

Lecture 36 (Walker 18.8, 18.5-6,)

Entropy 2nd Law of Thermodynamics Heat Engines Dec. 11, 2009

Help Session: Today, 3:10-4:00, TH230

Review Session: Monday, 3:10-4:00,
TH230

Solutions to practice final on web page
today

Lecture 36

The Physics 111 Final Exam

- On Wednesday, Dec. 16, 10:45-1:15 we have the Final Exam, covering Chapters 1-11 and 13-18 of Walker. Similar in format to midterms, with 60 pts of multiple choice questions and 140 pts of free-response questions. Exam is about 1.5 times longer than a midterm, but you have 150 minutes instead of 50 minutes.
- Sections not covered: 8-5, 9-6 details, 9-8, 11-8, 11-9, 13-6, 14-3, 14-9, 15-9 surface tension, 17-3, 18-3, 18-4, 18-9, 18-10.
- All *three* equation sheets provided on the Final

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Thermal Processes

Thermal Processes are things we do to a system that involve thermal energy - adding heat, changing system temperature, etc. In all cases, $\Delta U = Q - W$

Special Thermal Processes - Ideal Gas Systems

Constant temperature (isothermal) process:
Internal energy of ideal gas depends only on temperature, so no change in internal energy U . Thus, $W = Q$

Adiabatic process: $Q = 0$; no heat flow into or out of the system. Thus, $W = -\Delta U$.

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Heat versus Work

- Both heat and work represent the flow of energy from one system to another. However, heat, as "disordered" energy flow, has some special properties:
- Heat always flows spontaneously from a warmer object to a cooler one, although the opposite would not violate conservation of energy.
- It is easy to convert work to thermal energy via friction (rubbing hands together), but conversion of thermal energy to work requires an engine.
- We will see that heat carries entropy (disorder) with it, but work does not.

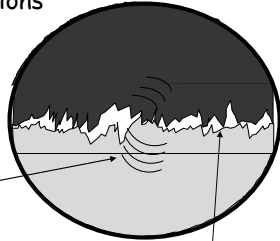
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Energy "dissipation" (conversion to thermal energy) by sliding friction

- As parts scrape by each other they start small-scale vibrations, which transfer kinetic and potential energy into atomic motions

The atoms' vibrations go back and forth- they have energy, but no average momentum. Random sound waves!

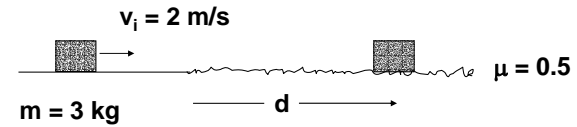


Many different forces F_i , displacements dr_i .
No way to keep track.

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Dissipation by Friction



- a) How far does block go after entering rough region?

$$W_{nc} = F d = \Delta(\text{KE}) = 0 - \frac{1}{2} m v_i^2 \longrightarrow \boxed{d = \frac{1}{2} v_i^2 / \mu g = 0.41 \text{ meters}}$$

$$F = -\mu_k m g$$

- b) How much internal energy is produced in block & floor?

System of block plus floor: $W = \Delta(\text{total energy}) = 0$

$$E_i = \frac{1}{2} m v_i^2 \quad E_f = \frac{1}{2} m v_f^2 + \Delta U_{\text{thermal}} \quad \boxed{\Delta U_{\text{thermal}} = \frac{1}{2} m v_i^2 = 6 \text{ J}}$$

Irreversible!

0

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A lead block weighing 1 kg is dropped from a height of 1m. It does not bounce.

What is the change in thermal energy of the block and floor?

