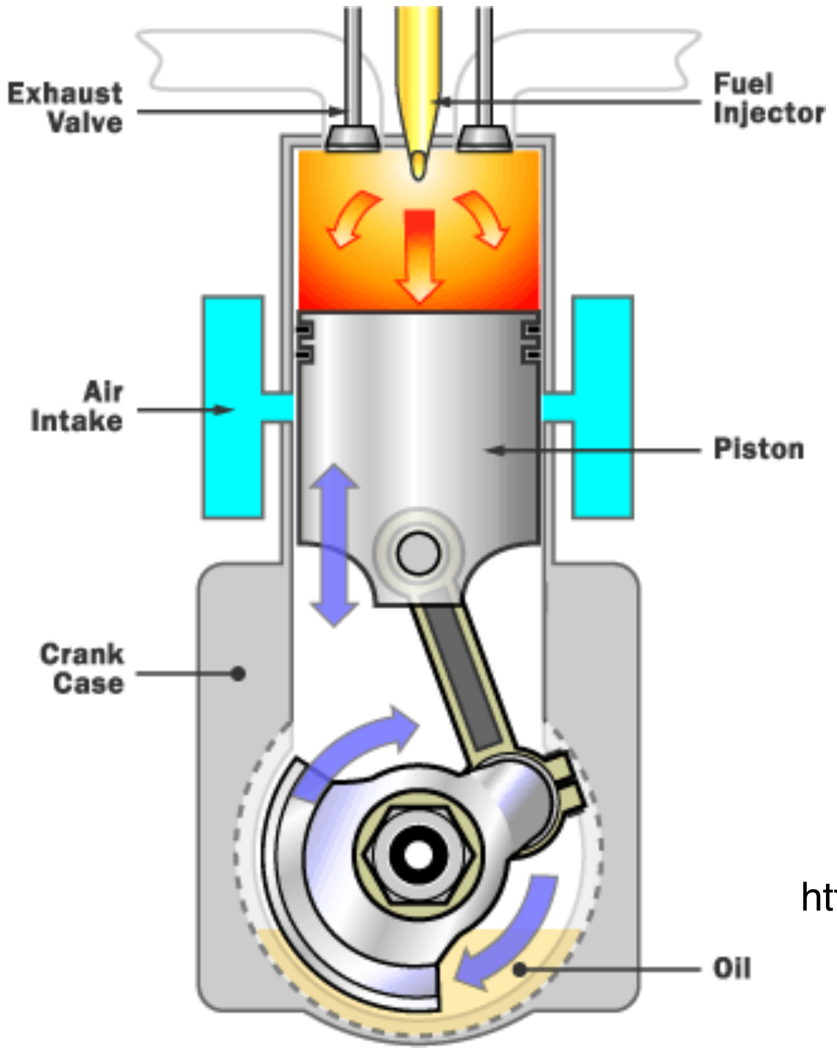
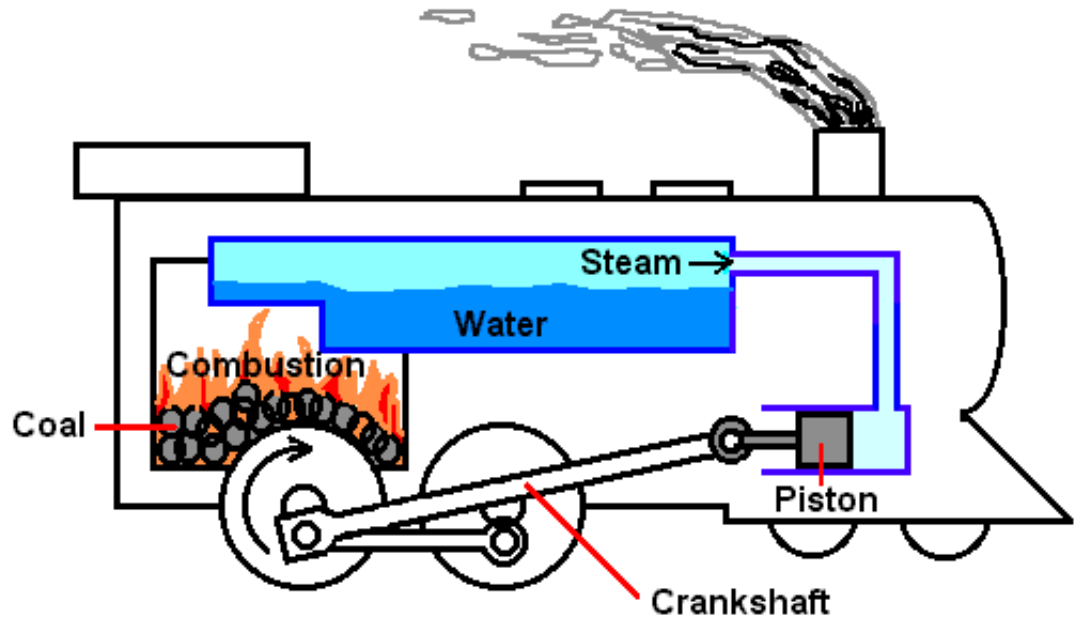
Physics 141.
Lecture 24.





http://mightymech.rf.gd/2018/11/13/heat-engine-classification/?i=1

Physics 141.
Lecture 24.

- Course Information.
- Continue our discussion of Chapter 13:
  - Equation of state.
  - The energy distribution of an ideal gas and energy exchange with its environment.
  - Engines and heat pumps.
  - Efficiency

Physics 141.
Course information.

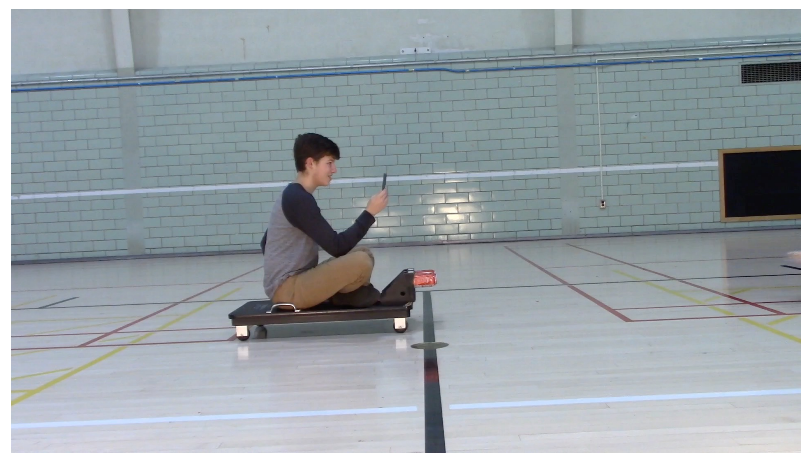
- Homework 10 is due on Friday December 6 at noon.
- Homework set 11 is due on Friday December 13 at noon.
- To calculate the final homework grade, I remove the lowest homework grade and then take the average of the remaining 10 homework grades. If you are happy with homework grades 1 – 10, you can consider homework 11 as optional.

Physics 141.
Course information.

- You will receive Exam 3 back during recitations this week.
- If you are unhappy with the grading of Exam 3, please return your blue booklet(s) to me with a note describing why you feel you deserve more points by the end of class on 12/5.
- The final exam will take place on Monday 12/16 at 4 pm in Hoyt. The exam will take 3 hours and cover all the material discussed in Phy 141, except the error analysis.
- There will be normal office hours on Wednesday and Thursday next week to answer any questions related to the final exam.

Analysis of experiment # 5. Updated Timeline.

- ✓11/14: collisions in the May room
- ✓ 11/18: analysis files available.
  - https://www.pas.rochester.edu/~tdimino/phy141/lab05/
- ✓ 11/25: each student has determined his/her best estimate of the velocities before and after the collisions.
- ✓ 11/25: complete discussion and comparison of results with colliding partners and submit final results (velocities and errors).
- ✓ 11/27: results will be compiled, linear momenta and kinetic energies will be determined, and results will be distributed.
- ✓ 12/2: office hours by lab TA/TIs to help with analysis and conclusions.
- 12/6: students submit lab report # 5.



