Lecture 8
(Heat Engines and the Second Law of Thermodynamics)

Physics 161-01 Spring 2012

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WHY???

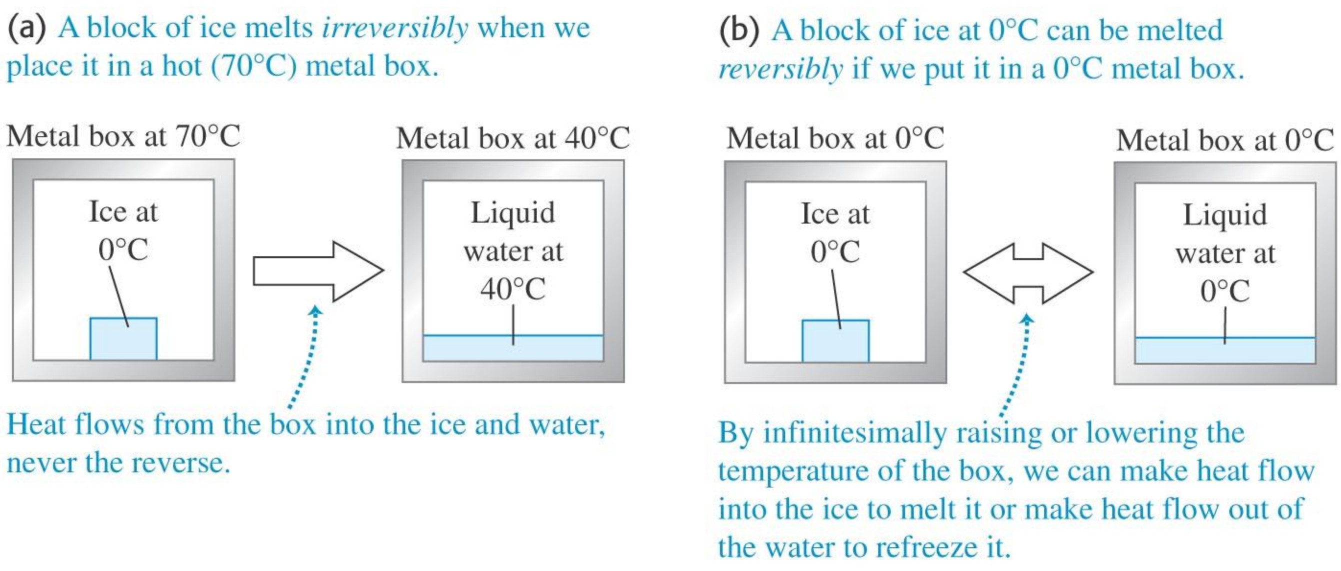
- At the beginning of our discussion on thermodynamics, we stated, as a fact, that heat flows from hot to cold objects.
- We know this intuitively, and it is true.
- But WHY is this true?
- It is also easy to convert mechanical energy completely into heat, but not the reverse.
- Why not?

Reversible and Irreversible Processes (Wikipedia)

- A reversible process is a process that, after it has taken place, can be reversed and causes no change in either the system ***or its surroundings***.
- A process that can be "reversed" by means of infinitesimal changes in some property of the system without loss or dissipation of energy.
- Due to these infinitesimal changes, the system ***is in thermodynamic equilibrium*** throughout the entire process.
- Since it would take an infinite amount of time for the reversible process to finish, ***perfectly reversible processes are impossible***. However, if the system undergoing the changes responds much faster than the applied change, the deviation from reversibility may be negligible. In a reversible cycle, the system and its surroundings will be exactly the same after each cycle.

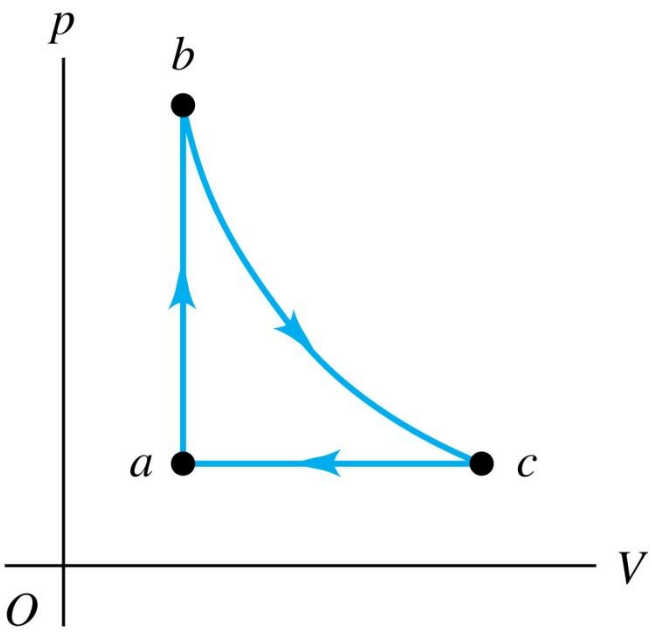
Reversible and Irreversible Processes (University Physics)

- Any time there is heat flow through a finite temperature drop, it is an irreversible process.
- If you want a reversible process, heat only should flow when the temperatures are infinitesimally different (which would take forever).



