

PHYS11 CH:12 The Universe's Accounting System

How Energy Becomes Unavailable

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Outline

- 1 Introduction
- 2 12.1 Zeroth Law: Thermal Equilibrium
- 3 12.2 First Law: Energy Conservation
- 4 12.3 Second Law: Entropy
- 5 12.4 Heat Engines
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The Mystery of the Perfect Engine

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Nature says: Impossible.

Energy Transforms



Figure: Steam engine: burning fuel transfers heat to do work

Energy Transforms



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The challenge: Most thermal energy escapes as waste heat.

Learning Objectives

By the end of this section, you will be able to:

- **12.1:** Explain the zeroth law of thermodynamics

12.1 When Things Stop Changing

The Mental Model

Place ice in warm water. What happens?

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Nature's Rule

They are now in **thermal equilibrium**.

12.1 The Zeroth Law

Universal Law: The Transitive Property

If system A is in thermal equilibrium with system B,
and B is in thermal equilibrium with system C,
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Why "zeroth"? Discovered after first and second laws, but more fundamental.

12.1 Real-World: Neonatal Incubators



Figure: Premature baby in incubator

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Figure: Premature baby in incubator

Zeroth law in action:

Air, incubator walls, and baby all reach thermal equilibrium at safe temperature.

12.1 Why Not Earth and Sun?

Question for Discussion

Sun transfers heat to Earth. Why don't they reach thermal equilibrium?

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Answer: Empty space separates them.

Thermal equilibrium requires **thermal contact** - ability to freely exchange energy.

Fortunately! Otherwise Earth would be as hot as sun's surface (~ 5800 K).

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- **12.2:** Describe how pressure, volume, temperature relate using ideal gas law
- **12.2:** Describe pressure-volume work
- **12.2:** State first law verbally and mathematically
- **12.2:** Solve first law problems

12.2 Pressure: Force over Area

Definition: Pressure

$$P = \frac{F}{A}$$

Pressure is force per unit area perpendicular to surface.

12.2 Pressure: Force over Area

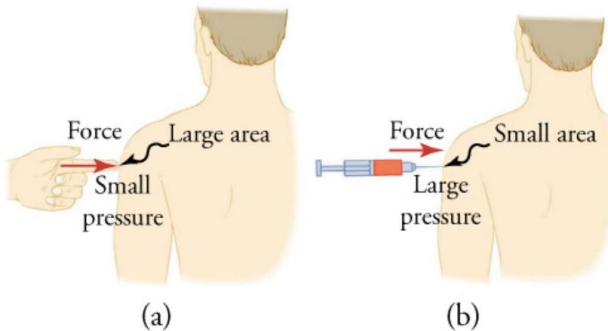
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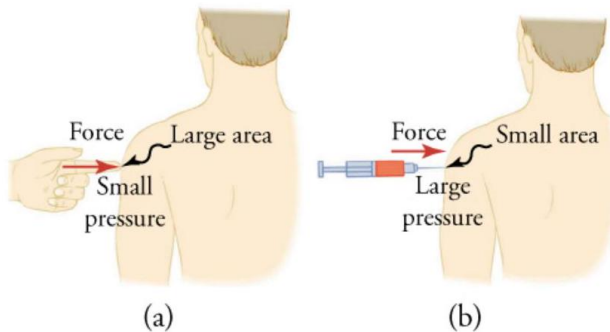
Pressure is force per unit area perpendicular to surface.

SI unit: Pascal (Pa), where $1 \text{ Pa} = 1 \text{ N/m}^2$

12.2 Same Force, Different Pressure



12.2 Same Force, Different Pressure



Civilian View vs. Reality

Civilian: "The needle pushes harder."

Physicist: "Same force, smaller area = higher pressure."

12.2 The Ideal Gas Law

Universal Law: Gas Behavior

$$PV = NkT$$

Pressure times volume equals particles times Boltzmann constant times absolute temperature.

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Pressure times volume equals particles times Boltzmann constant times absolute temperature.