https://www.pas.rochester.edu/~tdimino/phy141/lab05/

Col	Ver L	Ver R	CL 1	CL 2	CL 3	CL 4	CR 1	CR 2	CR 3	CR 4	PLi	dPLi	PRi	dPRi	PLf	dPLf	PRf	dPRf	KLi	dKLi	KRi	dKRi	KLf	dKLf	KRf	dKRf
Ref. Length																										
1	Safiya Pious	Caeli Martino	11.9	11.7	11.9	11.9	12	11.9	12	12	-0.1	0.5	-112.0	5.2	-57.5	11.7	-42.6	7.3	0.0	0.0	94.1	10.8	21.1	10.3	13.6	5.8
2	Safiya Pious	Caeli Martino	5.2	11.8	12	12	3.9	11.8	12	12	0.0	0.1	-126.0	4.1	-83.1	11.0	-63.6	10.0	0.0	0.0	119.2	9.6	44.1	14.0	30.3	11.8
3	Safiya Pious	Caeli Martino	11.9	11.8	11.1	7.1	12	12	10.9	4.5	-0.2	0.6	-152.3	9.8	-82.0	12.0	-70.8	9.0	0.0	0.0	174.2	27.7	42.9	15.1	37.6	11.8
4	Turi Useda	Peter LaMonaca	12.2	12	11.1	7.2	11.8	10.2	7.8	7.4	0.1	0.6	-194.6	2.2	-102.4	6.0	-89.4	5.0	0.0	0.0	236.5	6.5	61.5	8.5	49.9	6.6
5	Peter LaMonaca	Turi Useda	9	6.9	9.3	7	12.2	11.9	12.2	12.2	-0.2	0.5	-187.2	1.7	-88.4	2.0	-80.8	5.3	0.0	0.0	205.4	4.4	48.7	2.6	38.2	5.9
6	Peter LaMonaca	Turi Useda	11.8	11.9	11.4	11.8	11.3	12	11.7	12.1	0.0	0.2	-187.9	2.9	-85.7	2.1	-78.2	5.3	0.0	0.0	206.9	7.5	45.9	2.7	35.9	5.7
7	Gulinky Lu	Manav Koradia	12.6	12.6	5.5	3.8	12.1	12	9.5	7.1	-0.1	0.1	-214.0	10.1	-92.1	4.9	-118.8	7.0	0.0	0.0	262.2	29.1	65.2	8.7	80.9	11.2
8	Gulinky Lu	Manav Koradia	12.6	12.6	9.6	12.6	9.8	12	9.8	9.3	-0.1	0.1	-215.4	5.2	-88.2	4.2	-109.4	9.0	0.0	0.0	265.7	14.9	59.9	7.2	68.5	13.2
9	Gulinky Lu	Manav Koradia	12.6	11.6	10.7	7.4	12	12	10.4	6.8	-0.1	0.1	-205.3	2.4	-87.7	4.1	-117.9	8.6	0.0	0.0	241.5	6.7	59.1	6.9	79.7	13.6
10	Jake Portale	Jacob Lieberman	12.2	12.2	9.5	8.2	12.2	12.2	10.3	9.2	0.0	0.3	-208.2	2.3	-101.0	3.4	-71.9	3.5	0.0	0.0	277.7	7.5	54.7	4.2	33.1	3.9
11	Jake Portale	Jacob Lieberman	10.6	11.2	11.8	11.8	11.2	11.7	12.2	12.2	0.0	0.1	-182.3	1.2	-89.7	0.9	-57.7	0.8	0.0	0.0	212.8	3.3	43.2	1.0	21.3	0.7
12	Jake Portale	Jacob Lieberman	12.1	11.8	11.5	10.3	12.2	11.1	11.7	9.9	0.2	0.1	-193.6	2.0	-91.3	0.4	-68.9	0.2	0.0	0.0	240.1	5.8	44.7	0.4	30.4	0.2
13	Lucas Sabatini	Johanna Anderson	12.2	12.2	10.9	5.2	12.2	12.2	12.1	9.4	2.8	2.9	-154.7	7.8	-56.7	8.4	-74.6	12.7	0.1	0.1	140.7	16.8	21.2	7.6	32.7	13.1
14	Lucas Sabatini	Johanna Anderson	12.2	11.7	12.1	12.1	12.2	12	11.1	12	-0.4	0.4	-162.5	1.0	-92.9	7.5	-59.1	9.0	0.0	0.0	155.3	2.3	56.8	11.1	20.5	7.4
15	Johanna Anderson	Lucas Sabatini	12.2	12.2	7.5	9.8	12.2	12.2	12.2	8.7	-0.8	0.1	-152.9	16.2	-79.5	9.8	-62.8	7.8	0.0	0.0	153.8	39.2	37.2	10.8	25.9	7.7
16	Quinn Kasdan-Gro	Henry Carbone	12.2	12.2	12.2	11.8	12.2	12.2	6.7	6.7	0.0	0.1	-170.5	0.2	-87.4	0.0	-69.0	1.1	0.0	0.0	185.5	0.5	39.5	0.0	30.4	1.1
17	Henry Carbone	Quinn Kasdan-Grol	12.2	12.2	9.6	5.6	12.2	12.2	12.2	8.4	0.0	0.1	-974.5	1.1	-435.2	4.4	-469.8	0.7	0.0	0.0	4907.4	12.4	1209.4	29.2	1140.7	3.8
18	Henry Carbone	Quinn Kasdan-Grol	12.2	6.9	8.2	6.5	12.2	12.2	12.2	12.2	0.0	0.1	-974.5	1.1	-435.2	4.4	-469.8	0.7	0.0	0.0	4907.4	12.6	1209.4	29.0	1140.7	3.7
19	Matthew Alaniz	Mike Biglan	12.2	11.1	10	9.5	12.2	12.2	12.2	10.7	1.0	1.7	-226.3	9.4	-102.1	8.9	-94.6	10.0	0.0	0.0	278.9	26.9	68.9	14.5	48.7	12.0
20	Matthew Alaniz	Mike Biglan	12.2	11.7	10.1	6.9	12.2	12.1	10.4	7.8	-0.7	0.9	-208.9	13.2	-119.8	8.2	-118.7	11.4	0.0	0.0	237.7	35.0	94.8	15.7	76.7	17.1
21	Matthew Alaniz	Mike Biglan	12.2	12.2	6.5	4.8	12.2	12.2	5.9	6.2	-1.0	1.8	-316.3	13.3	-141.0	3.6	-154.5	12.6	0.0	0.0	545.1	53.4	131.5	8.0	130.0	24.6
22	Dejie Chen	Donovan Bradley	12.2	12.2	9.8	10	11.8	11.6	10.7	10	-0.7	1.5	-175.4	7.4	-78.2	5.9	-82.4	9.1	0.0	0.0	186.8	18.7	41.9	7.6	41.2	10.7
23	Dejie Chen	Donovan Bradley	11.5	11.1	12.2	11	11.8	11	11.7	11.6	-0.7	0.7	-177.1	6.6	-79.7	5.1	-86.5	7.4	0.0	0.0	190.3	16.8	43.4	6.8	45.4	9.2
24	Dejie Chen	Donovan Bradley	10.1	12.2	11.7	8.2	11.6	9.7	7.7	10.5	-0.7	0.7	-191.9	8.2	-91.4	4.4	-98.8	9.1	0.0	0.0	223.5	22.8	57.1	6.7	59.3	12.9
Ref. Length																										
25	Jeremy Shiu	Phillip Brooke	11.8	12	11.9	12	12	11.8	11.9	12	0.0	0.1	-142.0	1.4	-73.2	1.4	-73.1	1.4	0.0	0.0	118.6	2.7	37.7	1.7	31.5	1.4
26	Phillip Brooke	Jeremy Shiu	4.6	5.4	10.8	11.7	4.7	9.5	11.9	11.5	-0.1	0.1	-210.5	3.5	-90.2	3.0	-93.1	5.0	0.0	0.0	311.5	12.6	47.8	3.7	61.0	8.0
27	Jeremy Shiu	Phillip Brooke	3.5	3.5	12	12	3.6	5.2	11.4	11.7	0.0	0.0	-217.7	1.3	-96.7	0.7	-101.2	1.5	0.0	0.0	278.7	3.9	65.8	1.2	60.2	2.1
28	Ryan Dugan	Jacob Bitsky	6.5	5.9	12.4	12.4	11.4	12.1	10	12.5	0.5	0.3	-147.7	1.5	-88.2	1.1	-59.8	3.4	0.0	0.0	131.7	3.2	46.2	1.4	21.6	2.9
29	Jacob Bitsky	Ryan Dugan	12.1	9	11.4	11.2	11.4	8.9	6.2	5.3	-0.1	0.1	-93.9	19.4	-85.4	61.6	-77.6	11.5	0.0	0.0	52.4	25.6	44.0	75.3	35.7	12.5
30	Ryan Dugan	Jacob Bitsky	8.1	9.9	6.9	9.1	12.4	12.5	12	12.5	-0.7	1.3	-13.8	6.7	-101.7	4.1	-74.4	6.1	0.0	0.0	1.2	1.3	61.4	5.9	33.4	6.5
31	Michael Li	Thomas Qian	3	12.4	12.4	12.4	5.6	11.9	12.4	12.4	-0.1	0.4	-176.7	4.3	-78.9	2.2	-88.9	9.7	0.0	0.0	160.0	9.0	43.8	3.0	40.4	10.1
32	Thomas Qian	Michael Li	12.4	12.2	12.4	12.4	7.1	5.8	9.8	12.4	-0.1	0.2	-135.8	3.9	-79.1	2.1	-56.2	1.6	0.0	0.0	129.7	9.1	32.0	2.0	22.2	1.5
33	Michael Li	Thomas Qian	12.4	12.1	8.4	4.8	12.4	12.4	10.5	7.5	-0.1	0.2	-158.2	2.0	-66.3	1.4	-79.1	4.9	0.0	0.0	128.1	3.6	30.9	1.6	32.0	4.6
34	Yiding Wang	Edward Caine	12.2	12.2	12.1	12.3	10	10	11.75	11.25	0.0	0.1	-167.1	3.3	-73.6	3.3	-88.5	3.9	0.0	0.0	166.4	7.7	39.1	4.3	46.7	4.8
35	Yiding Wang	Edward Caine	6.1	7.1	12.3	12.3	11.75	10.25	4.25	4.5	-182.5	6.9	-0.1	1.8	-98.2	9.1	-121.5	10.9	240.5	18.1	0.0	0.0	69.6	15.9	87.9	18.7
36	Yiding Wang	Edward Caine	12.1	12.2	12.2	12.2	9.25	8.75	9.25	10.5	-152.2	3.8	-0.4	0.8	-81.7	2.2	-96.6	3.0	167.2	8.3	0.0	0.0	48.1	3.1	55.6	4.1
37	Yashica Rawat	Bond Qiu	12.1	10.1	12.3	12.4	9.1		12	12	-1.4	1.7	-159.1	6.6	-88.7	6.0	-116.4	12.1	0.0	0.0	157.1	15.5	61.1	10.3	84.1	20.8
38	Yashica Rawat	Bond Qiu	12.6	9.8	12.3	11.6	12	11.5	8.8	12	-24.2	4.8	-183.4	12.1	-87.6	4.1	-106.8	6.3	4.6	1.8	208.8	32.8	59.6	7.0	70.8	10.0
39	Yashica Rawat	Bond Qiu	12.5	12.4	12.5	12.4	12	12	11.8	12	-6.3	1.1	-144.9	11.2	-65.5	6.1	-127.3	7.5	0.3	0.1	130.3	23.9	33.3	7.8	100.5	14.2
40	Stella Qu	Tamako Oi	12.5	12.5	12.5	12.5	12.1	12.2	12.3	12.3	0.0	0.1	-188.0	15.6	-62.8	3.0	-117.5	14.8	0.0	0.0	151.0	28.2	34.0	4.2	59.0	16.7
41	Stella Qu	Tamako Oi	12.5	11	10.1	12.5	10.3	10.4	12.3	12.3	0.0	0.1	-219.9	17.6	-70.1	4.8	-134.4	17.1	0.0	0.0	206.7	37.1	42.4	7.4	77.2	22.1
42	Tamako Oi	Stella Qu	12.3	12.5	11.5	11	11.4	11.8	11.3	11.6	0.0	0.2	-115.2	8.7	-107.3	9.6	-47.8	8.5	0.0	0.0	114.3	22.2	49.2	9.9	19.7	9.0
43	Stella Qu	Edward Caine	9.5	11.5	11.75	11.75	6.5	7	11.25	9.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
44											0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
45	JT Glenchur	Odin Choy	12.2	12.2	12.2	12.2	8.1	7.8	8.8	11.8	0.0	0.1	-250.0	8.7	-109.7	5.3	-94.0	6.4	0.0	0.0	364.5	29.9	69.4	7.8	51.5	8.3
46	Odin Choy	JT Glenchur	11.8	8.2	8.6	5.1	6.8	12.2	9.4	6.3	-0.2	0.5	-241.1	13.0	-113.2	3.3	-92.6	5.1	0.0	0.0	335.4	42.5	74.8	5.2	49.5	6.4
47	JT Glenchur	Odin Choy	12.2	10.6	12.2	12.2	11.7	8.1	4.8	4.4	0.0	0.1	-225.1	11.8	-117.8	4.8	-96.0	9.4	0.0	0.0	295.5	36.4	80.2	7.7	53.7	12.4
48	Zemon Xiao	Justin Kenneally	12.2	12.4	12.1	10.6	11.15	9.79	10.47	9.97	-0.1	1.2	-226.2	2.5	-110.7	5.3	-80.3	6.4	0.0	0.0	311.8	8.2	65.2	7.2	39.3	7.4
49	Justin Kenneally	Zemon Xiao	11.86	11.88	8.82	7.35	12.2	11.6	8.7	8.5	0.1	0.1	-250.9	3.4	-116.4	6.4	-115.1	6.9	0.0	0.0	334.8	10.5	82.5	10.7	70.5	9.8
50	Justin Kenneally	Zemon Xiao	11.93	11.84	8.03	3.63	4.1	11.3	12.3	12.5	-0.4	0.1	-277.4	2.7	-142.5	5.4	-124.0	5.3	0.0	0.0	409.1	9.2	123.7	11.1	81.8	8.2
51	Sidratul Montaha	Fan Zhang	10.5	10.9	8.7	7.1	12.5	6	10	10.5	0.0	0.1	-226.5	6.5	-101.4	7.5	-97.6	6.5	0.0	0.0	266.4	17.8	52.6	9.0	49.5	7.6
52	Fan Zhang	Sidratul Montaha	8	12.5	8.3	9.1	12.2	8.6	7.1	12.2	0.0	4.2	-201.7	11.1	-92.9	5.4	-92.7	4.7	0.0	0.0	208.4	26.5	44.8	6.0	44.0	5.1
53	Sidratul Montaha	Fan Zhang	11	10.8	11.5	12.2	7.5	4.8	4.9	12.5	0.2	0.7	-210.2	5.4	-106.2	4.4	-98.9	3.7	0.0	0.0	229.5	13.6	57.8	5.5	50.8	4.3
54	Min Zhao	Zekuan Guo	11.3	12.2	12.3	11.8	12.5	11.5	12.5	12.5	-0.7	1.2	-211.9	11.2	-87.5	5.3	-81.8	8.1	0.0	0.0	263.9	33.0	52.5	7.7	39.3	9.1
55	Min Zhao	Zekuan Guo	5.9	4.2	12.5	12.2	6.7	7.3	12.5	12.5	0.4	1.2	-182.5	9.8	-95.4	5.8	-61.9	9.3	0.0	0.0	195.7	24.7	62.4	9.2	22.5	8.0
56	Min Zhao	Zekuan Guo	12.1	12.5	12.5	12.5	12.5	12.5	12.5	12.5	2.9	6.7	-202.1	9.6	-140.1	8.1	-56.3	7.1	0.1	0.3	240.2	27.0	134.7	18.9	18.7	5.5
57	Nicholas Kissel	Brad Li	7.5	5.8	11.5	12	12	11.5	5.3	9.6	-0.7	1.0	-174.7	4.0	-105.7	9.5	-55.3	6.3	0.0	0.0	212.6	12.0	63.1	13.2	21.3	5.9
58	Brad Li	Nicholas Kissel	12	10.4	11.2	9.5	12	11.9	11.4	12	-12.8	0.7	-206.8	5.6	-96.3	6.1	-97.3	7.1	1.1	0.1	241.8	15.3	64.6	10.0	53.5	9.2
59	Nicholas Kissel	Brad Li	7.4	5.9	12	12	4.3	11.8	5.5	12	-0.8	0.0	-180.7	9.4	-104.6	8.8	-64.8	8.5	0.0	0.0	227.5	29.0	61.9	12.2	29.2	9.3