CPS 8-1

An ideal gas is taken around the cycle shown in this *p*-*V* diagram, from *a* to *b* to *c* and back to *a*. Process $b \to c$ is isothermal. Which of the processes in this cycle could be *reversible*?



A. $a \to b$

B. $b \to c$

C. $c \to a$

D. two or more of A., B., and C.

E. none of A., B., or C.

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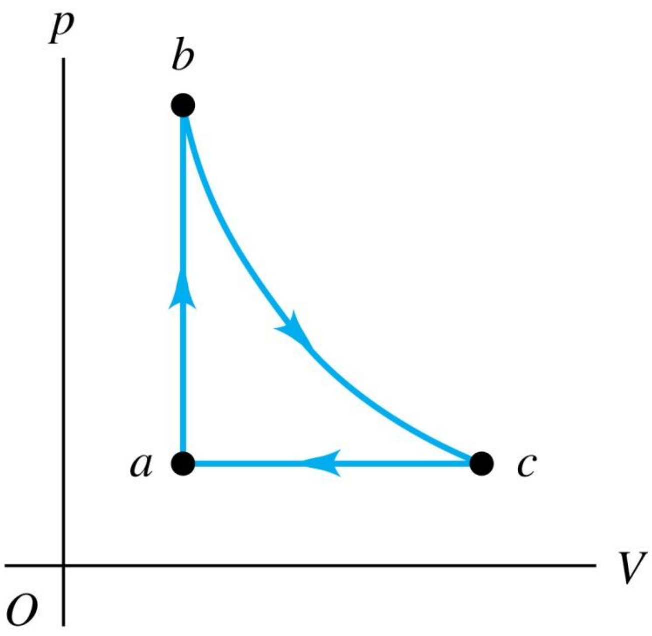

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✓ B. $b \rightarrow c$

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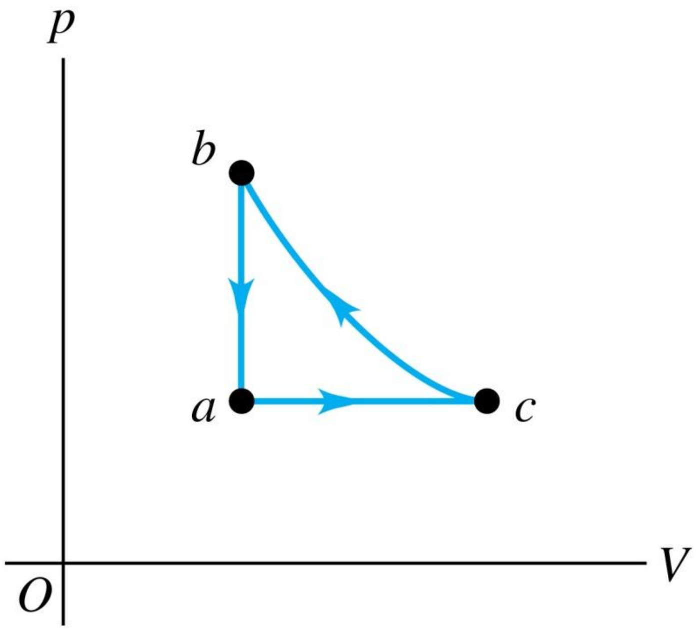
CPS 8-2

An ideal gas is taken around the cycle shown in this *p*-*V* diagram, from *a* to *c* to *b* and back to *a*. Process $c \to b$ is adiabatic. Which of the processes in this cycle could be *reversible*?



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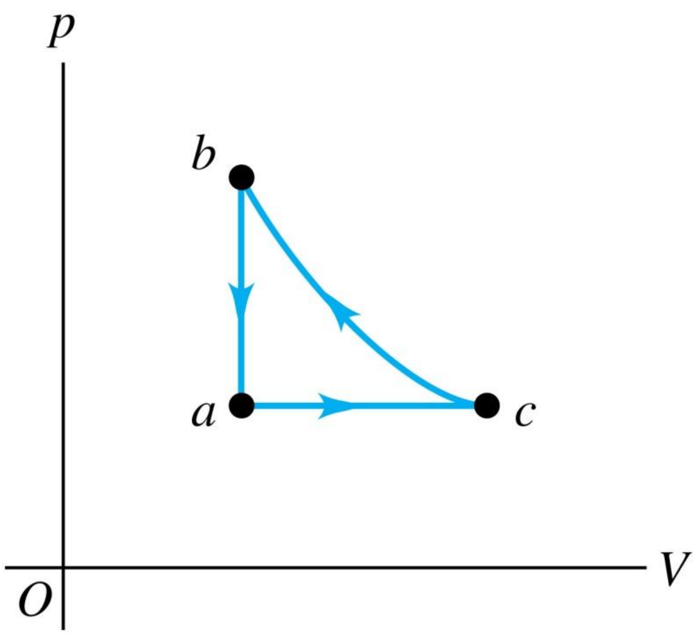