Where:

- P = pressure (Pa)
- V = volume (m^3)
- N = number of particles
- $k = 1.38 \times 10^{-23}$ J/K (Boltzmann constant)
- T = absolute temperature (K)

12.2 Gas Law Relationships

For fixed amount of gas:

- **Constant volume:** $P \propto T$ (pressure rises with temperature)

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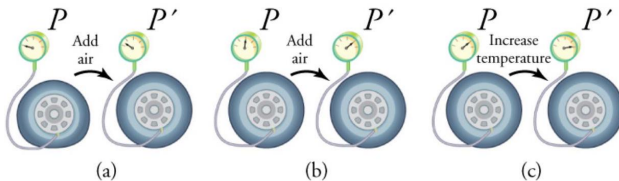
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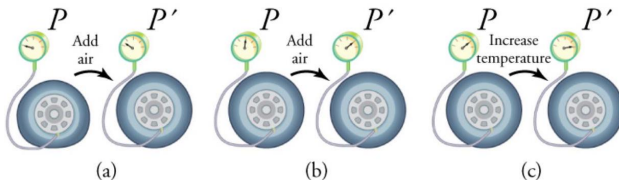
The Mental Model

Pumping tire: volume increases, then pressure builds, tire warms up.

12.2 Pumping a Tire



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(a) Volume increases. (b) Pressure increases. (c) Temperature increases.

12.2 Pressure-Volume Work



Figure: Gas expansion does work pushing piston

12.2 Pressure-Volume Work



Figure: Gas expansion does work pushing piston

Nature's Rule for Gases

$$W = P\Delta V$$

Work equals pressure times change in volume.

12.2 The First Law of Thermodynamics

Universal Law: Energy Conservation

$$\Delta U = Q - W$$

Change in internal energy equals heat added minus work done by system.

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Where:

- ΔU = change in internal energy
- Q = net heat into system (positive if in, negative if out)
- W = net work by system (positive if out, negative if in)

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Where:

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- W = net work by system (positive if out, negative if in)

This is conservation of energy for thermal systems.

12.2 Understanding the Signs

Heat Q :

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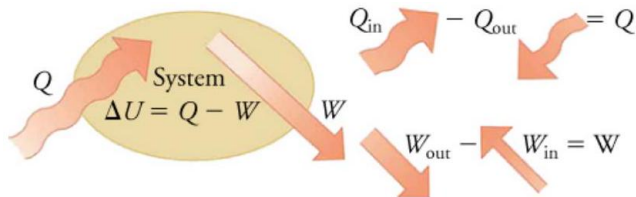
Work W :

- Positive: done BY system (removes energy)
- Negative: done ON system (adds energy)

Key Insight

Positive Q adds energy. Positive W removes energy.

12.2 Energy Flow Diagram



Q in adds energy. W out removes energy. ΔU is net change.

Attempt: Energy Accounting

The Challenge (3 min, silent)

System absorbs 40.0 J of heat, does 10.0 J of work.
Later, 25.0 J heat leaves, 4.0 J work done ON system.

Find: Net change in internal energy ΔU

Can you track energy? Work silently.

Compare: Energy Tracking

Turn and talk (2 min):

- 1 What was net heat Q ? How calculate?
- 2 What was net work W ? Signs correct?
- 3 Did you use $\Delta U = Q - W$?

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Reveal: Energy Conservation

Self-correct in different color:

Step 1 - Net heat:

$$Q = 40.0 \text{ J} - 25.0 \text{ J} = 15.0 \text{ J}$$

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$$\Delta U = 9.0 \text{ J}$$

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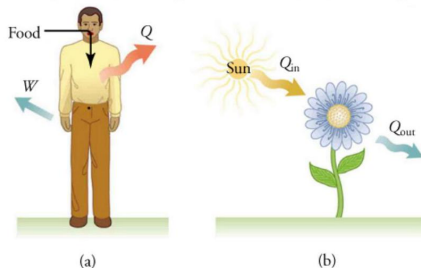
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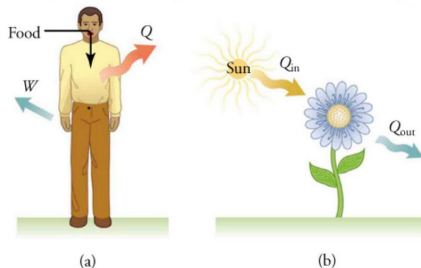
$$\Delta U = 9.0 \text{ J}$$

Check: More heat in than work out \rightarrow internal energy increases.