A Note To Students:
Rows Highlighted in the orange/dark yellow are collisions that we are uncertain of the accuracy of their analysis. The values turned in were not within the accepted ranges. Please be cautious if you choose to use those data runs.

The first law of thermodynamics. Adding/removing heat from a system.

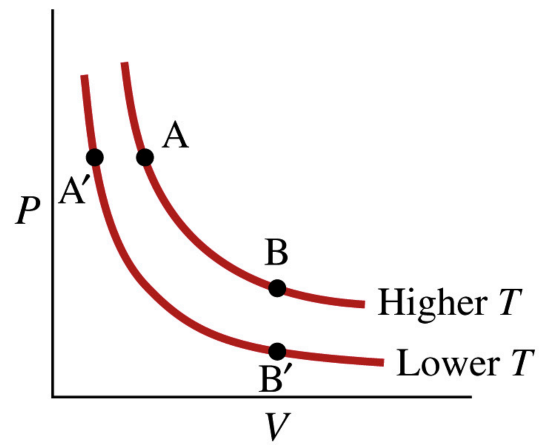
- Consider a closed system:
  - Closed system
    - No change in mass
    - Change in energy allowed (exchange with environment)
  - Isolated system:
    - Closed system that does not allow an exchange of energy

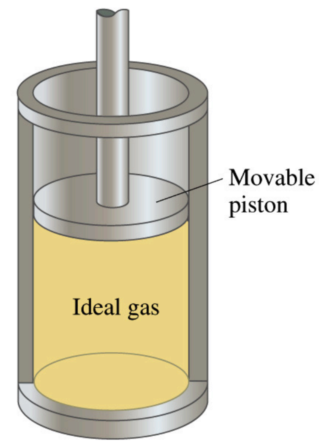
- The internal energy of the system can change and will be equal to the heat added to the system minus the work done by the system: $\Delta U = Q - W$ (note: this is the work-energy theorem).

- Note: keep track of the signs:
  - Heat: $Q > 0$ J means heat added, $Q < 0$ J means heat lost
  - Work: $W > 0$ J means work done by the system, $W < 0$ J means work done on the system

The first law of thermodynamics. Isothermal processes.

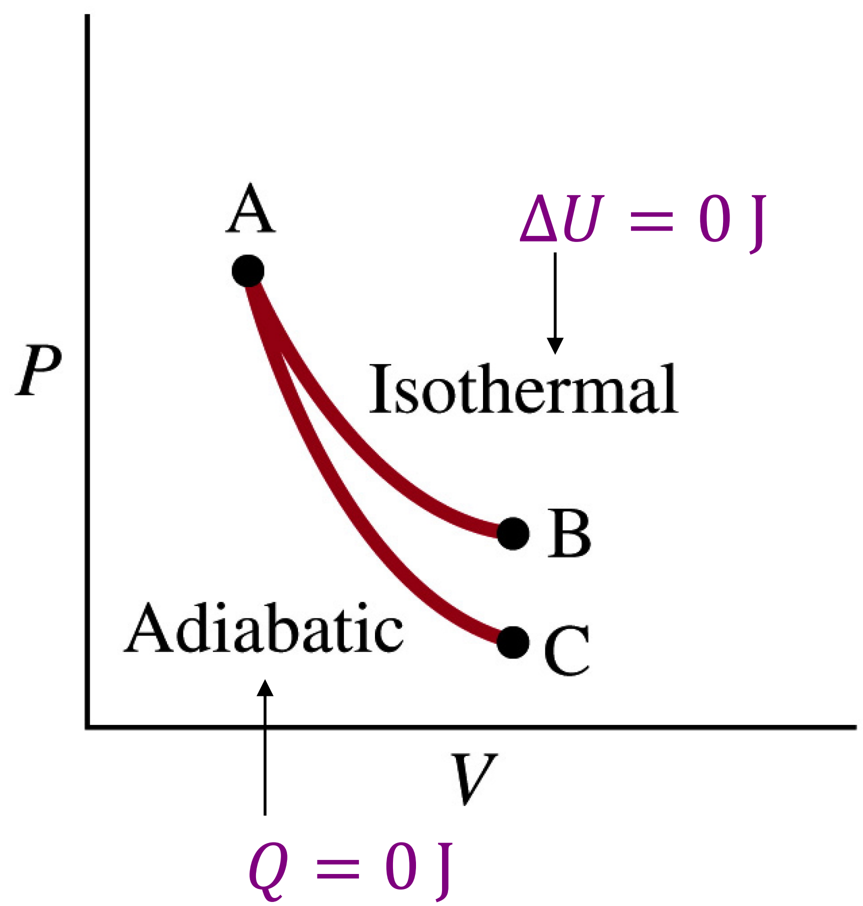
- An isothermal process is a process in which the temperature of the system is kept constant.
- This can be done by keeping the system in contact with a large heat reservoir and making all changes slowly.
- Since the temperature of the system is constant, the internal energy of the system is constant: $\Delta U = 0$ J.
- The first law of thermodynamics thus tells us that $Q = W$.





The first law of thermodynamics. Adiabatic processes.

- An adiabatic process is a process in which there is no flow of heat (the system is an isolated system).
- Adiabatic processes can also occur in non-isolated systems if the change in state is carried out rapidly. A rapid change in the state of the system does not allow sufficient time for heat flow.
- The expansion of gases differs greatly depending on the process that is followed (see Figure).



Work done during expansion/compression.

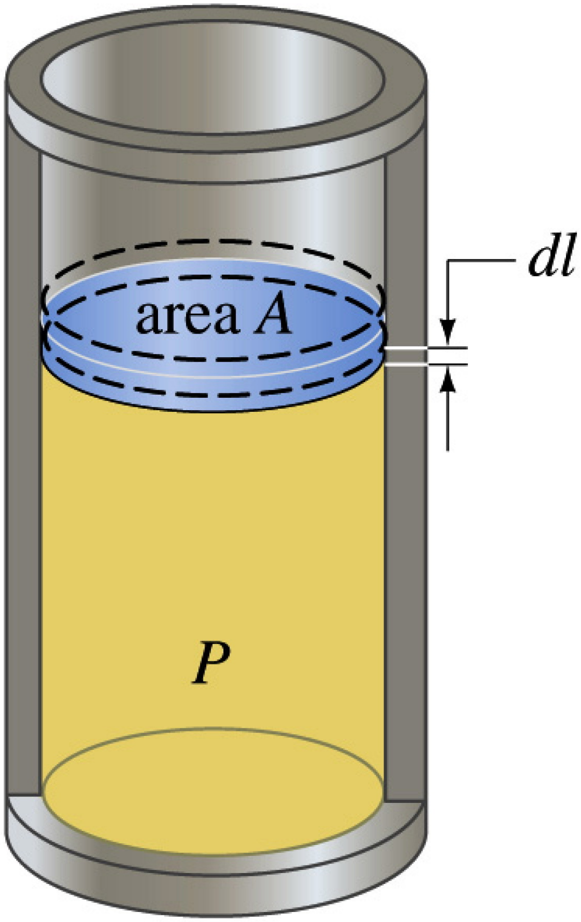
- Consider an ideal gas at pressure p.
- The gas exerts a force F on a moveable piston, and $F = pA$.
- If the piston moves a distance dl, the gas will do work:

$$dW = Fdl$$

Note: F and dl are parallel.