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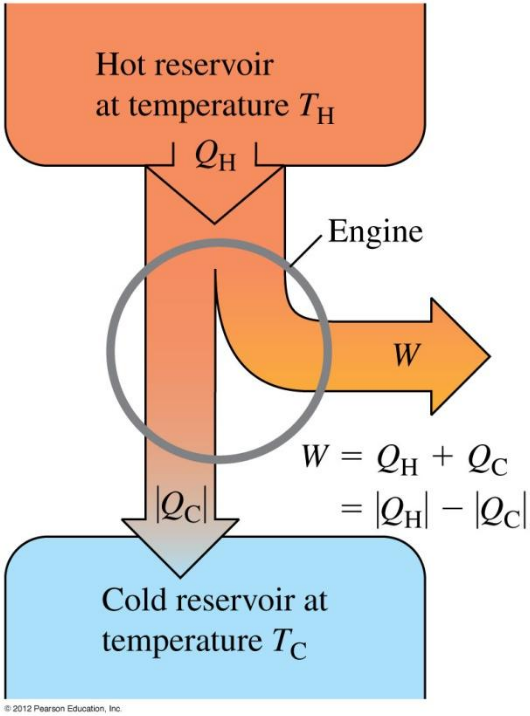
Heat Engines

- A device that (partially) converts heat into work is called a heat engine.
- Examples:
  - Automobile engine.
  - Jet Engine.
  - Human (or other life form) body.
- An idealized heat engine has several components:
  - Working substance (takes in and gives off heat, undergoes compression and expansion, does work, etc)
  - Hot reservoir (supplies heat to the working substance)
  - Cold reservoir (takes heat from the working substance)
- Additionally, since one would normally want to convert heat into work over and over again, the process to do that would be cyclic – the system would return again and again to the same state and repeat the conversion process.

Energy Flow Diagrams

- Energy flow diagrams are useful to show the flow of heat from the hot reservoir through the engine and to the cold reservoir.
- For a real working car engine, the hot reservoir is also the working substance (gas-air mixture when burned supplies the heat). The cold reservoir is the outside air.



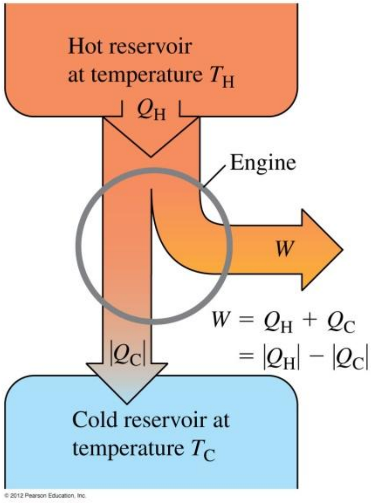
Efficiency

- The efficiency of a heat engine is defined as the ratio of the work done to the amount of heat brought in from the hot reservoir:

$$e = \frac{W}{Q_H}$$

- For a cyclic process, the internal energy of the working substance returns to its initial value, so Q = W. Then,

$$e = \frac{W}{Q_H} = \frac{Q_H + Q_C}{Q_H} = 1 - \frac{|Q_C|}{Q_H}$$



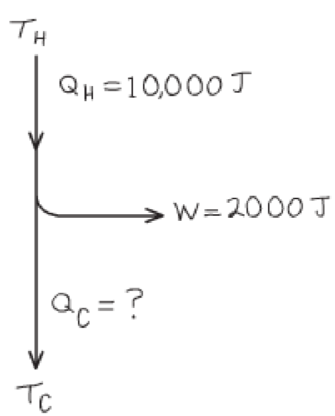
Example 20.1 Analyzing a heat engine

A gasoline truck engine takes in 10,000 J of heat and delivers 2000 J of mechanical work per cycle. The heat is obtained by burning gasoline with heat of combustion $L_c = 5.0 \times 10^4$ J/g. (a) What is the thermal efficiency of this engine? (b) How much heat is discarded in each cycle? (c) If the engine goes through 25 cycles per second, what is its power output in watts? In horsepower? (d) How much gasoline is burned in each cycle? (e) How much gasoline is burned per second? Per hour?