12.2 Biology: Your Body as Heat Engine

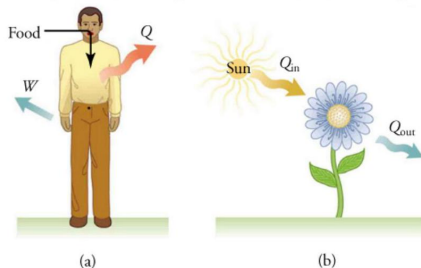


12.2 Biology: Your Body as Heat Engine



$$\Delta U = Q - W + \text{food energy}$$

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$$\Delta U = Q - W + \text{food energy}$$

- Food adds chemical potential energy
- Work (exercise) removes energy
- Heat (body temp) removes energy
- Leftover stored as fat

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By the end of this section, you will be able to:

- **12.3:** Describe entropy

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- **12.3:** Solve entropy problems

12.3 The Arrow of Time

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Nature has preferred direction.

12.3 Entropy: Measure of Disorder

Definition: Entropy

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Change in entropy equals heat transfer divided by absolute temperature.

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What entropy measures:

- Disorder in system
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SI unit: J/K (joules per kelvin)

12.3 Ice Melting: Entropy Increases

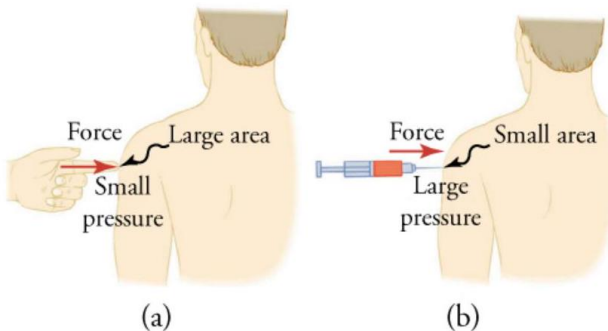


Figure: Ice melts: ordered crystal becomes disordered liquid

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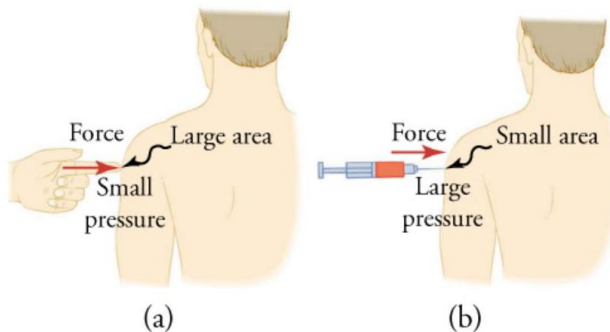


Figure: Ice melts: ordered crystal becomes disordered liquid

Entropy increases because:

- Structured ice \rightarrow random liquid
- System becomes more disordered

12.3 The Second Law

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For any spontaneous process, total entropy of universe either increases or remains constant. Never decreases.