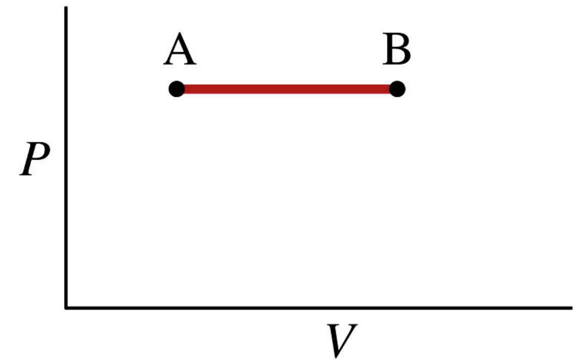
- The work done can be expressed in terms of the pressure and volume of the gas:

$$dW = pAdl = pdV$$



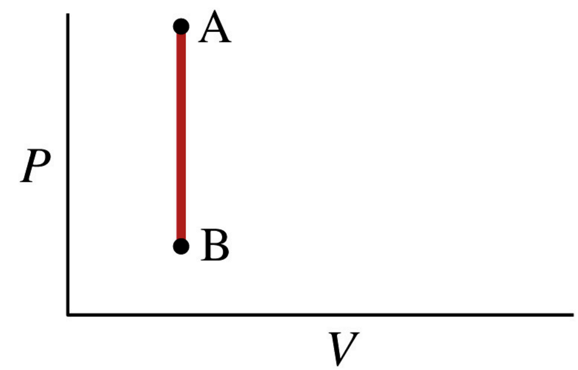
Work done during expansion/compression. Isobaric and isochoric processes.

- **Isobaric process**:
  - Processes in which the pressure is kept constant.
  - $W_{A\rightarrow B} = pdV = p_A(V_B - V_A)$



(a) Isobaric

- **Isochoric process**:
  - Processes in which the volume is kept constant.
  - $W_{A\rightarrow B} = p(V_B - V_A) = 0$



(b) Isochoric

Work done during expansion/compression. Isothermal process.

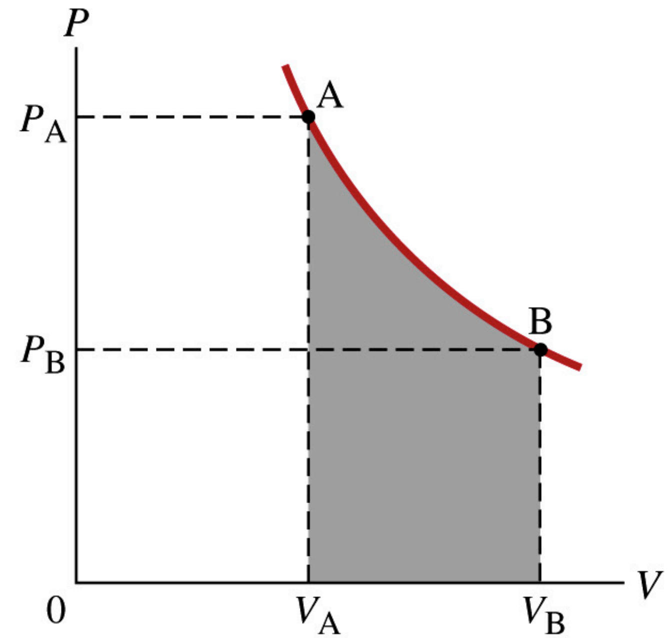
- **Isothermal process**:

$$p = \frac{NkT}{V}$$

- The work done during the change from state *A* to state *B* is

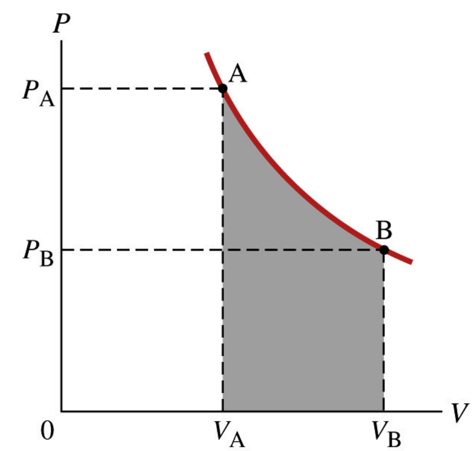
$$W = \int_{V_A}^{V_B} p dV = NkT \int_{V_A}^{V_B} \frac{1}{V} dV$$

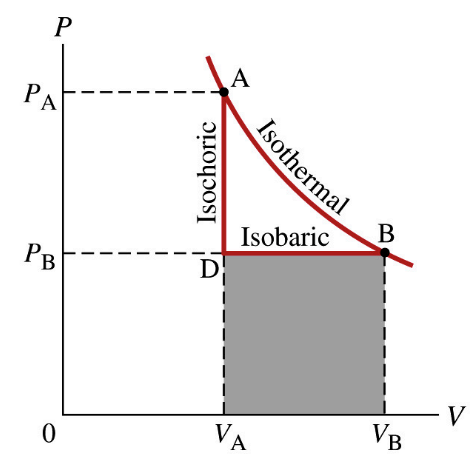
$$= NkT \ln\left(\frac{V_B}{V_A}\right)$$



Work done during expansion/compression.

- The work done during the expansion of a gas is equal to the area under the pV curve.
- Since the shape of the pV curve depends on the nature of the expansion, so does the work done:
  - Isothermal: $W = NkT \ln(V_B / V_A)$
  - Isochoric: $W = 0$
  - Isobaric: $W = p_B (V_B - V_A)$
- The work done to move state A to state B can take on any value!





First law of thermodynamics. Molecular specific heat.

- When we add heat to a system, its temperature will increase.
- For solids and liquids, the increase in temperature is proportional to the heat added, and the constant of proportionality is called the specific heat of the solid or liquid.
- When we add heat to a gas, the increase in temperature will depend on the other parameters of the system. For example, keeping the volume constant will results in a temperature rise that is different from the rise we see when we keep the pressure constant (the heat capacities will differ):
  - $Q = NC_V\Delta T$ (Constant Volume)
  - $Q = NC_P\Delta T$ (Constant Pressure)

  Here, C_V and C_P are the molecular specific heats for constant volume and constant pressure.

First law of thermodynamics. Molecular specific heat (p = constant).

- Consider what happens when we add Q_p to the system while keeping its pressure constant:

$$p = \frac{NkT}{V} = \text{constant}$$

- The work done by the gas will be $p\Delta V$.
- Using the ideal gas law, we can rewrite the work done by the gas as

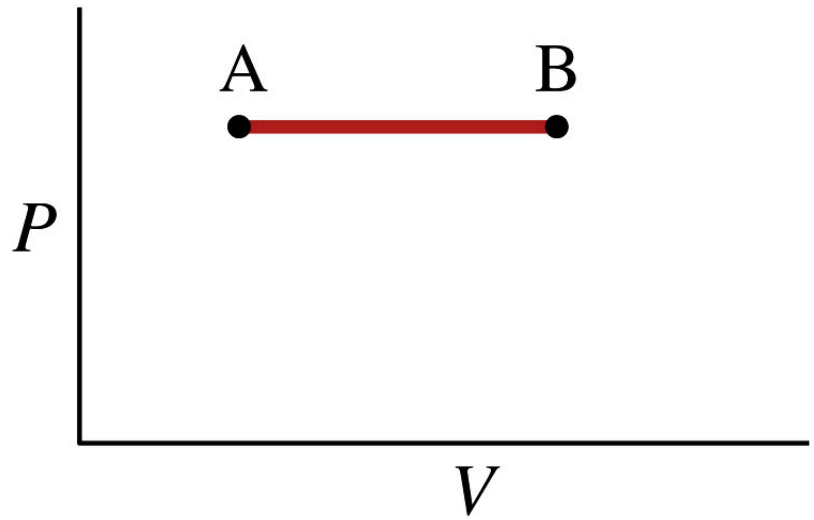
$$W = p\Delta V = Nk\Delta T$$

- The change in the internal energy of the gas is thus equal to

$$\Delta U = Q_P - W = Q_P - Nk\Delta T$$

- Using the definition of C_P we can rewrite this relation as

$$\Delta U = NC_P\Delta T - Nk\Delta T = N(C_P - k)\Delta T$$



(a) Isobaric

First law of thermodynamics. Molecular specific heat (V = constant).

- Consider what happens when we add Q_V to the system while keeping its volume constant

$$V = \frac{NkT}{p} = \text{constant}$$

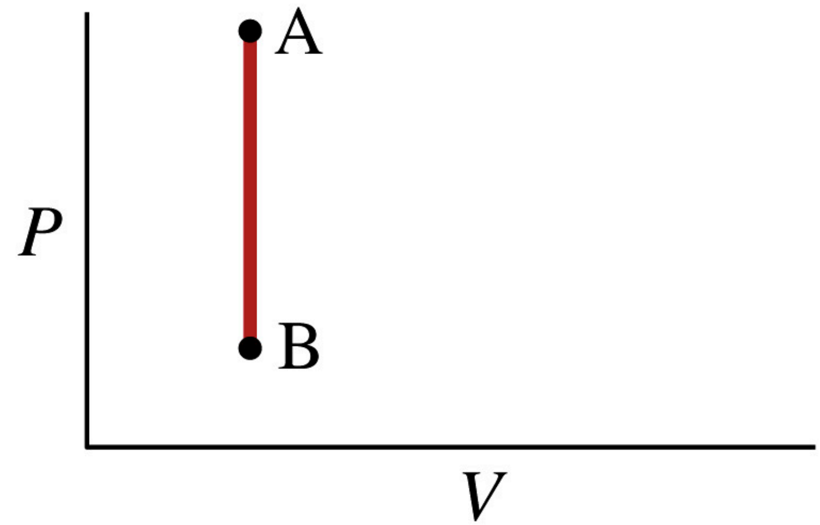
- The work done by the gas will be $p\Delta V = 0$ J.
- The change in the internal energy of the gas is thus equal to

$$\Delta U = Q_V = NC_V\Delta T$$

- Note: we also know from the Boltzmann distribution that

$$\Delta U = \frac{3}{2}Nk\Delta T$$

- We thus conclude that $C_V = \frac{3}{2}k$.



(b) Isochoric

Note: if the molecules have more than 3 degrees of freedom, C_V will increase!

First law of thermodynamics. Molecular specific heat.

