PHYS11 CH:12 The Universe's Accounting System

How Energy Becomes Unavailable

Mr. Gullo

December 2025

Outline

The Mystery of the Perfect Engine

What if you could build an engine
that converts all heat into work?

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Nature says: Impossible.

Energy Transforms

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

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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

The Mental Model

Place ice in warm water. What happens?

12.1 When Things Stop Changing

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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,
then A is also in thermal equilibrium with C.

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Why "zeroth"? Discovered after first and second laws, but more fundamental.

12.1 Real-World: Neonatal Incubators

Figure: Engineer monitoring thermal systems

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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

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

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

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- **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

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Pressure is force per unit area perpendicular to surface.

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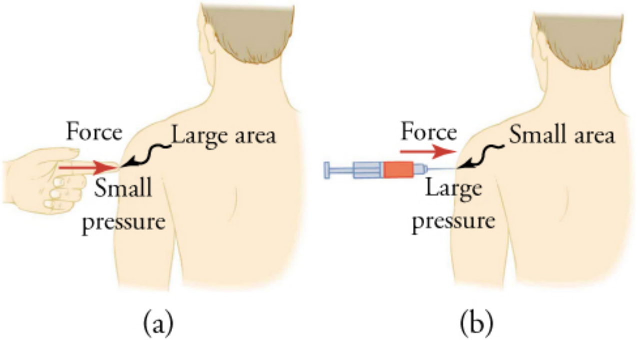
SI unit: Pascal (Pa), where 1 Pa $=$ 1 N/m^2

12.2 Same Force, Different Pressure



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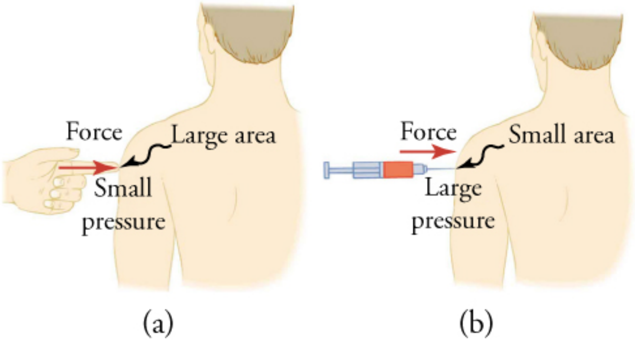

Civilian View vs. Reality

Civilian: "The needle pushes harder."
Physicist: "Same force, smaller area = higher pressure."

12.2 The Ideal Gas Law

Universal Law: Gas Behavior

$$\boxed{PV = NkT}$$

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

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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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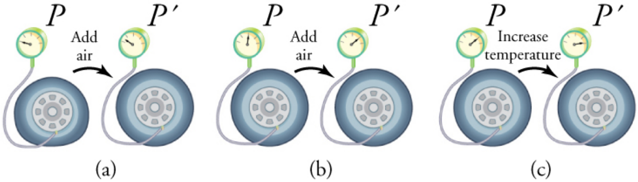
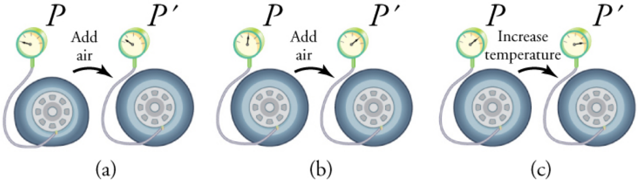
The Mental Model

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

12.2 Pumping a Tire





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

12.2 Pressure-Volume Work

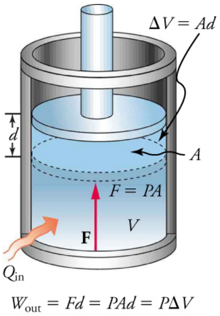


Figure: Gas expansion does work pushing piston

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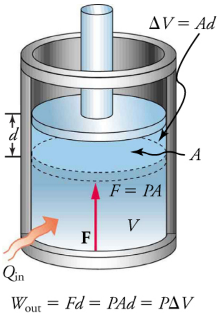

Figure: Gas expansion does work pushing piston

Nature's Rule for Gases

$$\boxed{W = P\Delta V}$$

Work equals pressure times change in volume.

12.2 The First Law of Thermodynamics

Universal Law: Energy Conservation

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

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This is conservation of energy for thermal systems.

