

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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Engineers have been trying for 300 years...

Nature says: Impossible.

Energy Transforms



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

Energy Transforms



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

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: 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 (~ 5800 K).

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- **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

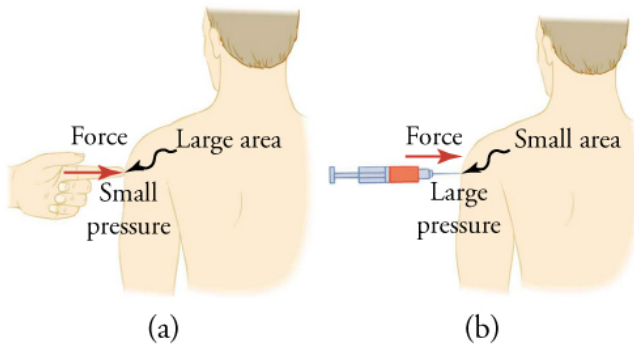
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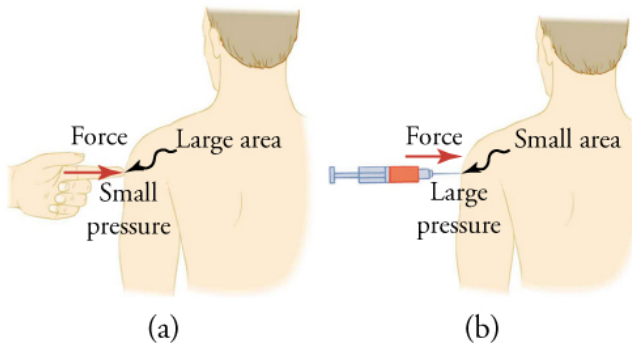
Pressure is **force** per unit **area** perpendicular to surface.

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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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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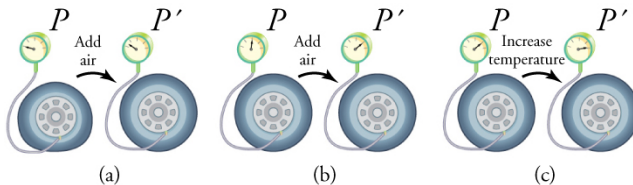
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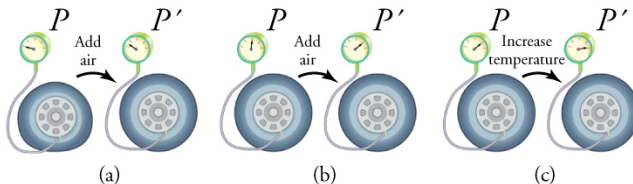
The Mental Model

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

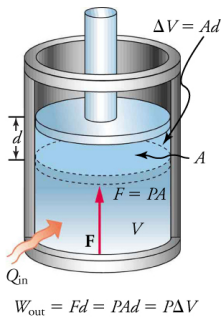


Figure: Gas expansion does work pushing piston

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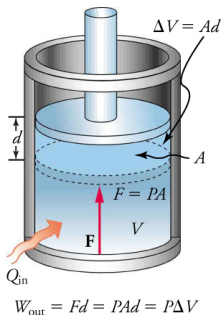


Figure: Gas expansion does work pushing piston

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:

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- 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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This is conservation of energy for thermal systems.

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Heat Q :

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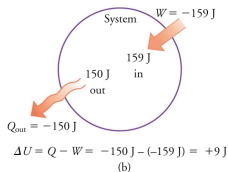
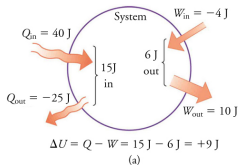
Work W :

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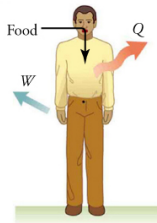
$$\Delta U = 9.0 \text{ J}$$

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

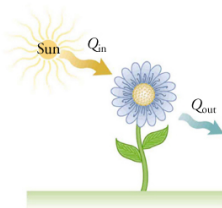
12.2 Biology: Your Body as Heat Engine

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

$$\Delta U = \text{stored food energy}$$



(a)