- Compare the isobaric and isochoric transitions that produce the same temperature change:

$$\Delta U = N(C_P - k)\Delta T$$

  and

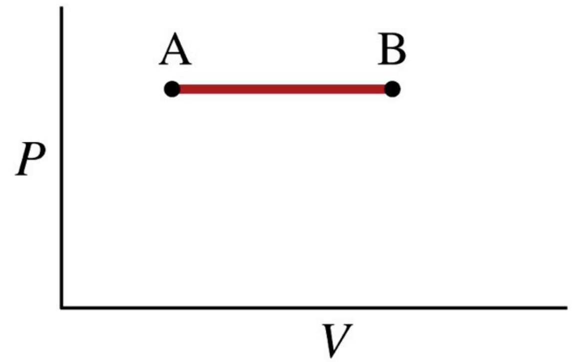
$$\Delta U = Q_V = NC_V\Delta T$$

- Since in both cases the temperature changes by the same amount ΔT, the change in the internal energy ΔU will also be the same.
- We thus conclude that

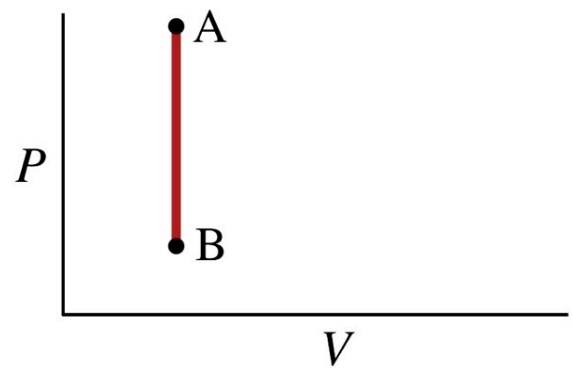
$$C_P - k = C_V$$

  or

$$C_P = C_V + k = \frac{3}{2}k + k = \frac{5}{2}k$$



(a) Isobaric



(b) Isochoric

Adiabatic processes ($Q = 0$ J).
What is the shape of the pV curve?

- The change in the internal energy of the gas is $N\frac{3}{2}k\Delta T = NC_V\Delta T$.
- The first law of thermodynamics thus tells us that

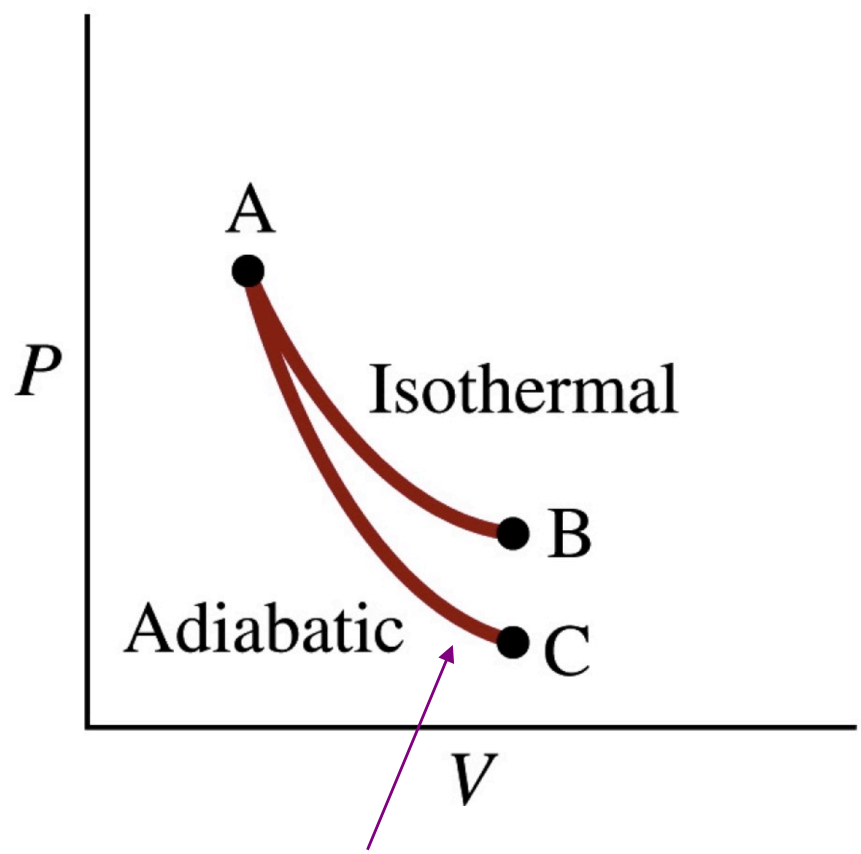
$$NC_V\Delta T = NC_V\int_{V_A}^{V_B} dT = -\int_{V_A}^{V_B} pdV$$

- Comparing the integrands we must require that

$$NC_V dT = -pdV = -\frac{NkT}{V}dV$$

or

$$\frac{C_V}{k}\frac{dT}{T} + \frac{dV}{V} = 0$$



What is the shape of the pV curve?

Adiabatic processes ($Q = 0$ J).

- Integrating each term in the previous expression shows that

$$\frac{C_V}{k}\ln T + \ln V = \ln T^{\frac{C_V}{k}} + \ln V = \ln V T^{\frac{C_V}{k}} = \text{ constant}$$

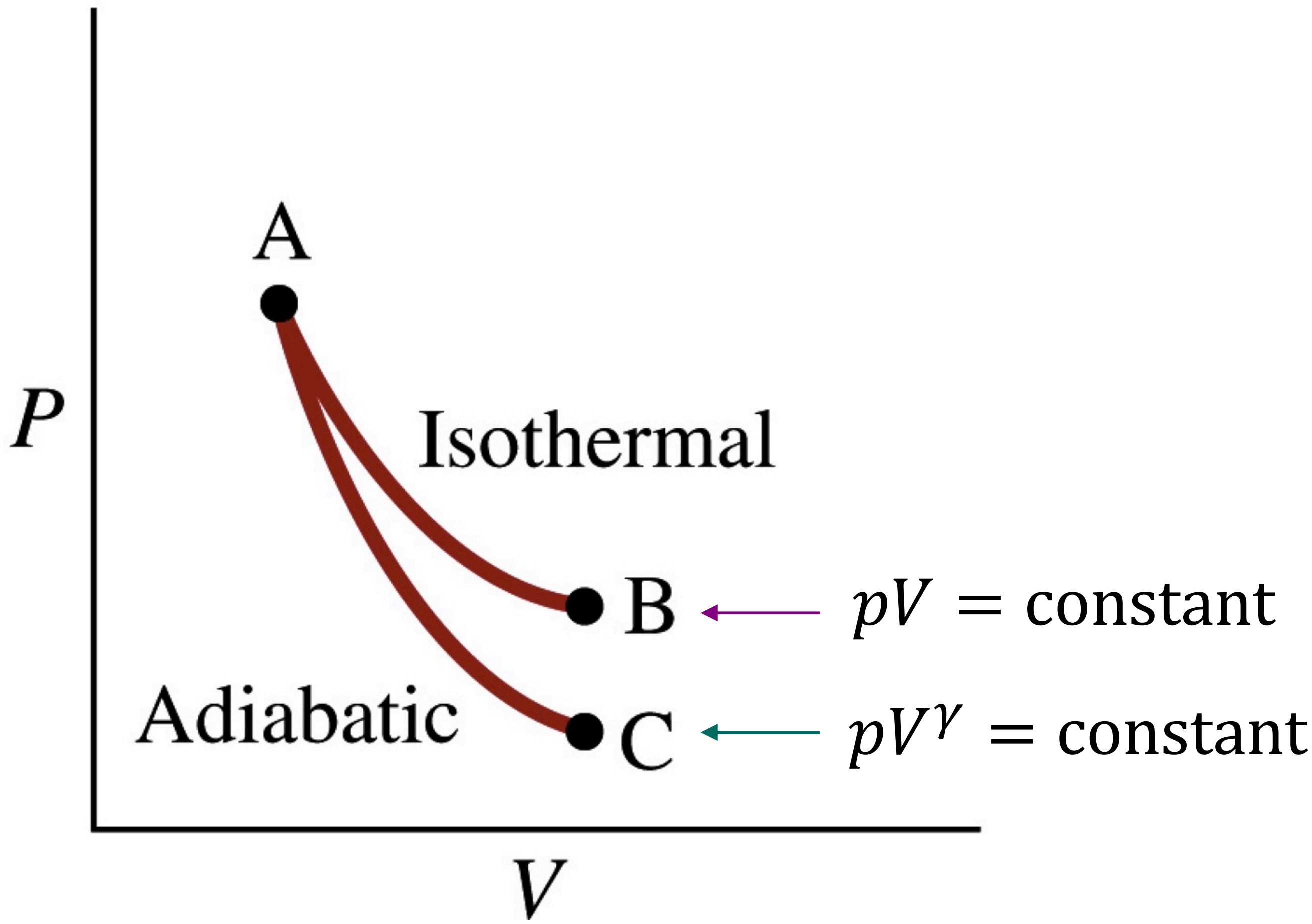
or

$$V T^{\frac{C_V}{k}} = \left(T V^{\frac{k}{C_V}}\right)^{\frac{C_V}{k}} = \text{ constant}$$

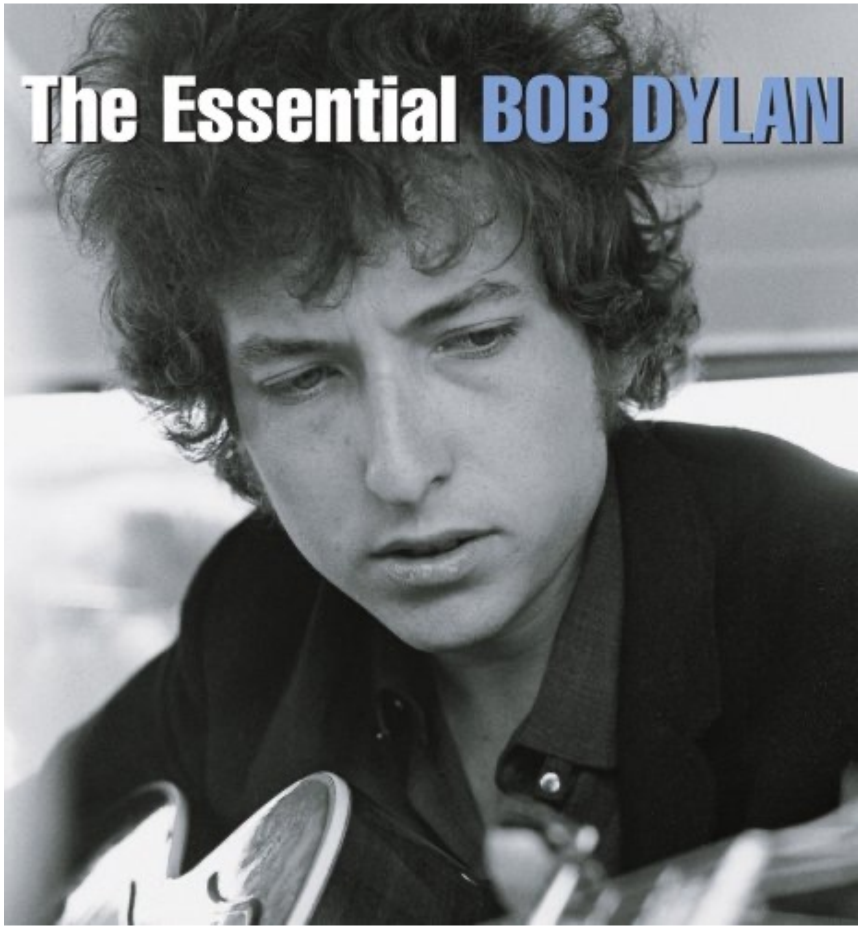
- This expression can also be written in terms of the pressure and volume (which is of course what we need to defined the curve in the pressure versus volume graph):

$$T V^{\frac{k}{C_V}} = \left(\frac{pV}{Nk}\right) V^{\frac{k}{C_V}} = \frac{pV^{\frac{C_V+k}{C_V}}}{Nk} = \frac{pV^{\gamma}}{Nk} = \text{constant}$$

What do we conclude?