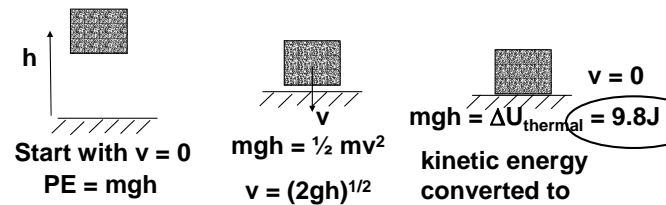
- a. 0 b. 4.9 J
c. 9.8 J d. cannot be determined

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For isolated system (block+Earth), energy is conserved: $W_{on} = 0 \quad E_{\text{tot}} = \text{constant}$

As time proceeds, the energy changes form:



Potential energy \longrightarrow Kinetic energy \longrightarrow Thermal energy

Irreversible process

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One-way Flow of Thermal Energy

Hot object

Cold object

Which way does heat energy flow?

- Earlier, we saw that many processes are governed by conservation of energy, in the form of The First Law of Thermodynamics
- Doesn't give the flow *direction* -- energy is conserved *either* way. Need The Second Law of Thermodynamics: Total *entropy* never decreases.
- A consequence of the Second Law is that the spontaneous flow of heat is always from hot to cold.
- To understand this, we need to define entropy.

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Entropy (S)

- The entropy S of a system is a measure of the amount of disorder in the system.
- SI unit of entropy: J/K
- Entropy depends on the temperature and phase of the system
- The entropy of a solid at absolute zero can be taken to be zero
- The entropy of a system can be increased by bringing in heat (Q)
- The entropy of a system can be reduced by removing heat

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Entropy Change ΔS

If an amount Q of heat is brought into a system at (Kelvin) temperature T , the change in the entropy of the system is defined as follows

Definition of Entropy Change, ΔS

$$\Delta S = \frac{Q}{T}$$

SI unit: J/K

Example: What is the entropy change of an ideal gas at 100K if 200 J of heat enter the system?

$$\Delta S = Q/T = 2 \text{ J/K}$$

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Second Law of Thermodynamics In Terms of Entropy Change

Second Law of Thermodynamics:

$$\Delta S_{\text{universe}} \geq 0$$

- The total entropy of the universe increases whenever an irreversible process occurs.
- The total entropy of the universe is unchanged whenever a reversible process occurs.
- Entropy cannot be destroyed

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Alternate Statements of 2nd Law

1. Heat always flows spontaneously from hot to cold; heat never flows from cold to hot without extra energy being supplied.

2. No engine can continuously convert heat completely to work. Any engine that works continuously must give off some waste heat.

As we will see, both of these statements follow from our statement of the 2nd Law:

$$\Delta S_{\text{universe}} \geq 0$$

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Net Entropy Change in Heat Flow

- 300 J of heat flows from large metal block at $T_H = 300\text{K}$ to another large block at $T_C = 100\text{K}$. What is the net change in entropy (change in entropy of universe)?
- Hot block, $\Delta S_H = Q/T_H = -300\text{J}/300\text{K} = -1 \text{ J/K}$
- Cold block, $\Delta S_C = Q/T_C = +300\text{J}/100\text{K} = +3 \text{ J/K}$
- Total (net) change in S: $\Delta S_{\text{Tot}} = \Delta S_H + \Delta S_C = +2 \text{ J/K}$
- $\Delta S_{\text{Tot}} \geq 0$ so 2nd Law of Thermo. satisfied spontaneous flow
- Could same heat flow naturally from cold block to hot? Then $\Delta S_C = -300\text{J}/100\text{K} = -3\text{J/K}$
 $\Delta S_H = +100\text{J}/300\text{K} = 0.33\text{J/K}$
 $\Delta S_{\text{Tot}} = -2.66 \text{ J/K}$. Since $\Delta S_{\text{Tot}} < 0$, not allowed by 2nd Law; can't happen naturally

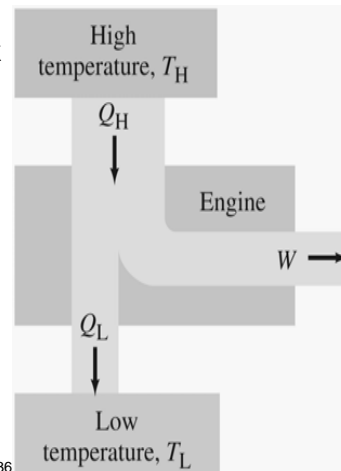
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Heat Engines

It is easy to produce thermal energy using work (friction, dissipation), but how does one produce work using thermal energy?

