

SCIENCE OLYMPIAD • 2027 SEASON • DIVISION B / C

Thermodynamics

Written Test Study Notes

Content expectations from Rule 5.c(i–vii): thermodynamic systems, phases and the ideal gas law, heat transfer, processes and the laws of thermodynamics, the history of the field, blackbody radiation, and (Division C) entropy and enthalpy.

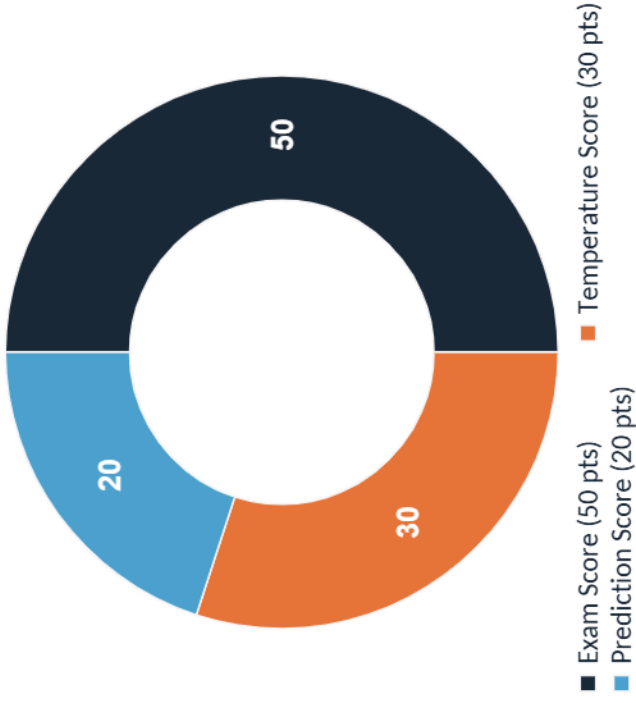
Compiled for the written-test portion (Part I) of the event.

Event Overview

Rule 1-2: Description & Event Parameters

- **Team size** Up to 2 competitors
- **Time** Approximately 50 minutes
- **Format** Part I: written test on thermodynamic concepts. Part II: device heats water under a lamp.
- **Notes & calculators** Any printed notes/binder, plus 2 Class III calculators, are allowed.
- **Impound** Device and spare parts only (must be at room temperature).

Final Score Composition



$$FS = ES + TS + PS \quad (\text{max } 100 \text{ pts})$$

Quick reference: TS = Temperature Score, PS = Prediction Score, ES = Exam Score.

The Seven Content Areas — Rule 5.c

The written test includes at least three questions from each area below.

i

Systems, properties, temperature & the zeroth law

ii

Phases of matter, phase diagrams, latent/sensible heat, ideal gas law

iii

Heat transfer, thermal conductivity, heat capacity, specific heat

iv

Processes, thermodynamic cycles, engines, efficiency, 1st & 2nd laws

v

History: Black, Carnot, Joule, Kelvin, Clausius, Maxwell, Boltzmann, Planck

vi

State/Nationals only: blackbody radiation, Stefan-Boltzmann, 3rd law

vii

Division C only: entropy and enthalpy

Thermodynamic Systems

- A system is the part of the universe under study; everything else is the surroundings.
- The boundary between them may allow matter, energy, both, or neither to pass.
- Open system: exchanges both matter and energy (e.g., a boiling, uncovered pot).
- Closed system: exchanges energy only, not matter (e.g., a sealed, conducting can).
- Isolated system: exchanges neither — an idealization (e.g., a perfect thermos).





Intensive vs. Extensive Properties

- Every measurable property of a system is either intensive or extensive.
- Intensive properties do not depend on the size or amount of the system — temperature, pressure, and density are the classic examples.
- Extensive properties scale directly with the amount of matter present — mass, volume, and total internal energy are extensive.
- Test for either: split the sample in half. Intensive values stay the same; extensive values are halved.
- Ratio of two extensive properties is intensive — e.g., density = mass / volume.