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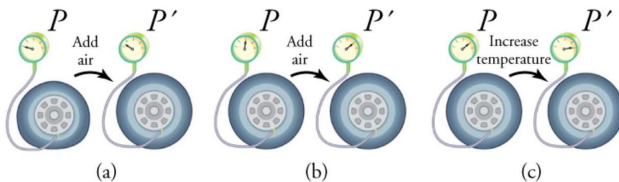
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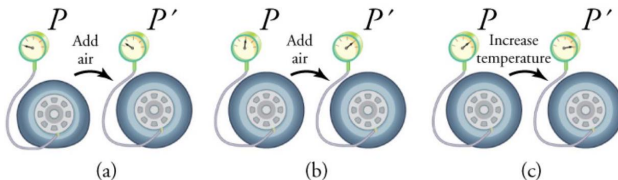
Key Consequences

- Heat flows spontaneously hot to cold, never cold to hot
- Energy becomes less available over time
- Disorder increases

12.3 Heat Flow and Entropy



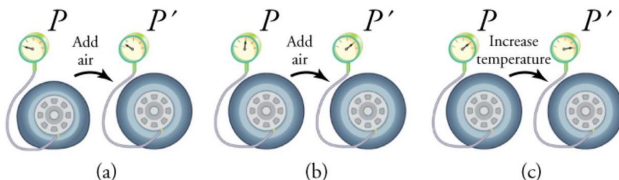
12.3 Heat Flow and Entropy



Why heat flows hot to cold:

Larger entropy increase at low T than decrease at high T .

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$$\Delta S = \frac{Q}{T} \rightarrow \text{smaller } T \text{ means larger } \Delta S$$

12.3 Can Entropy Decrease?

Yes, locally! But total entropy of universe must increase.

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Local Entropy Decrease Examples

- Clean room (you do work)
- Build bridge from ore (energy input)
- Plant grows (uses solar energy)
- Freezer makes ice (work input)

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- Build bridge from ore (energy input)
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In all cases, environment entropy increases **MORE** than system entropy decreases.

Attempt: Ice Melting Entropy

The Challenge (3 min, silent)

Find entropy increase when 1.00 kg ice at 0°C melts to water at 0°C .

Given:

- Mass: $m = 1.00 \text{ kg}$
- Temperature: $T = 0^{\circ}\text{C} = 273 \text{ K}$
- Latent heat fusion: $L_f = 334 \text{ kJ/kg}$

Find: ΔS

Can you quantify disorder? Work silently.

Compare: Entropy Calculation

Turn and talk (2 min):

- 1 Formula for heat Q ?
- 2 Convert to Kelvin?
- 3 Equation connecting Q and ΔS ?

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Name wheel: One pair share approach (not answer).

Reveal: Entropy of Melting

Self-correct in different color:

Step 1 - Heat to melt:

$$Q = mL_f = (1.00)(334 \text{ kJ/kg}) = 3.34 \times 10^5 \text{ J}$$

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Step 3 - Entropy:

$$\Delta S = \frac{Q}{T} = \frac{3.34 \times 10^5}{273}$$

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$$\Delta S = 1.22 \times 10^3 \text{ J/K}$$

Check: Positive - disorder increased as ice melted.

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By the end of this section, you will be able to:

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12.4 What Is Heat Engine?

Definition: Heat Engine

Machine that converts thermal energy into mechanical work using heat transfer.

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Examples:

- Car engines (gasoline, diesel)
- Jet engines
- Steam turbines
- Your body

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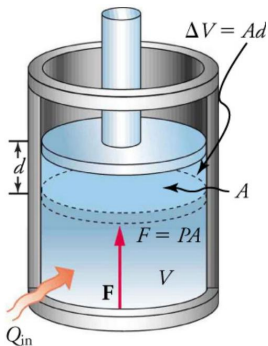
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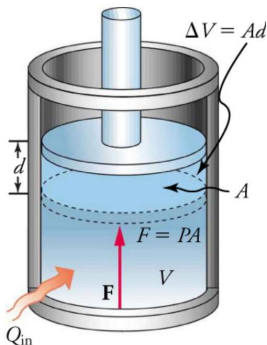
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All use cyclical processes.