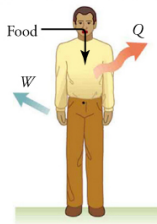


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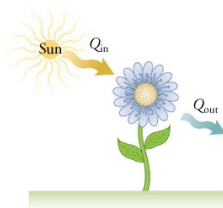
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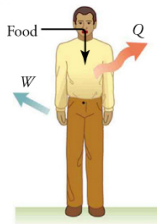
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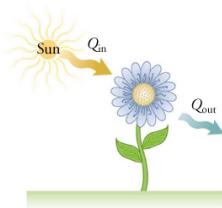
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$$\Delta U = Q - W + \text{food energy}$$

- 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:

- **12.3:** Describe entropy

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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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SI unit: J/K (joules per kelvin)

12.3 Ice Melting: Entropy Increases

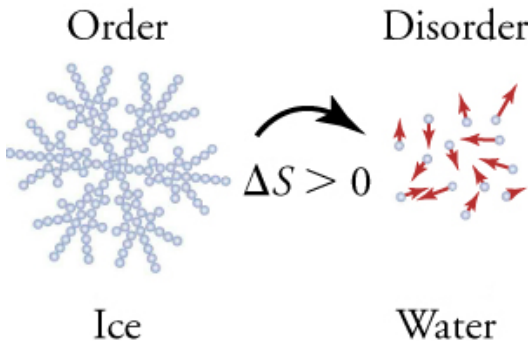


Figure: Ice melts: ordered crystal becomes disordered liquid

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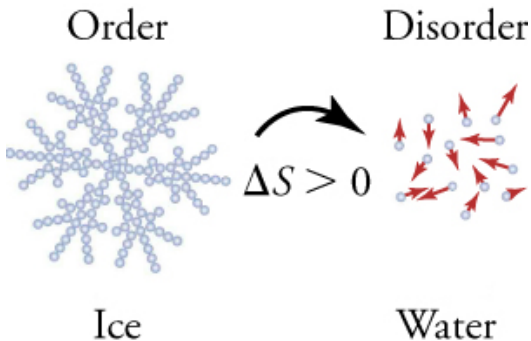


Figure: Ice melts: ordered crystal becomes disordered liquid

Entropy increases because:

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

12.3 The Second Law

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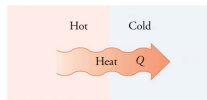
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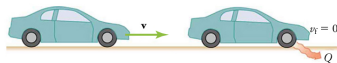
Key Consequences

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

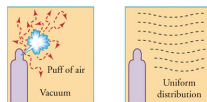
12.3 Heat Flow and Entropy



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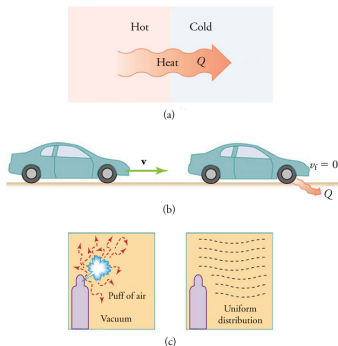


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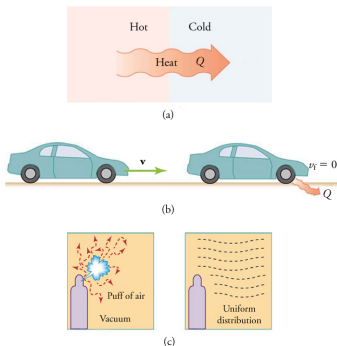
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$$\Delta S = \frac{Q}{T} \rightarrow \text{smaller } T \text{ means larger } \Delta S$$

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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: $m = 1.00 \text{ kg}$
- 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):

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- 2 Convert to Kelvin?
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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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Check: Positive - disorder increased as ice melted.