INTENSIVE

does NOT depend on amount

Temperature
Pressure
Density

cut a sample in half → T, P, ρ unchanged



EXTENSIVE

scales with amount

Mass
Volume
Total energy

cut a sample in half → m, V, U are halved



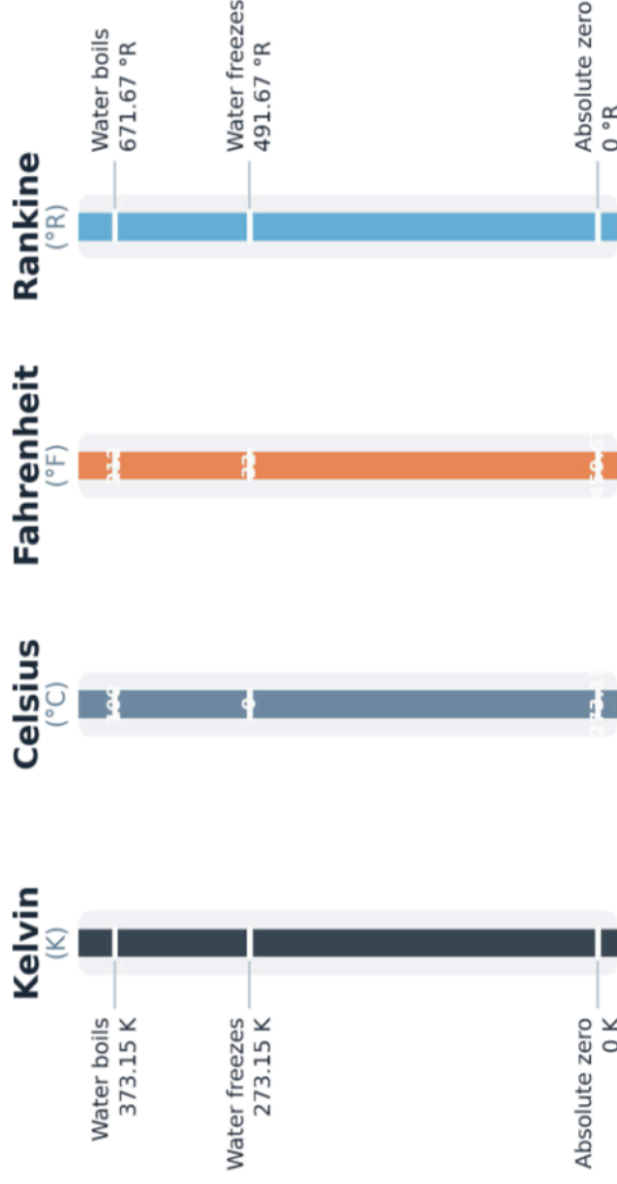


Temperature Scales & the Zeroth Law

Zeroth Law of Thermodynamics

If system A is in thermal equilibrium with system C, and system B is also in thermal equilibrium with system C, then A and B are in thermal equilibrium with each other. This is what allows a thermometer to give a meaningful reading.