A heat engine converts some of the heat flowing into it to work.



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Heat Engines

We will discuss only engines that run in a repeating cycle; the change in internal energy over a cycle is zero, as the system returns to its initial state.

The high temperature reservoir transfers an amount of heat Q_H to the engine, where part of it is transformed into work W and the rest, Q_L (or Q_C), is exhausted to the lower temperature reservoir. Note that all three of these quantities are positive.

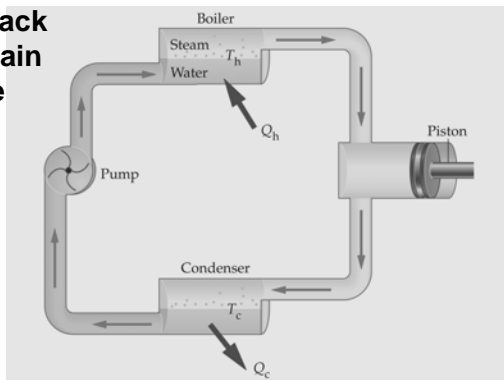
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Heat Engines

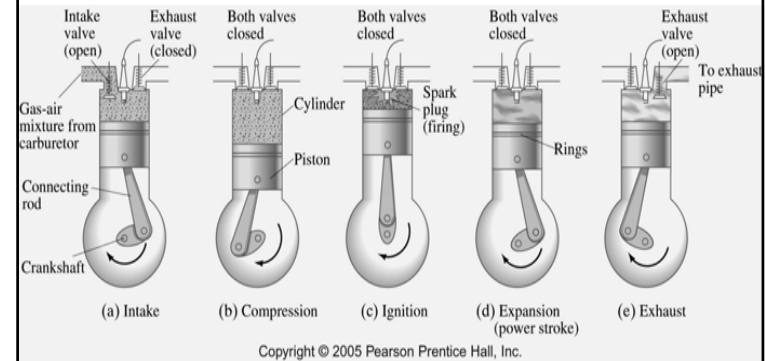
A classic heat engine example is the steam engine. Fuel heats the water; the vapor expands and does work against the piston; the vapor

condenses back into water again and the cycle repeats.



Heat Engines

The internal combustion engine is a type of heat engine as well.

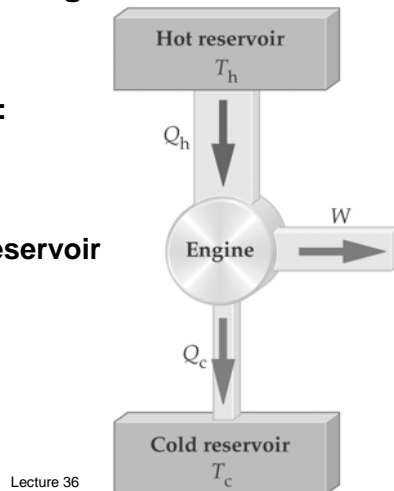


Heat Engines

All heat engines have:

- a high-temperature reservoir at T_H
- a low-temperature reservoir at T_C (or T_L)
- a cyclical engine

These are illustrated schematically here.



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Heat Engines- Efficiency

An amount of heat Q_h is supplied from the hot reservoir to the engine during each cycle. Of that heat, some appears as work, and the rest, Q_c , is given off as waste heat to the cold reservoir. The amount of work is:

$$W = Q_h - Q_c$$

The efficiency is the fraction of the heat supplied to the engine that appears as work.