2 Minute 48 Second Intermission.

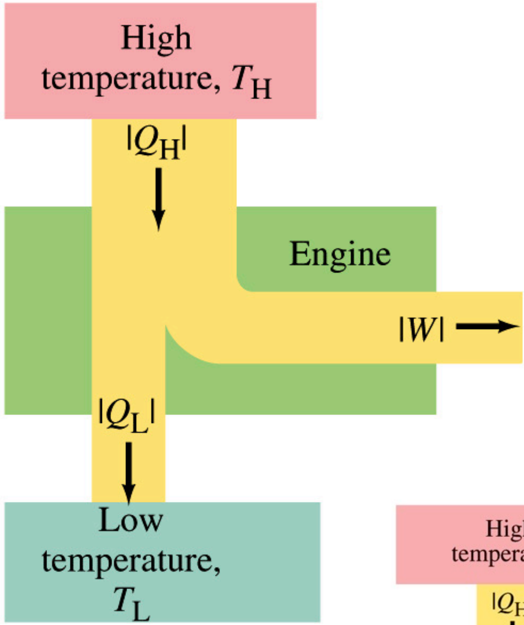


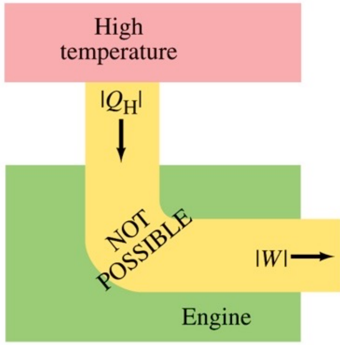
- Since paying attention for 1 hour and 15 minutes is hard when the topic is physics, let's take a 2 minute 48 second intermission.
- You can:
  - Stretch out.
  - Talk to your neighbors.
  - Ask me a quick question.
  - Enjoy the fantastic music.
  - Solve a WeBWorK problem.

The second law of thermodynamics. Heat flow.

- There are several different forms of the second law of thermodynamics:
  - It is not possible to completely change heat into work with no other change taking place.
  - Heat flows naturally from a hot object to a cold object; heat will not flow spontaneously from a cold object to a hot object.

- Many naturally processes do not violate conservation of energy when executed in reverse but will violate the second law.





The second law of thermodynamics. Heat engines.

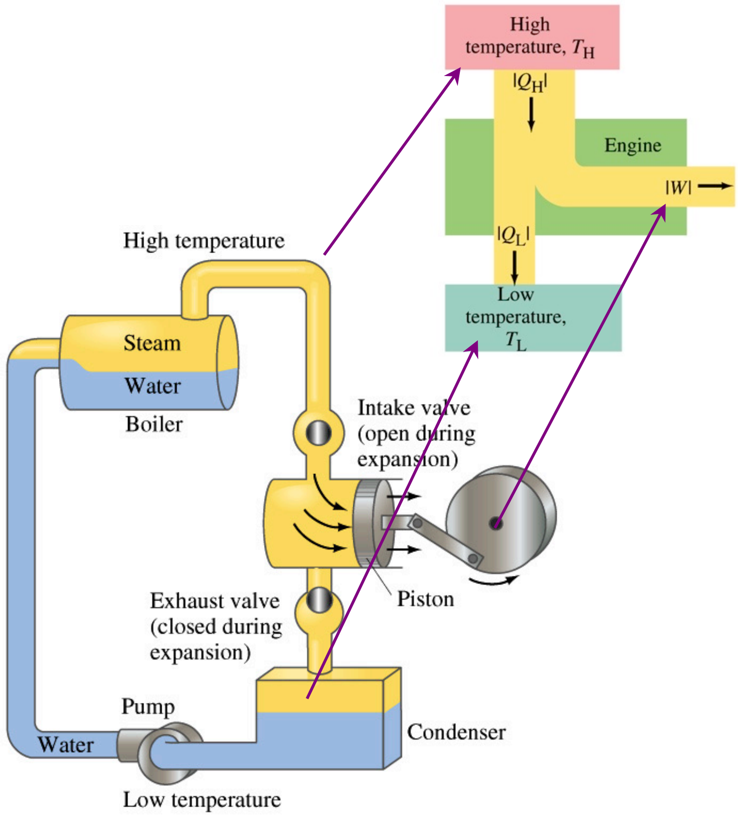
- Most engines rely on a temperature difference to operate.
- Let's understand why:
  - The steam pushes the piston to the right and does work on the piston:

$$W_{in} = NkT_{in}\ln\left[\frac{V_{in}}{V_{out}}\right]$$

  - To remove the steam, the piston has to do work on the steam:

$$W_{out} = NkT_{out}\ln\left[\frac{V_{out}}{V_{in}}\right]$$

  - If $T_{in} = T_{out}$: $W_{in} + W_{out} = 0$ (no net work is done).
  - In order to do work, $T_{in} > T_{out}$. We must thus cool the steam before compression starts.



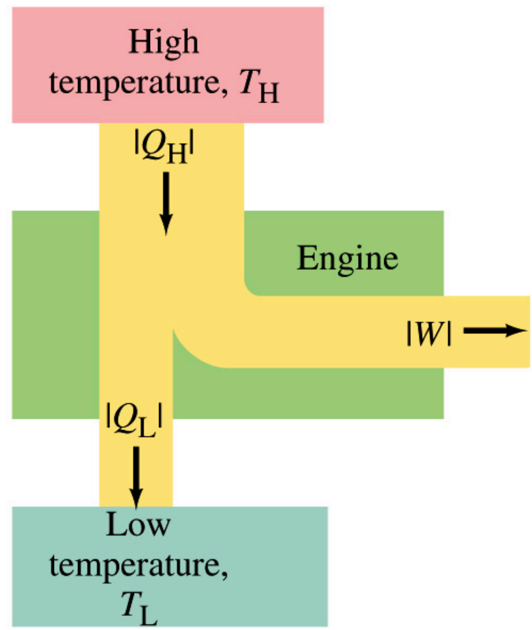
(a) Reciprocating type

The second law of thermodynamics. Heat engines.

- The efficiency of a heat engine is defined as

$$e = \frac{|W|}{|Q_H|} = \frac{|Q_H| - |Q_C|}{|Q_H|}$$

- The work done and the heat extracted are usually measured per engine cycle.
- Since the heat flow to the low temperature reservoir can never be 0 J (this would violate the second law), the efficiency *e* can never be 100%.

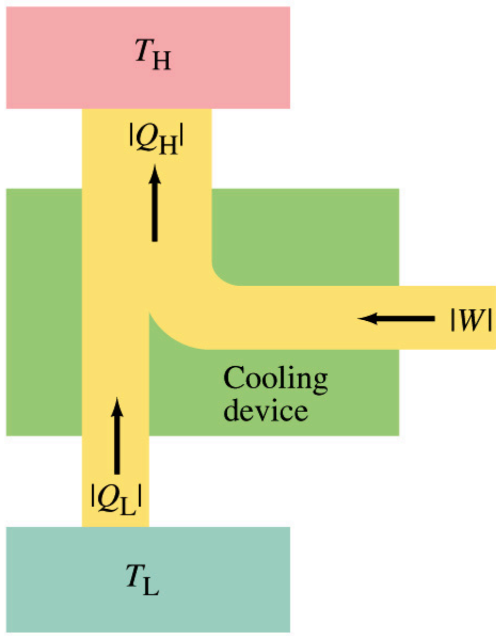


Note: the cost of operation does not only depends on the cost of maintaining the high temperature reservoir, but may also include the cost of maintaining the cold temperature reservoir.

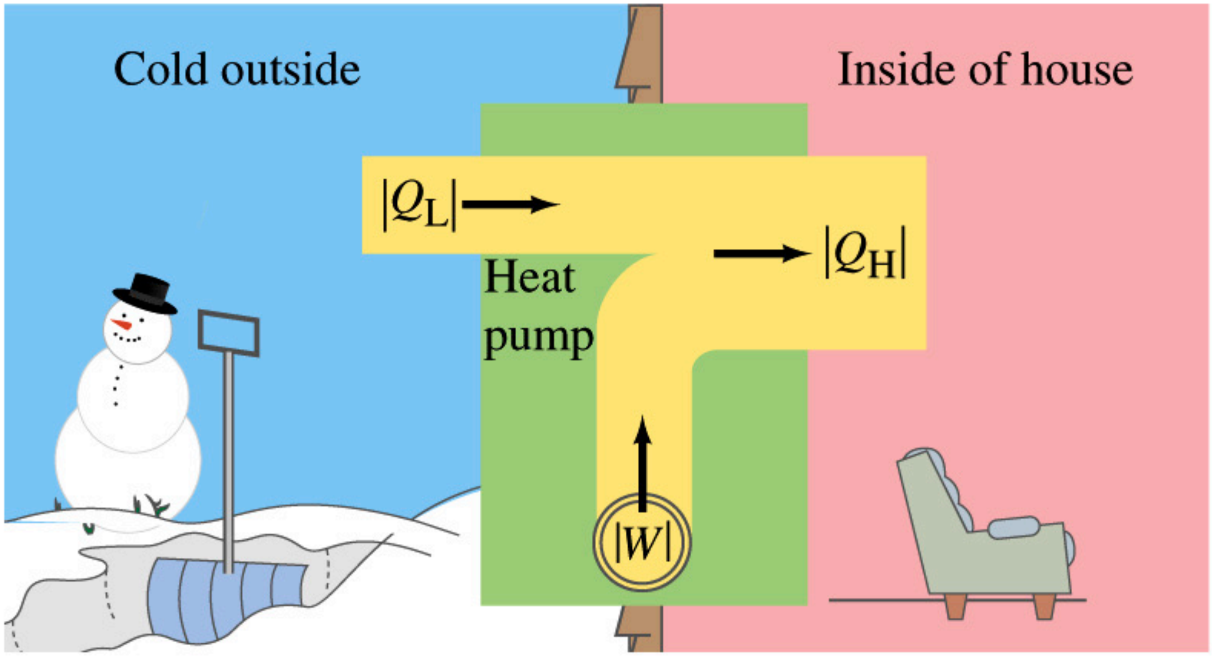
The second law of thermodynamics. Heat pumps.