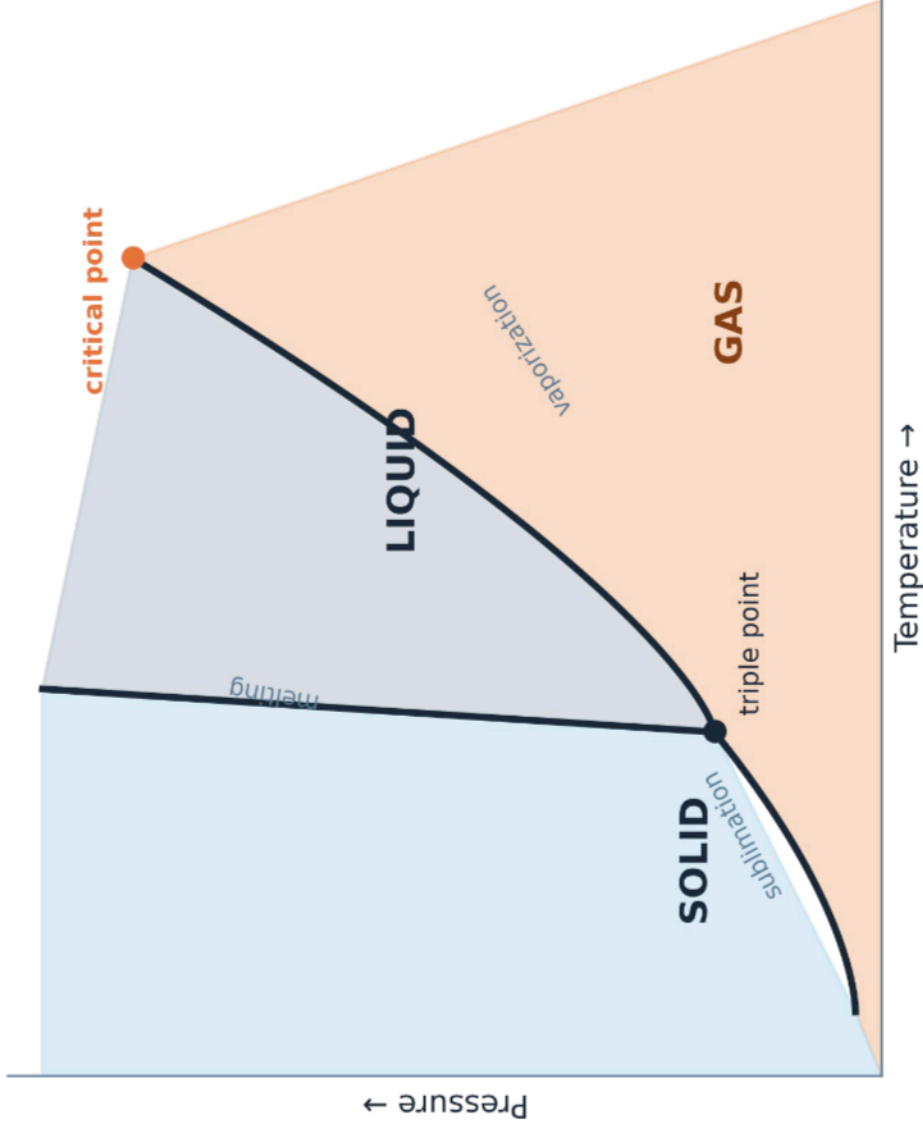
- Temperature is a measure of the average kinetic energy of a substance's particles.
- Heat-related SI unit: the joule (J); other common units include the calorie (cal) and the BTU.
- 1 cal = 4.184 J. 1 BTU = 1055 J (raises 1 lb of water 1 °F).



$$\begin{aligned} \text{K} &= \text{°C} + 273.15 & \text{°F} &= \text{°C} \times \frac{9}{5} + 32 & \text{°R} &= \text{°F} + 459.67 = \text{K} \times \frac{9}{5} \\ \text{same-size degree: } 1 \text{ K change} &= 1 \text{ °C change} & | & 1 \text{ °R change} &= 1 \text{ °F change} \end{aligned}$$

Phase Diagrams & Phase Transitions

- A phase diagram maps which phase (solid, liquid, gas) is stable at each pressure and temperature.
- Triple point: the unique P–T condition where all three phases coexist in equilibrium.
- Critical point: beyond this P and T, liquid and gas become indistinguishable (a supercritical fluid).
- Melting/freezing, vaporization/condensation, and sublimation/deposition are the phase-transition pairs.



Latent & Sensible Heat · Ideal Gas Law

SENSIBLE HEAT

$$Q = m c \Delta T$$

Heat that changes temperature without changing phase. c is specific heat ($\text{J}/(\text{kg}\cdot\text{K})$)
— an intensive property of the material.

LATENT HEAT

$$Q = m L$$

Heat absorbed or released during a phase change at constant temperature. L is the latent heat of fusion or vaporization.