SOLUTION

IDENTIFY and SET UP: This problem concerns a heat engine, so we can use the ideas of this section. Figure 20.4 is our energy-flow diagram for one cycle. In each cycle the engine does $W = 2000$ J of work and takes in heat $Q_H = 10{,}000$ J. We use Eq. (20.4), in the form $e = W/Q_H$, to find the thermal efficiency. We use Eq. (20.2) to find the amount of heat Q_C rejected per cycle. The heat of combustion tells us how much gasoline must be burned per cycle and hence per unit time. The power output is the time rate at which the work W is done.

20.4 Our sketch for this problem.



EXECUTE: (a) From Eq. (20.4), the thermal efficiency is

$$e = \frac{W}{Q_H} = \frac{2000 \text{ J}}{10{,}000 \text{ J}} = 0.20 = 20\%$$

(b) From Eq. (20.2), $W = Q_H + Q_C$, so

$$Q_C = W - Q_H = 2000 \text{ J} - 10{,}000 \text{ J} = -8000 \text{ J}$$

That is, 8000 J of heat leaves the engine during each cycle.

(c) The power P equals the work per cycle multiplied by the number of cycles per second:

$$P = (2000 \text{ J/cycle})(25 \text{ cycles/s}) = 50{,}000 \text{ W} = 50 \text{ kW}$$

$$= (50{,}000 \text{ W})\frac{1 \text{ hp}}{746 \text{ W}} = 67 \text{ hp}$$

(d) Let m be the mass of gasoline burned during each cycle. Then $Q_H = mL_c$ and

$$m = \frac{Q_H}{L_c} = \frac{10{,}000 \text{ J}}{5.0 \times 10^4 \text{ J/g}} = 0.20 \text{ g}$$

(e) The mass of gasoline burned per second equals the mass per cycle multiplied by the number of cycles per second:

$$(0.20 \text{ g/cycle})(25 \text{ cycles/s}) = 5.0 \text{ g/s}$$

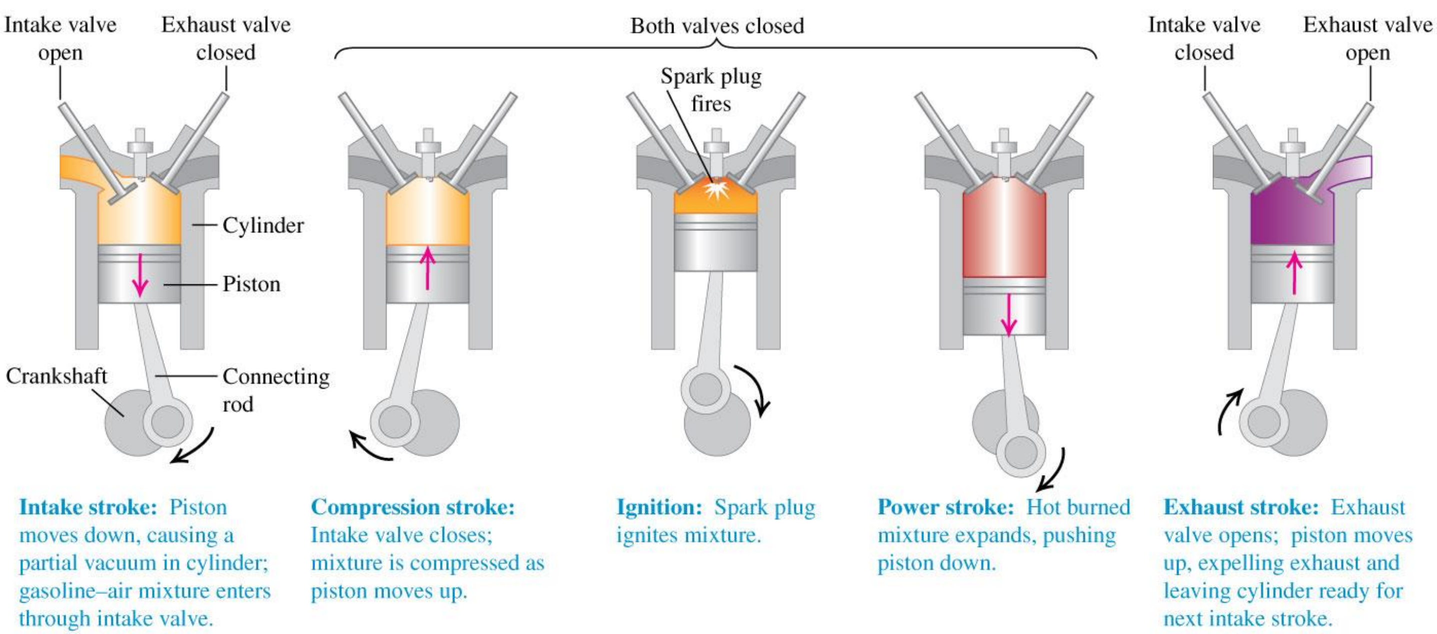
The mass burned per hour is

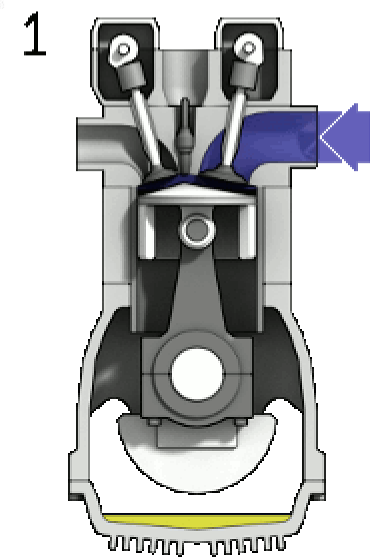
$$(5.0 \text{ g/s})\frac{3600 \text{ s}}{1 \text{ h}} = 18{,}000 \text{ g/h} = 18 \text{ kg/h}$$

EVALUATE: An efficiency of 20% is fairly typical for cars and trucks if W includes only the work delivered to the wheels. We can check the mass burned per hour by expressing it in miles per gallon ("mileage"). The density of gasoline is about 0.70 g/cm^3, so this is about 25,700 cm^3, 25.7 L, or 6.8 gallons of gasoline per hour. If the truck is traveling at 55 mi/h (88 km/h), this represents fuel consumption of 8.1 miles/gallon (3.4 km/L). This is a fairly typical mileage for large trucks.

Internal Combustion Engines

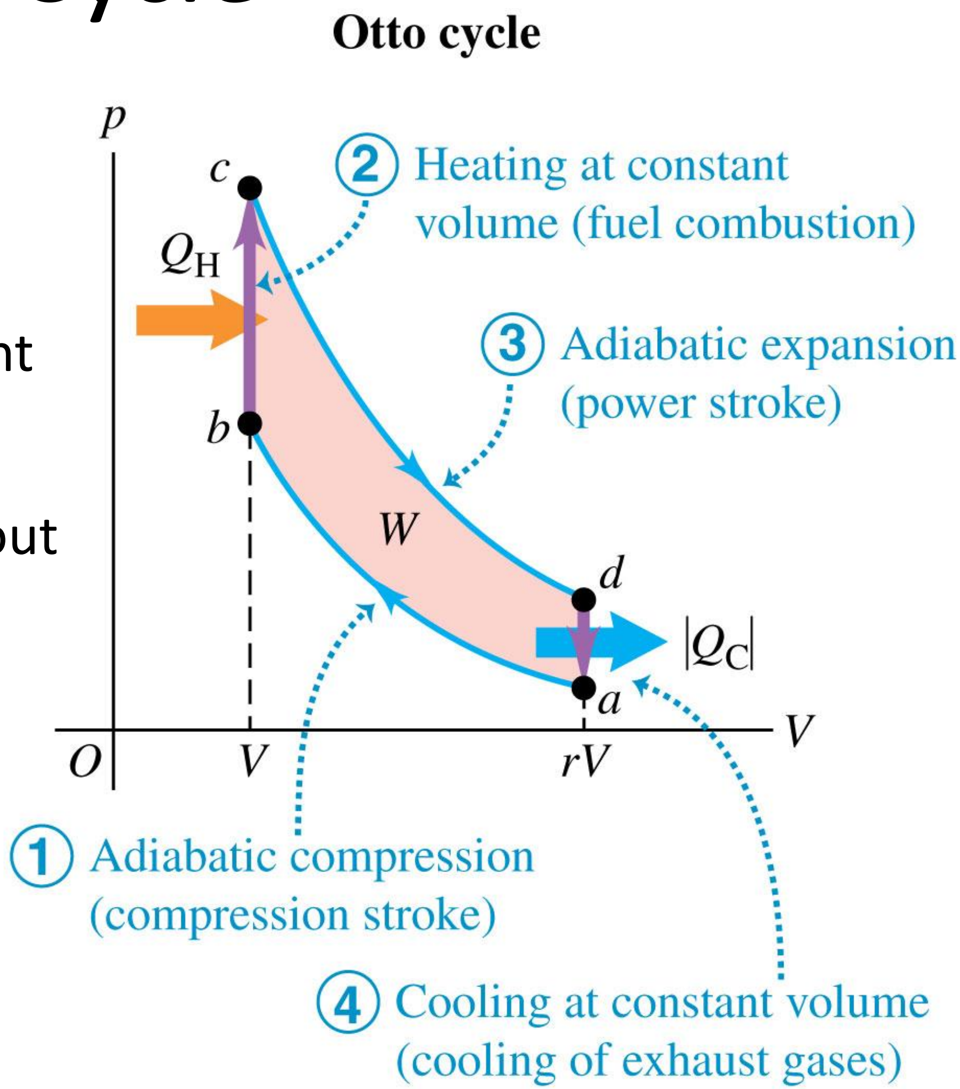
- Let's examine more closely the workings of the internal combustion engine, first from a mechanics perspective.
- Since the hot and cold reservoirs are set by the fuel energy and the outside temperature respectively, differences in engines are mostly in the amount the volume changes, and are given in terms of the ratio of expanded to compressed volumes, or the compression ratio $r = V_2/V_1$.