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

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

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Definition: Heat Engine

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

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Examples:

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- Jet engines
- Steam turbines
- Your body

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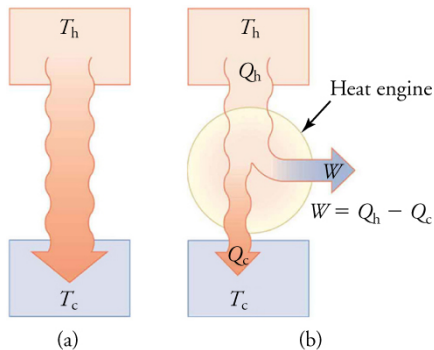
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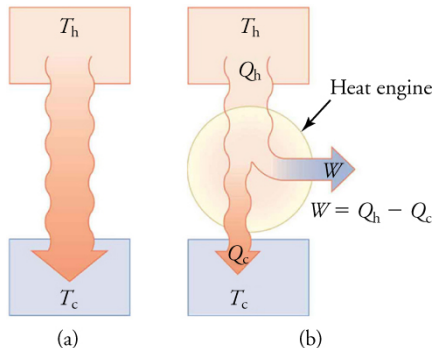
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All use cyclical processes.

12.4 How Heat Engines Work

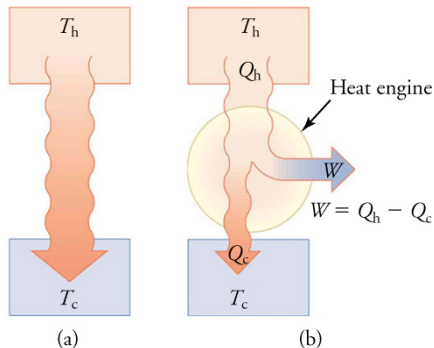


12.4 How Heat Engines Work



- 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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Typical efficiencies:

- Gasoline car: 25-30%
- Diesel engine: 35-40%
- Coal plant: 40-45%
- Human body: 25%

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- Gasoline car: 25-30%
- Diesel engine: 35-40%
- Coal plant: 40-45%
- Human body: 25%

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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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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Turn and talk (2 min):

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

Reveal: Power Plant Analysis

Self-correct in different color:

(a) **Work** output:

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

Reveal: Power Plant Analysis

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Reveal: Power Plant Analysis

Self-correct in different color:

(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

Self-correct in different color:

(a) **Work** output:

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

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(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:

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

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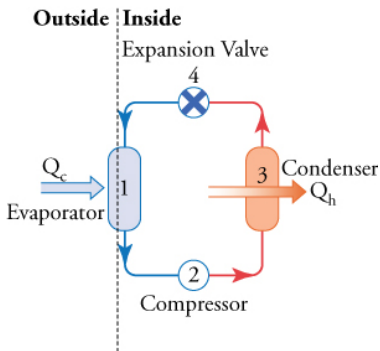
(b) **Efficiency:**

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

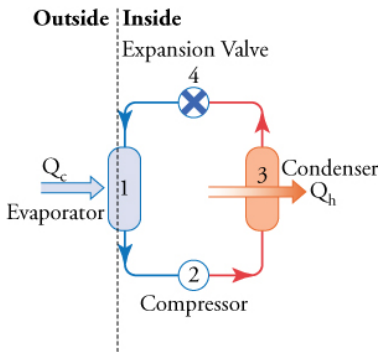
$$\text{Eff} = 0.408 = 40.8\%$$

Check: Typical for coal. 59.2% wasted!

12.4 Heat Pumps and Refrigerators



12.4 Heat Pumps and Refrigerators



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

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Four Laws of Thermodynamics

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- 2 **First:** Energy conserved: $\Delta U = Q - W$
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- 4 **Third:** (Not covered) Absolute zero unreachable

What You Now Know

Four Laws of Thermodynamics

- ① **Zeroth:** **Temperature** equilibrium transitive
- ② **First:** Energy conserved: $\Delta U = Q - W$
- ③ **Second:** **Entropy** always increases
- ④ **Third:** (Not covered) Absolute zero unreachable

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

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Second law gives time its direction.

Complete assigned problems
posted on LMS

Temporary page!

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