IDEAL GAS LAW

$$PV = nRT$$

P Pressure (Pa)

V Volume (m^3)

n Amount of gas (mol)

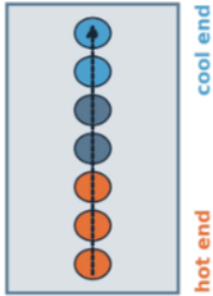
R Gas constant, $8.314 \text{ J}/(\text{mol}\cdot\text{K})$

T Absolute temperature (K)

Combined gas law: $P_1 V_1 / T_1 = P_2 V_2 / T_2$ (fixed n)

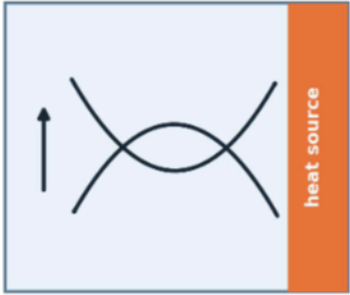
Kinds of Heat Transfer

CONDUCTION



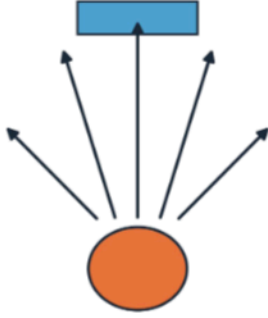
direct contact,
vibrating particles

CONVECTION



fluid currents
carry heat

RADIATION



electromagnetic
waves — no medium

Thermal conductivity (k)

How readily a material conducts heat, $W/(m \cdot K)$. Metals: high k .
Insulators/air: low k .

Heat capacity (C)

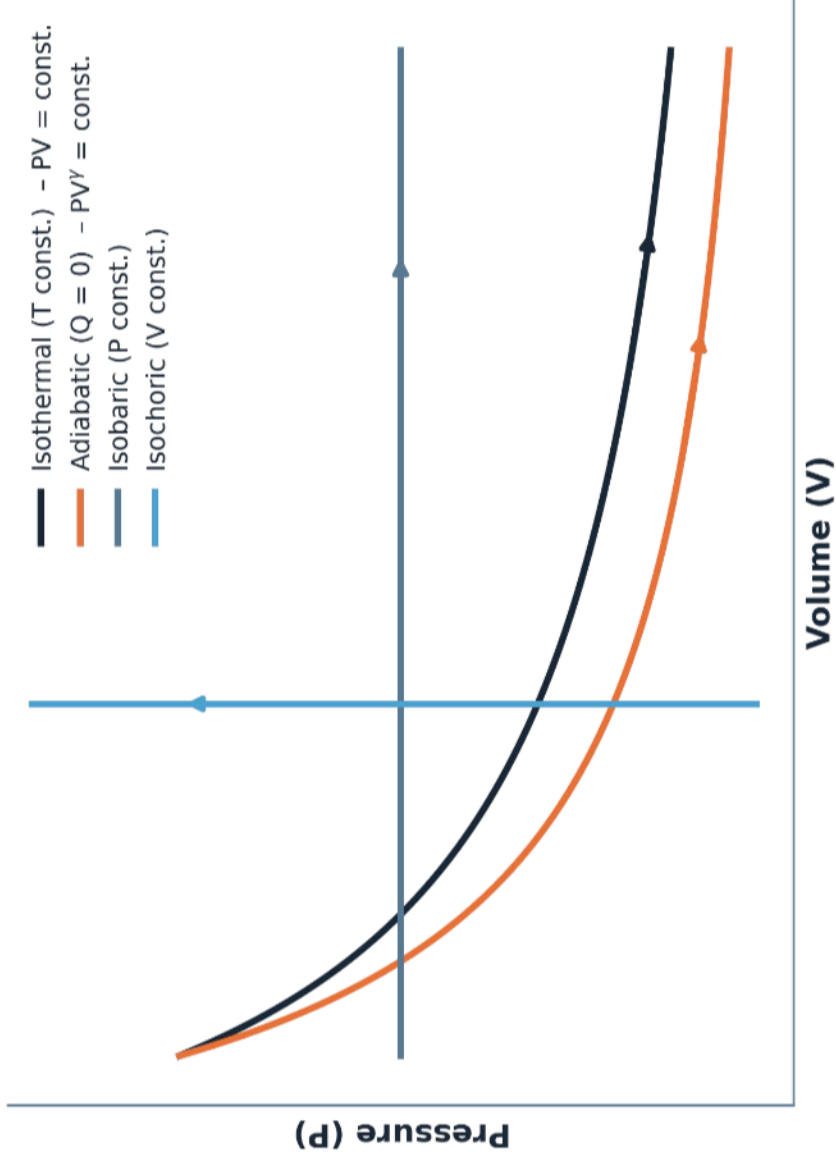
Energy needed to raise an object's temperature 1 K: $C = Q/\Delta T$ (extensive).