12.4 How Heat Engines Work

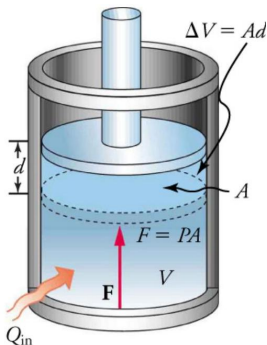


12.4 How Heat Engines Work



- 1 Absorb heat Q_h from hot reservoir
- 2 Do work W
- 3 Reject waste heat Q_c to cold reservoir

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$$W = Q_h - Q_c$$

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Efficiency equals useful work divided by energy input.

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Typical efficiencies:

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- Diesel engine: 35-40%
- Coal plant: 40-45%
- Human body: 25%

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100% impossible! (Second law forbids)

12.4 Why Engines Cannot Be Perfect

Perfect efficiency requires: $Q_c = 0$ (no waste heat)

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But second law says:

- Entropy must increase
- Heat **MUST** flow to cold reservoir
- Some energy **MUST** become unavailable

12.4 Why Engines Cannot Be Perfect

Perfect efficiency requires: $Q_c = 0$ (no waste heat)

But second law says:

- Entropy must increase
- Heat **MUST** flow to cold reservoir
- Some energy **MUST** become unavailable

Fundamental Limit

Second law sets absolute ceiling on efficiency.

Attempt: Power Plant Efficiency

The Challenge (3 min, silent)

Coal plant absorbs 2.50×10^{14} J, releases 1.48×10^{14} J as waste in one day.

Find:

- 1 Work output W
- 2 Efficiency

Can you measure wastefulness? Work silently.

Compare: Efficiency Analysis

Turn and talk (2 min):

- 1 How find work W ?
- 2 Which formula for efficiency?
- 3 Is 40% good or bad?

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Reveal: Power Plant Analysis

Self-correct in different color:

(a) Work output:

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(a) Work output:

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$$W = 1.02 \times 10^{14} \text{ J}$$

(b) Efficiency:

$$\text{Eff} = \frac{W}{Q_h} = \frac{1.02 \times 10^{14}}{2.50 \times 10^{14}}$$

Reveal: Power Plant Analysis

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$$W = Q_h - Q_c = 2.50 \times 10^{14} - 1.48 \times 10^{14}$$

$$W = 1.02 \times 10^{14} \text{ J}$$

(b) Efficiency:

$$\text{Eff} = \frac{W}{Q_h} = \frac{1.02 \times 10^{14}}{2.50 \times 10^{14}}$$

$$\text{Eff} = 0.408 = 40.8\%$$

Reveal: Power Plant Analysis

Self-correct in different color:

(a) Work output:

$$W = Q_h - Q_c = 2.50 \times 10^{14} - 1.48 \times 10^{14}$$

$$W = 1.02 \times 10^{14} \text{ J}$$

(b) Efficiency:

$$\text{Eff} = \frac{W}{Q_h} = \frac{1.02 \times 10^{14}}{2.50 \times 10^{14}}$$

$$\text{Eff} = 0.408 = 40.8\%$$

Check: Typical for coal. 59.2% wasted!

12.4 Heat Pumps and Refrigerators



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Heat engines in reverse:

- Use work to move heat cold to hot
- Refrigerators cool interior, warm exterior
- Heat pumps warm house using outside air

What You Now Know

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Universe's Accounting System

Energy conserved, but becomes less useful over time.

Key Equations

$$P = \frac{F}{A} \quad (\text{Pressure}) \quad (1)$$

$$PV = NkT \quad (\text{Ideal gas}) \quad (2)$$

$$W = P\Delta V \quad (\text{P-V work}) \quad (3)$$

$$\Delta U = Q - W \quad (\text{First law}) \quad (4)$$

$$\Delta S = \frac{Q}{T} \quad (\text{Entropy}) \quad (5)$$

$$\text{Eff} = \frac{W}{Q_h} \quad (\text{Efficiency}) \quad (6)$$

You now understand why time moves forward.

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Entropy increases:

- Ice melts, doesn't spontaneously freeze
- Gas expands, doesn't spontaneously compress
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Second law gives time its direction.

Complete assigned problems
posted on LMS