.00\ \text{L}\cdot\text{atm} = 304\ \text{J}$$

$$W_{CD} = P\Delta V = (1.00\ \text{atm})(1.0\ \text{L} - 2.5\ \text{L}) = -1.50\ \text{L}\cdot\text{atm} = -152\ \text{J}$$

$$W_{BC} = W_{DA} = 0 \qquad W_{\text{NET, ON}} = -W_{CD} - W_{AB} = -152\ \text{J}$$

(more work done by gas than on gas)

$$\Delta U = Q_{IN} - W_{BY} = Q_{\text{IN}} + W_{ON} \quad \text{but final state = initial, so}$$

$$\Delta U = 0 \rightarrow Q_{\text{NET, IN}} = -W_{ON} \Rightarrow 152J \quad \text{(more Q in than out, per cycle)}$$

Why cyclic processes in ideal gas are important

- Ideal gas model approximates behavior of real gases
- Cyclic processes model behavior of heat engines

  Modern world uses heat engines in many ways, every day:

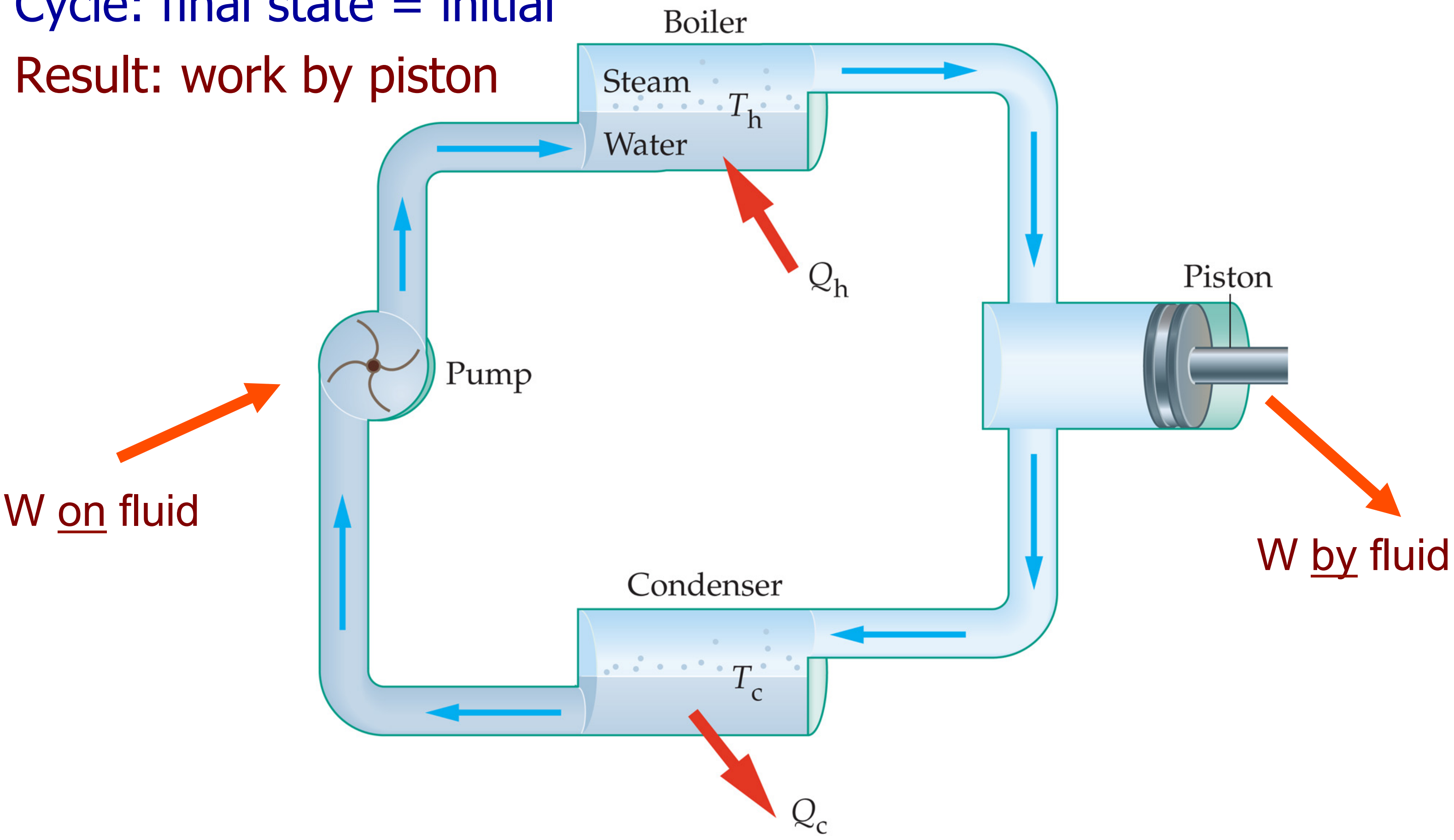
  - Almost all large motors (energy → mechanical motion) are heat engines (gasoline and diesel engines, turbines)
  - Refrigerators, air conditioners are heat engines
- Study of heat engines drove many important advances in physics and technology
  - Steam engine efficiency was topic of great economic interest!