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

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Heat Engines- Efficiency

The efficiency can also be written:

$$e = \frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} = 1 - \frac{Q_c}{Q_h}$$

SI unit: dimensionless

In order for the engine to run, there must be a temperature difference; otherwise heat will not be transferred. There must always be some waste heat Q_c , and thus efficiency will be limited.

Heat Engines and the Carnot Theorem

The maximum-efficiency heat engine is described in Carnot's theorem:

If an engine operating between two constant-temperature reservoirs is to have maximum efficiency, it must be an engine in which all processes are reversible. In addition, all reversible engines operating between the same two temperatures, T_c and T_h , have the same efficiency.

This is an idealization; no real engine can be perfectly reversible.

Heat Engines

The Carnot engine was created to examine the efficiency of a heat engine. It is idealized, as it has no friction. Each leg of its cycle is reversible.

The Carnot cycle consists of:

- Isothermal expansion of an ideal gas
- Adiabatic expansion
- Isothermal compression
- Adiabatic compression

An ideal Carnot engine would create no entropy. Any such reversible engine has the maximum possible efficiency.

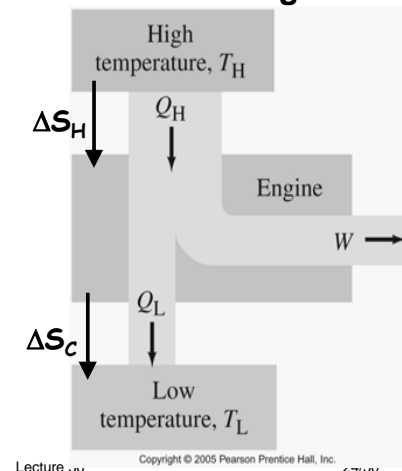
Entropy Balance in Reversible Engine

A reversible engine has an output entropy $\Delta S_c = Q_c/T_c$ equal to the input entropy $\Delta S_H = Q_H/T_H$:

$$\frac{Q_c}{T_c} = \frac{Q_h}{T_h}$$

Rewriting,

$$\frac{Q_c}{Q_h} = \frac{T_c}{T_h}$$



Heat Engines and the Carnot Cycle

The maximum work a heat engine can do for a given heat input Q_H is then:

$$W_{\max} = e_{\max} Q_H = \left(1 - \frac{T_C}{T_H}\right) Q_H$$

To maximize efficiency, make T_H as high as possible (high combustion temperature) and T_C as small as possible (good engine cooling).

Example: Power plant runs at $T_H = 600\text{K}$. What is maximum efficiency if T_C is air temp. (300K)?

$$e_{\max} = 1 - (300\text{K}/600\text{K}) = 0.5$$

Efficiency of Reversible Engines

Since the engine efficiency is given by:

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

SI unit: dimensionless

and $Q_C/Q_H = T_C/T_H$, we have

Maximum Efficiency of a Heat Engine

$$e_{\max} = 1 - \frac{T_C}{T_H}$$

Temperatures in Kelvin!

"Thermal Pollution"

- How much heat does this power plant put into environment for each Joule of work (electrical power) produced?

• Since the efficiency is 0.5, 2J of heat must come in for every 1J of work produced. The second 1J of input energy is rejected as waste heat.

Efficiency and ΔS of Real Engines

A real engine will operate at a lower efficiency than a reversible engine; this means that less heat is converted to work. Therefore.

$$\Delta S_{\text{total}} = -\frac{Q_H}{T_H} + \frac{Q_C}{T_C} > 0$$

$$e_{\text{real}} < e_{\max}$$

Any irreversible process and any friction result in lower efficiency and in an increase in the entropy of the universe.

Note that a complete conversion of heat to work would destroy entropy and violate 2nd Law.

End of Lecture 36

- For Monday, Dec. 14, read Walker 18.7.
- Homework Assignment 18a is due at 11:00 PM on Monday, Dec. 14.
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