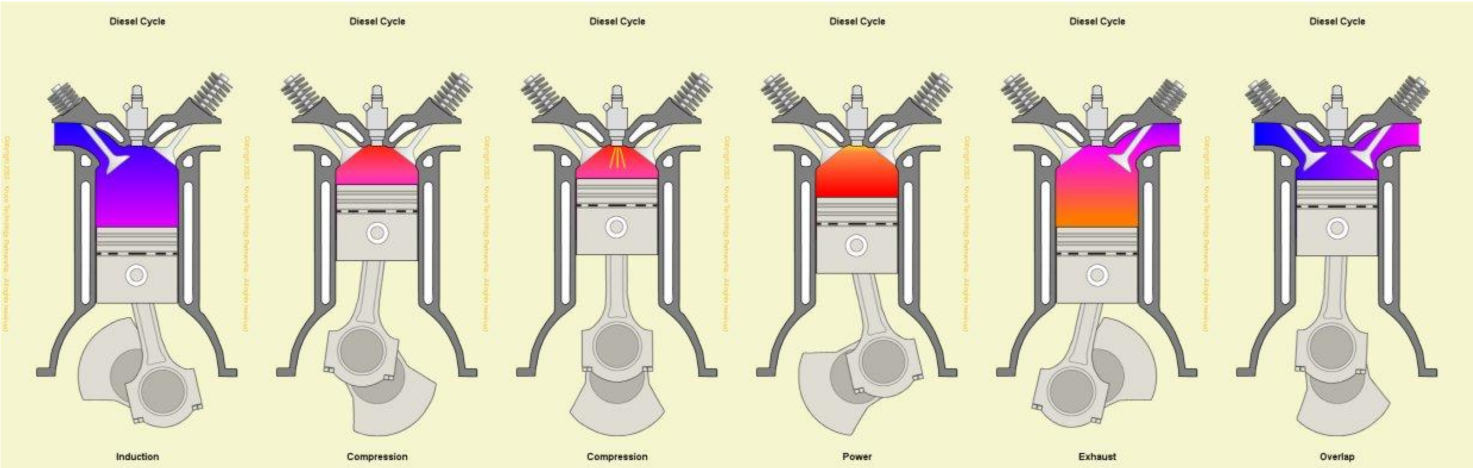
Otto-Cycle

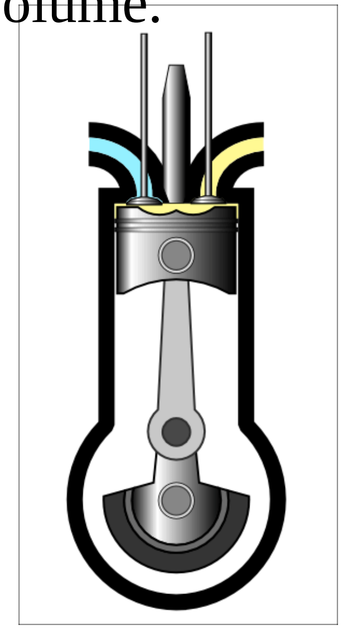
- From a thermodynamic perspective:
  - Heat is introduced in the combustion phase at constant volume.
  - During the power stroke, no new heat is added or taken out (it happens too fast for the cylinder to affect anything).
  - Heat is extracted in the exhaust phase, at constant volume.
  - The system returns to the original state during the compression stroke (again adiabatically).