- In many cases (heat engines), the conversion of flow of heat to work is the primary purpose of the engine (e.g. the car engine).

- In several other applications (e.g. heat pumps), work is converted into a flow of heat (e.g. air conditioning).



The second law of thermodynamics. Heat pumps.



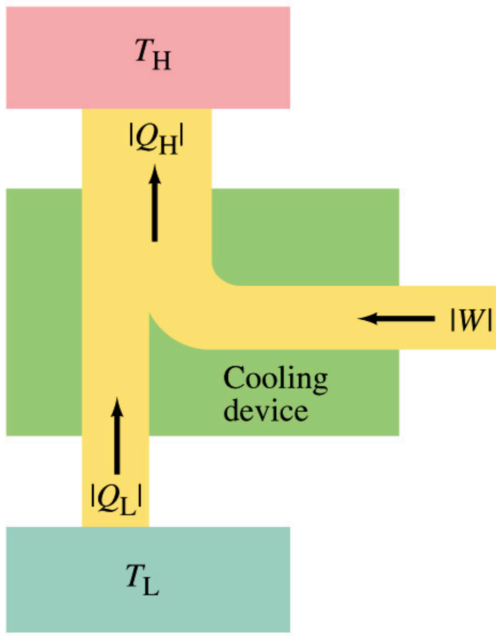
Note: You usually pay for the work done but not for the heat extracted from the outside. You can thus get more energy than what you pay for!

The second law of thermodynamics. Heat pumps.

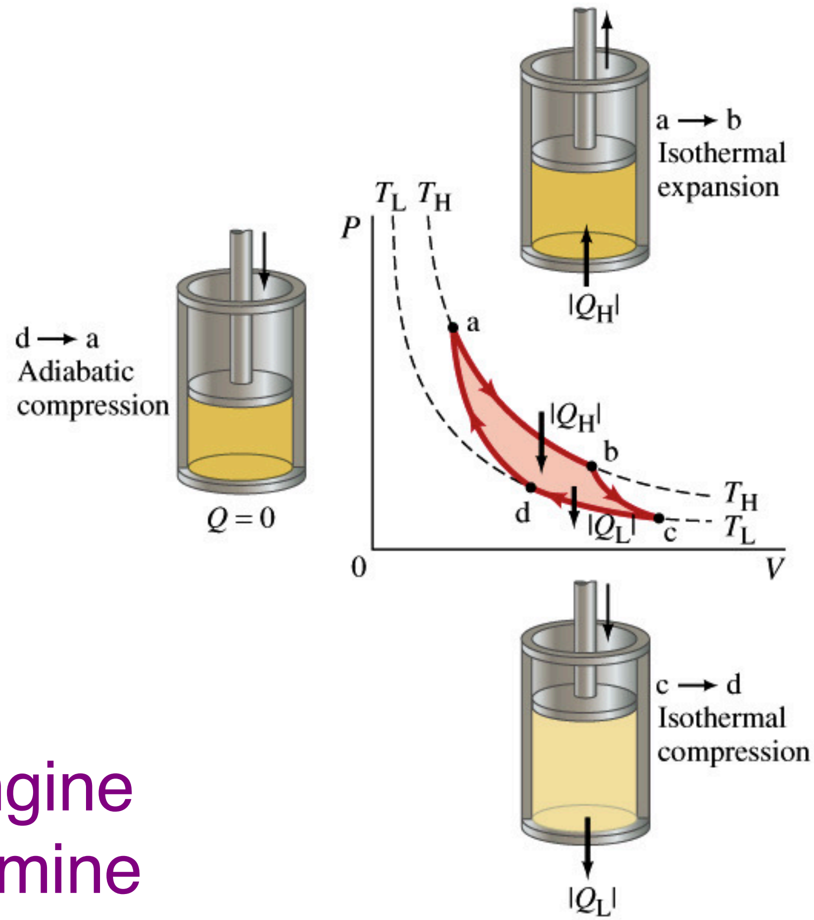
- In a heat pump we do work to move heat from a cold reservoir to a hot reservoir (note: we never have to do work to make heat flow the other way).

- The performance of a heat pump is usually specified by providing the coefficient of performance *K*:

$$K = \frac{|Q_C|}{|W|} = \frac{|Q_C|}{|Q_H| - |Q_C|}$$



The second law of thermodynamics.
The Carnot cycle.

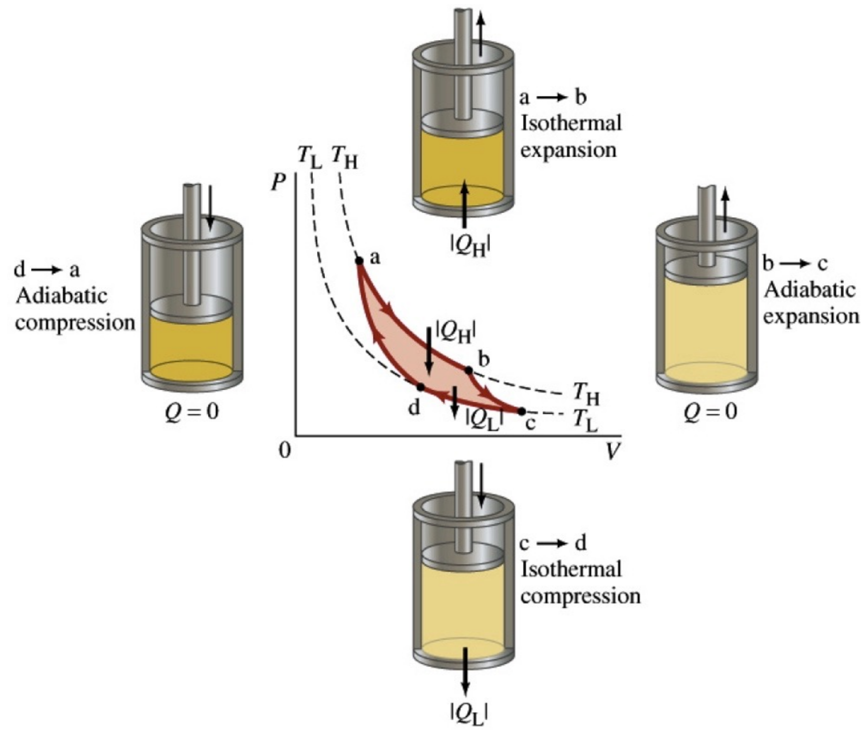


A "perfect" engine
used to determine
the limits on efficiency.

The second law of thermodynamics. The Carnot cycle.

- Step 1: *a* to *b*.
  - The gas is in contact with a heat bath at temperature T_H and weight is removed from the piston.
  - The gas expands, while maintaining a constant temperature (the change in the internal energy is thus equal to 0 J).
  - Using the first law of thermodynamics we see that

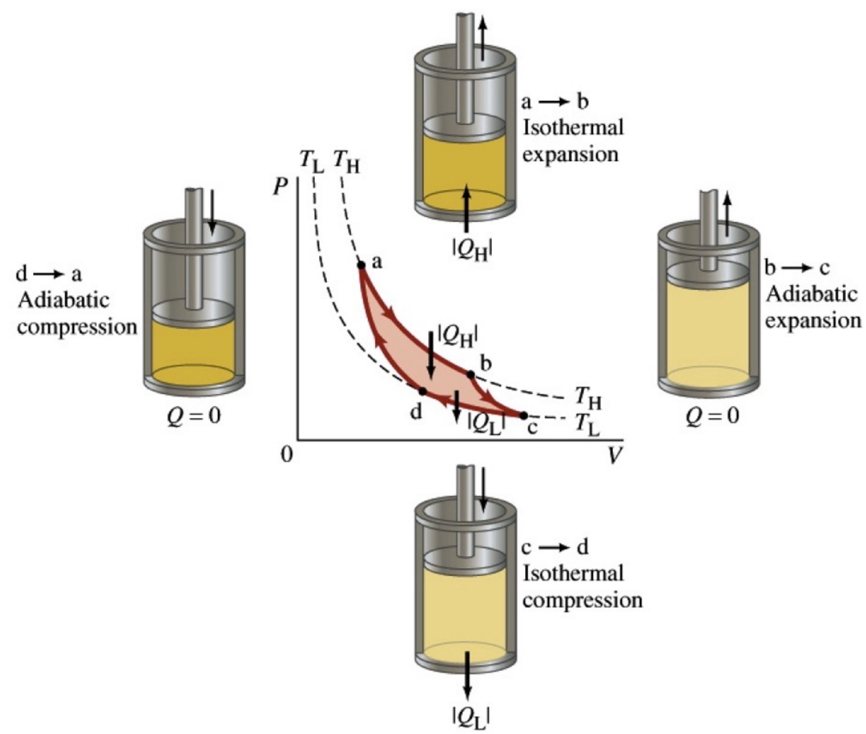
$$|Q_H| = |W_H| = NkT_H \ln\left[\frac{V_b}{V_a}\right]$$



The second law of thermodynamics. The Carnot cycle.