Heat Q:

- Positive: flows IN (adds energy)
- Negative: flows OUT (removes energy)

12.2 Understanding the Signs

Heat Q:

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- Negative: flows OUT (removes energy)

Work W:

- Positive: done BY system (removes energy)
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12.2 Understanding the Signs

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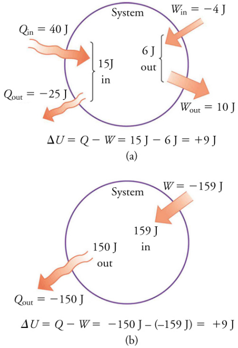
Key Insight

Positive Q adds energy. Positive W removes energy.



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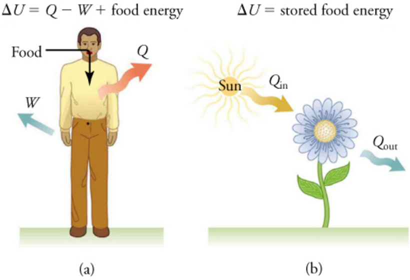
Check: More heat in than work out → internal energy increases.

12.2 Biology: Your Body as Heat Engine



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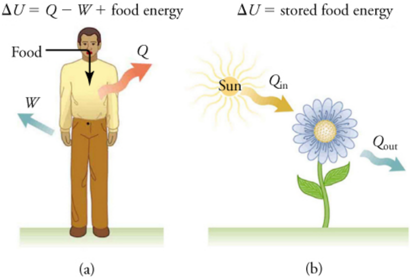

$$\Delta U = Q - W + \text{food energy}$$

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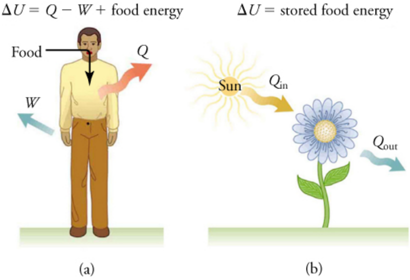

$$\Delta U = Q - W + \text{food energy}$$

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

Learning Objectives

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

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- **12.3:** Solve entropy problems

Why does time only move forward?

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12.3 The Arrow of Time

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Nature has preferred direction.

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Definition: Entropy

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SI unit: J/K (joules per kelvin)

12.3 Ice Melting: Entropy Increases

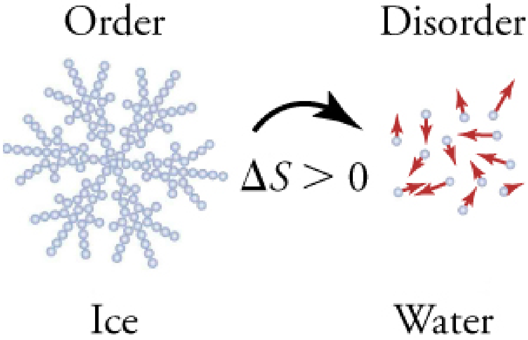

Figure: Ice melts: ordered crystal becomes disordered liquid

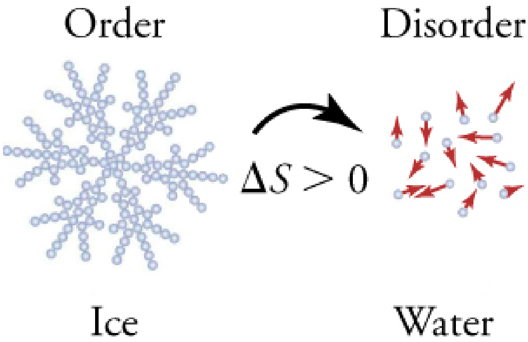

Figure: Ice melts: ordered crystal becomes disordered liquid

Entropy increases because:

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

Universal Law: Entropy Always Increases

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

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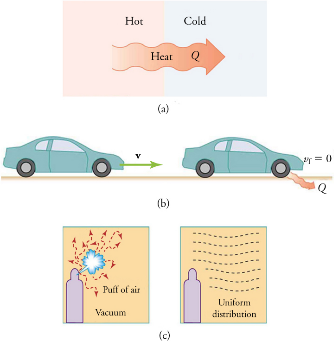
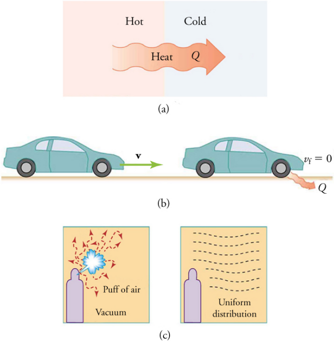
Key Consequences

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

12.3 Heat Flow and Entropy





Why heat flows hot to cold:

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

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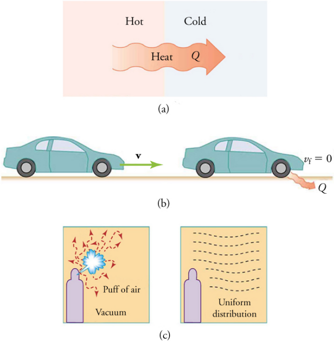

Why heat flows hot to cold:
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$$\Delta S = \frac{Q}{T} \rightarrow \text{smaller } T \text{ means larger } \Delta S$$

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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Local Entropy Decrease Examples

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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: $m = 1.00$ kg
- Temperature: $T = 0^\circ\text{C} = 273$ K
- Latent heat fusion: $L_f = 334$ 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?
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Self-correct in different color:

Step 1 - Heat to melt:

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

Reveal: Entropy of Melting

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Step 3 - Entropy:

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

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

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Check: Positive - disorder increased as ice melted.

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- **12.4:** Explain how heat engines work

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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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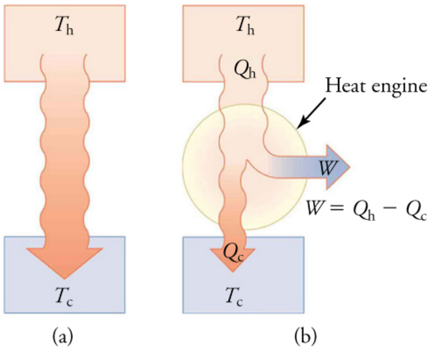
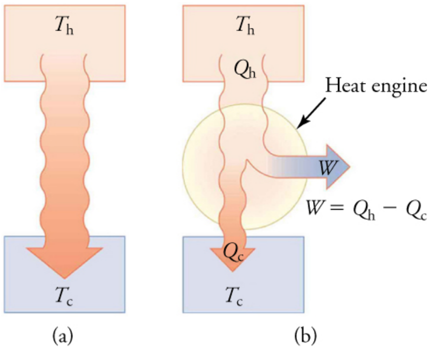
All use cyclical processes.

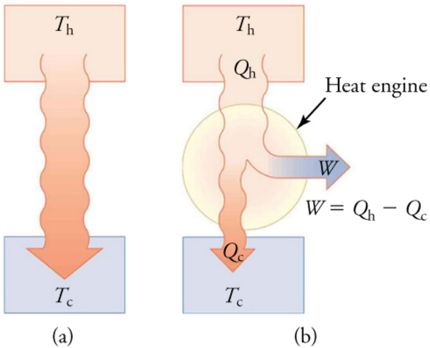
12.4 How Heat Engines Work



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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- Diesel engine: 35-40%
- Coal plant: 40-45%
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100% impossible! (Second law forbids)

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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
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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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Self-correct in different color:

(a) Work output:

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Self-correct in different color:

(a) Work output:

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

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

Reveal: Power Plant Analysis

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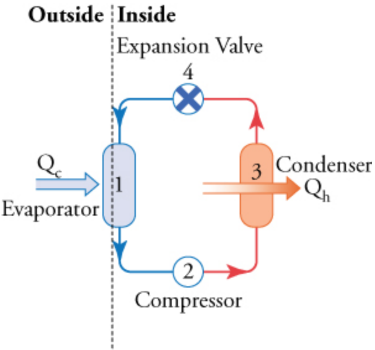
Check: Typical for coal. 59.2% wasted!

12.4 Heat Pumps and Refrigerators



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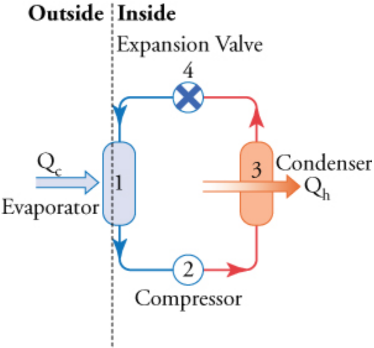

Heat engines in reverse:

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

What You Now Know

Four Laws of Thermodynamics

1. **Zeroth:** Temperature equilibrium transitive

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3. **Second:** Entropy always increases
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Universe's Accounting System

Energy conserved, but becomes less useful over time.

Key Equations

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

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

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

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

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

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

Arrow of Time

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
- Engines waste heat - cannot recover
- We age - time cannot run backward

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Second law gives time its direction.

Homework

Complete assigned problems

posted on LMS