Diesel Cycle

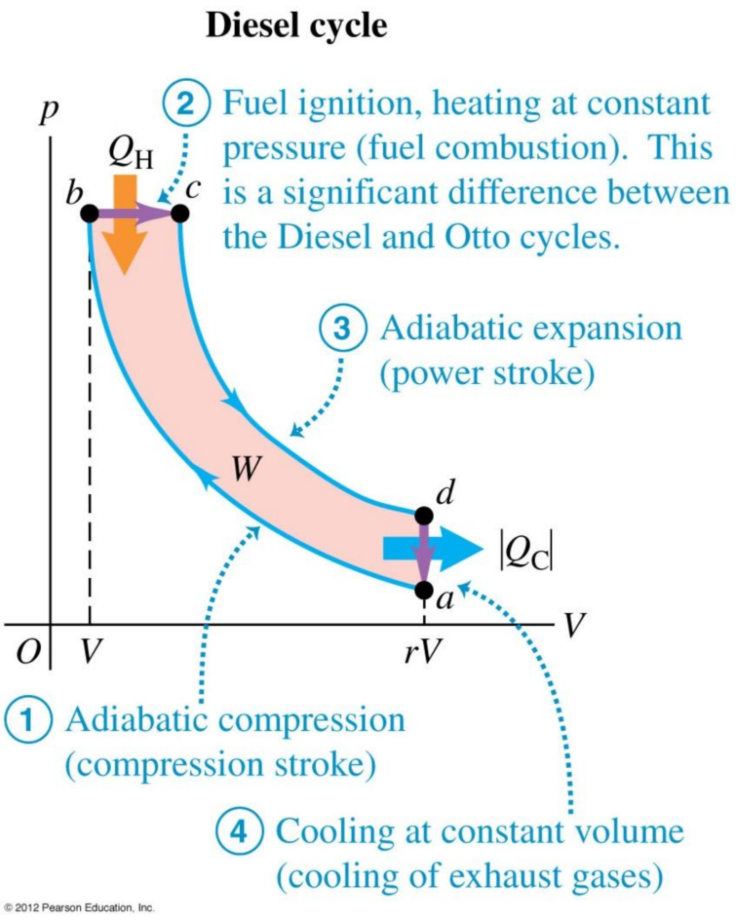
- The diesel engine is very similar to the gasoline (Otto) engine, with a couple of big differences:
  - There is no spark plug to ignite the fuel – it ignites because the air is compressed so much that it is hot enough for combustion.
  - The fuel isn't pre-mixed with the air, but injected at TDC. Heat then is added at constant pressure rather than constant volume.





Diesel Cycle

- Because of the constant pressure heating at high pressure, the work done (for the amount of heat delivered) is higher for a diesel cycle than it is for an Otto cycle.
- But, because of the higher pressures (higher compression ratios), diesel engines are more complicated to produce and have higher tolerances (they cost more!)



CPS 8-3

During one cycle, an automobile engine takes in 12,000 J of heat and discards 9000 J of heat. What is the efficiency of this engine?

A. 400%

B. 133%

C. 75%

D. 33%

E. 25%

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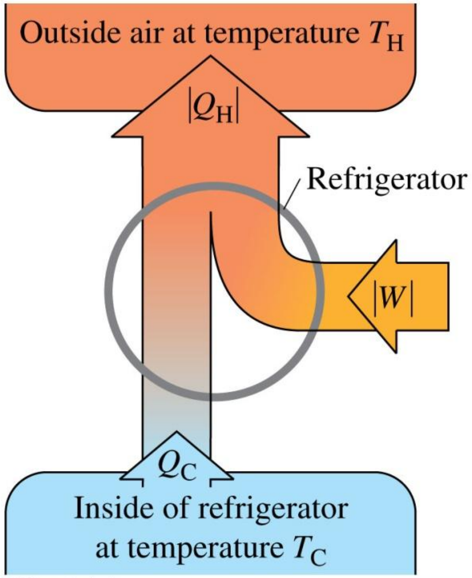
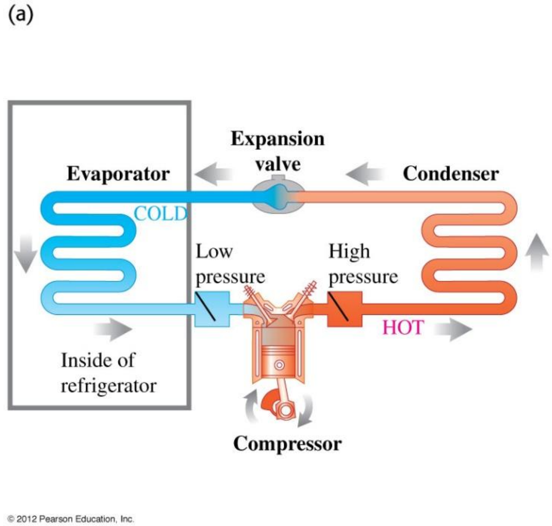
Refrigerators

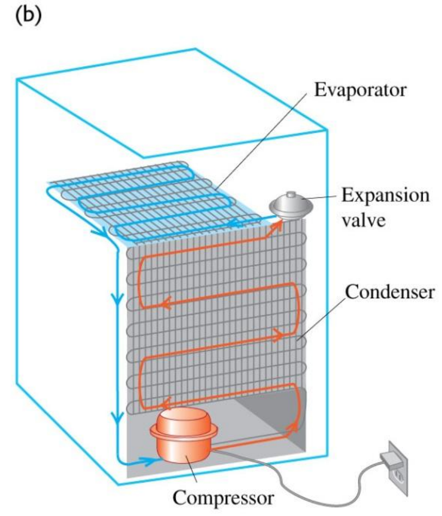
- Refrigerators are nothing more than engines run in reverse: they take heat out of a cold reservoir, and use work to put more heat into the hot reservoir.
- Instead of efficiency, we refer to the coefficient of refrigeration, K:

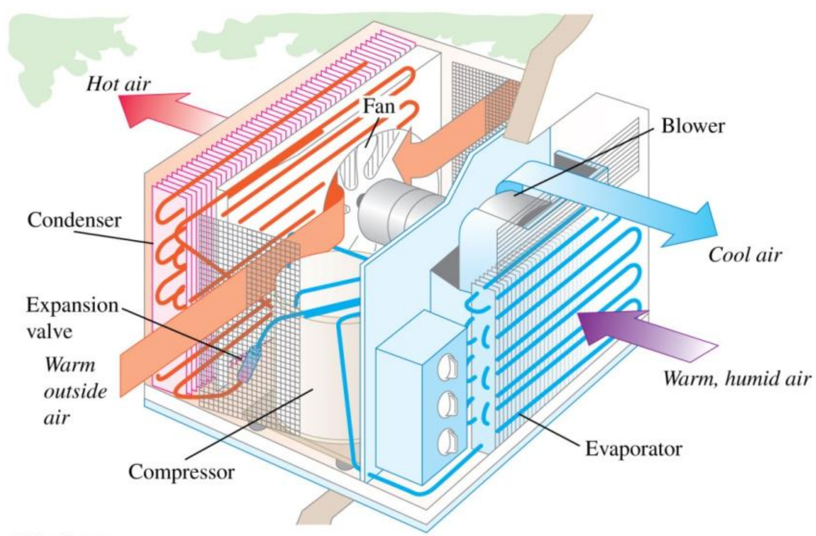
$$K = \frac{|Q_C|}{|W|} = \frac{|Q_C|}{|Q_H| - |Q_C|}$$



Refrigerators



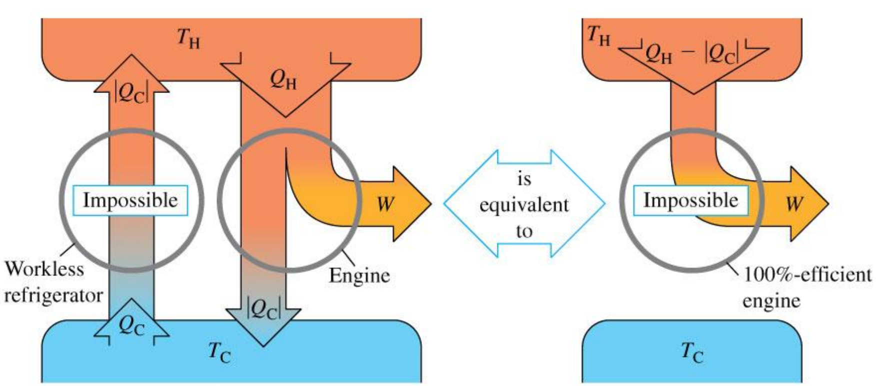




The 2nd Law of Thermodynamics

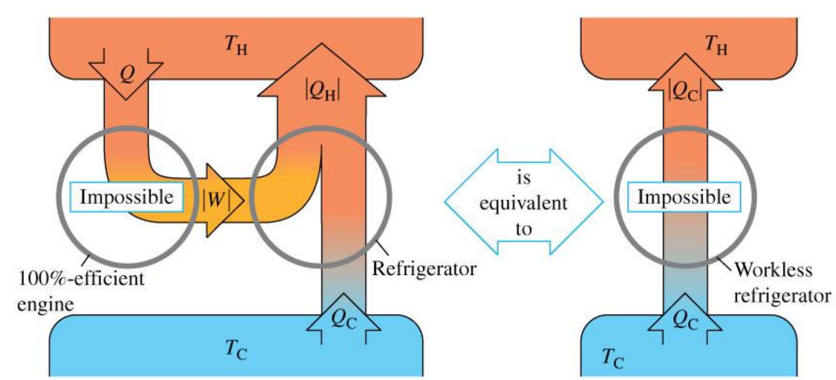
- *"No process is possible whose sole result is the transfer of heat from a body of lower temperature to a body of higher temperature." – Rudolf Clausius*
- *"No process is possible in which the sole result is the absorption of heat from a reservoir and its complete conversion into work." – Lord Kelvin*

(a) The "engine" statement of the second law of thermodynamics



If a workless refrigerator were possible, it could be used in conjunction with an ordinary heat engine to form a 100%-efficient engine, converting heat $Q_H - |Q_C|$ completely to work.

(b) The "refrigerator" statement of the second law of thermodynamics



If a 100%-efficient engine were possible, it could be used in conjunction with an ordinary refrigerator to form a workless refrigerator, transferring heat Q_C from the cold to the hot reservoir with no input of work.