Sadi Carnot (France, 1824): theory of heat engine efficiency, using Carnot engine model for ideal reversible cyclic process

- Led to development of 2nd Law of Thermodynamics

Steam engine as example of heat engine

- "Working fluid" is water
  - Changes phase from liquid to vapor, and back again
  - Heat is added and removed, work is done on and by fluid
  - Cycle: final state = initial
  - Result: work by piston



W on fluid

W by fluid

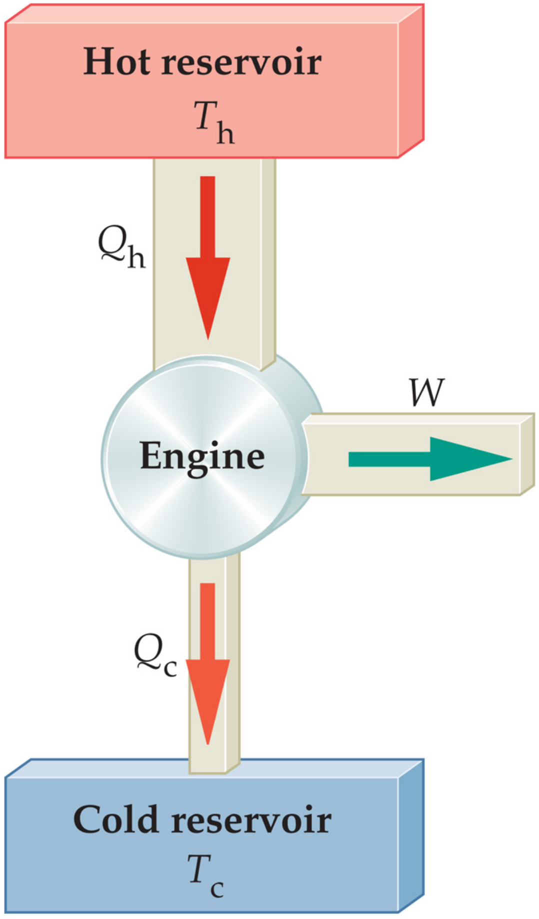
Carnot cycle

- Idealized model for heat engines
  - Heat is taken from a high-T reservoir
  - Engine uses some heat energy to do work
  - Remaining heat is sent to low T reservoir
    - "Exhaust heat" Q_C
  - Repeat …
- Efficiency of any heat engine cycle
  - Energy in = Q_H
  - Energy out = $W + Q_C$

  1^{st} Law: in = out! → $W = Q_H - Q_C$

  Efficiency = useful work out/energy in

$$\varepsilon = \frac{W}{Q_H} = \frac{Q_H - Q_C}{Q_H} = 1 - \frac{Q_C}{Q_H}$$



Carnot's theorem

- For any T_H and T_C , maximum efficiency possible is for an engine with all processes reversible
- All reversible engines operating between the same T_H and T_C have the same efficiency

Notice: says nothing about working fluid, cycle path, etc

- Since ε depends only on T's, Q's must be proportional

$$\varepsilon = 1 - \frac{Q_C}{Q_H} \Rightarrow \boxed{\frac{Q_C}{Q_H} = \frac{T_C}{T_H}} \to \varepsilon = 1 - \frac{T_C}{T_H}$$

Yet another way to define T :
Ratio of exhaust/input Qs

  - Carnot efficiency tell us the maximum work we can get per Joule of energy in:

$$\varepsilon = \frac{W}{Q_H} \to W = \varepsilon Q_H \to W_{MAX} = \varepsilon_{MAX} Q_H = \left(1 - \frac{T_C}{T_H}\right) Q_H$$