- Step 2: b to c.
  - The gas is isolated from the environment and some more weight is removed from the piston.
  - The gas expands and during the adiabatic expansion, the temperature of the gas will decrease.
  - For adiabatic expansion pV^γ is constant. This can be rewritten as $\left(\frac{NkT}{V}\right)V^\gamma = NkTV^{\gamma-1} = \text{constant}$
  - We can thus relate state b to state c:

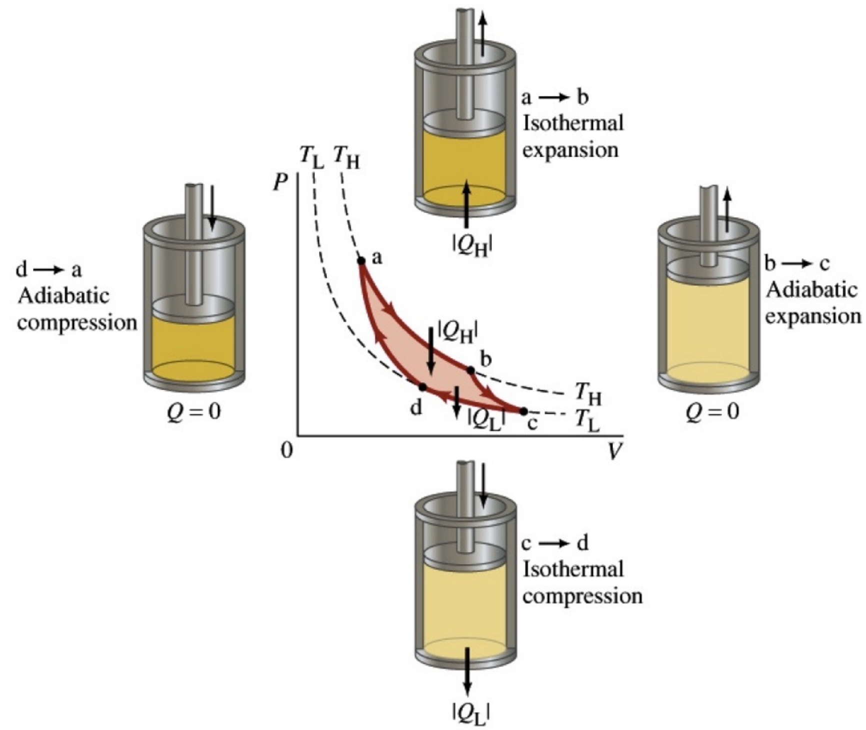
$$T_H V_b^{\gamma-1} = T_C V_c^{\gamma-1}$$



The second law of thermodynamics. The Carnot cycle.

- Step 3: *c* to *d*.
  - The gas is in contact with a heat bath at temperature T_C and weight is added to the piston.
  - The gas is compressed, while maintaining a constant temperature (the change in the internal energy is thus equal to 0 J).
  - Using the first law of thermodynamics we see that

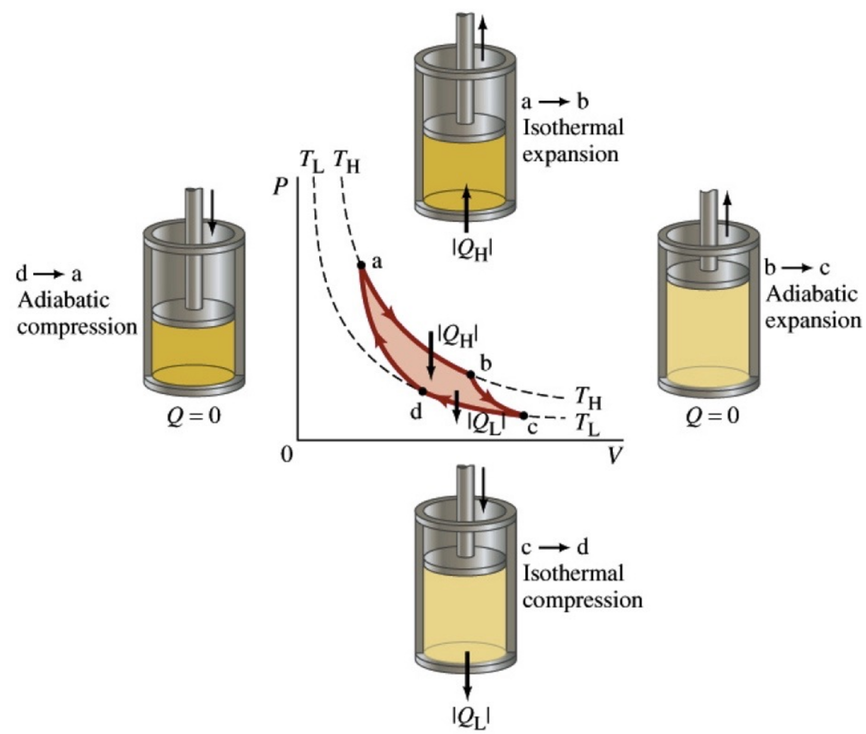
$$|Q_C| = |W_C| = NkT_C \ln\left[\frac{V_c}{V_d}\right]$$



The second law of thermodynamics. The Carnot cycle.

- Step 4: d to a.
  - The gas is isolated from the environment and some more weight is added to the piston.
  - The gas is compressed and during the adiabatic compression, the temperature of the gas will increase.
  - For adiabatic expansion pV^γ is constant. This can be rewritten as $\left(\frac{NkT}{V}\right)V^\gamma = NkTV^{\gamma-1} = \text{constant}$
  - We can thus relate state d to state a:

$$T_H V_a^{\gamma-1} = T_C V_d^{\gamma-1}$$



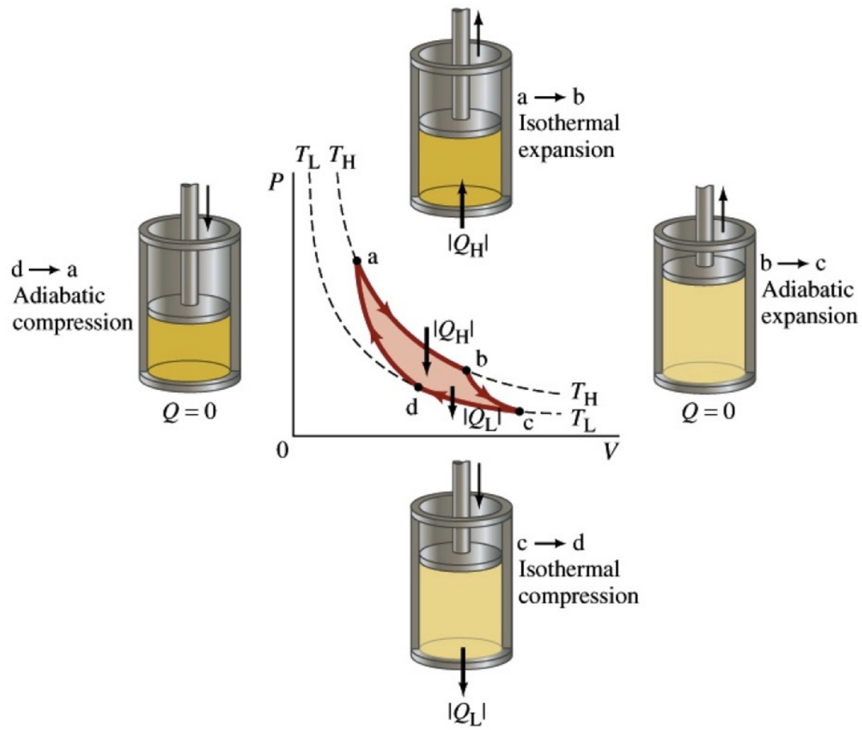
The second law of thermodynamics. The Carnot cycle.

- The adiabatic expansion and compression steps can be used to show that

$$\frac{V_b}{V_a} = \frac{V_c}{V_d}$$

- This relation between the volumes is very useful since it allows us to determine the ratio between the heat flows:

$$\frac{|Q_H|}{|Q_C|} = \frac{T_H \ln\left[\frac{V_b}{V_a}\right]}{T_C \ln\left[\frac{V_c}{V_d}\right]} = \frac{T_H}{T_C}$$

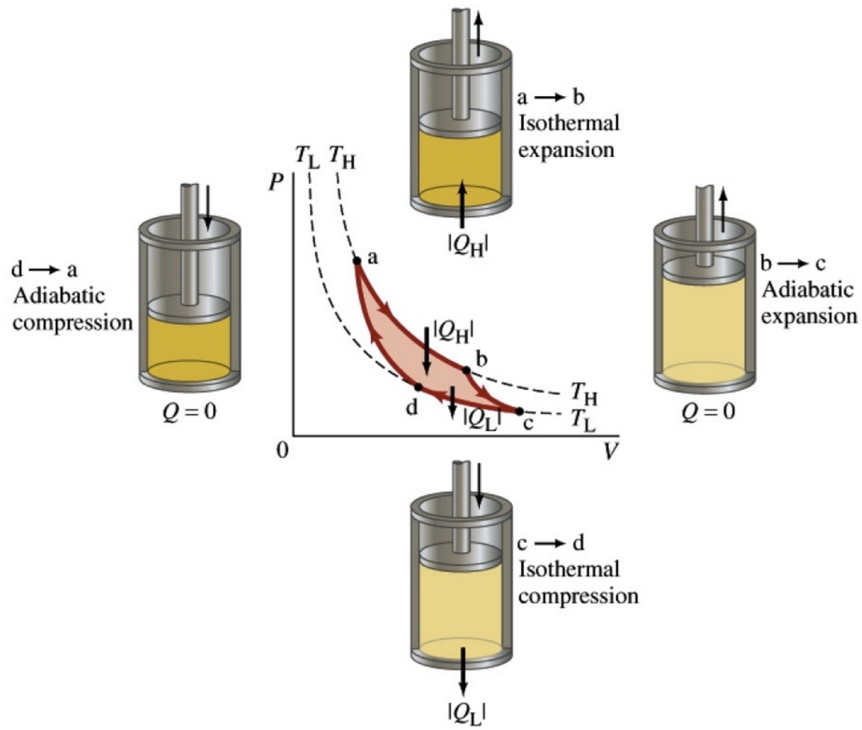


The second law of thermodynamics. The Carnot cycle.

- The efficiency of the Carnot cycle can now be determined.
- Note that the work done by the Carnot engine is the difference between the heat extracted from the hot reservoir and the heat dumped in the cold reservoir:

$$e = \frac{|W|}{[Q_H]} = \frac{|Q_H| - |Q_C|}{|Q_H|} = 1 - \frac{T_C}{T_H}$$

$$= \frac{T_H - T_C}{T_H}$$



The second law of thermodynamics. The Carnot cycle.

- If we look at the efficiency of the Carnot cycle:

$$e = \frac{T_H - T_C}{T_H}$$

  you see that the efficiency improves when the temperature difference between the hot and the cold bath increases. This is why it sometimes pays to increase the cooling of your engine!

- Carnot's theorem tells us that no real engine can have an efficiency more than that of the Carnot engine.

Physics 141. Do you violate the second law?

- During the past 4 months, your brain hopefully has absorbed much of what I have covered, and concepts associated with mechanics should be in a much more ordered state in your brain on December 16 compared to their order on August 27.

- Did you violate the second law by going from disorder to order?

- Not if you include the disorder you dumped into your environment due to sweating over the exams and homework assignments. If you include that disorder, this course has a resulted in a greater disorder in our Universe (since the impact of Physics 141 is clearly irreversible).

Done for today!
On Thursday: the physics of flying.