Specific heat (c)

Heat capacity per unit mass: $c = C/m$ (intensive). Water's $c \approx 4184$ $J/(kg \cdot K)$, unusually high.

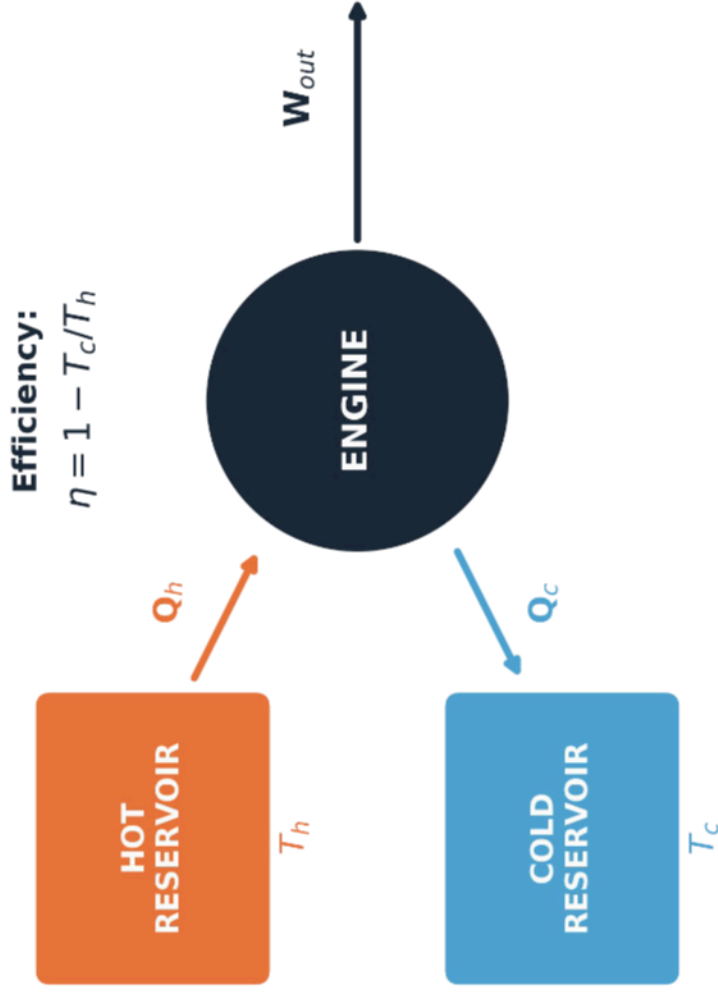
The Four Named Processes

- Isothermal — temperature constant; for an ideal gas, $\Delta U = 0$, so $Q = W$.
- Isobaric — pressure constant; work done $W = P\Delta V$.
- Isochoric (isovolumetric) — volume constant; no work is done, $W = 0$, so $Q = \Delta U$.
- Adiabatic — no heat exchange, $Q = 0$; described by $PV^\gamma = \text{constant}$.
- All four appear as distinct curves on a pressure-volume (PV) diagram.



Thermodynamic Cycles & Heat Engines

- A thermodynamic cycle returns a system to its initial state, so $\Delta U = 0$ over one full cycle.
- A heat engine converts heat flow from hot to cold into useful work.
- The Carnot cycle is the idealized, most efficient possible cycle between two reservoirs.
- No real engine can exceed the Carnot efficiency operating between the same two temperatures.
- Efficiency $\eta = W_{out} / Q_h = 1 - T_c/T_h$ (temperatures in kelvin).



First & Second Laws of Thermodynamics

FIRST LAW

$$\Delta U = Q - W$$

Conservation of energy.

The change in a system's internal energy equals the heat added to it minus the work it does on its surroundings. Energy is never created or destroyed, only converted between forms.

SECOND LAW

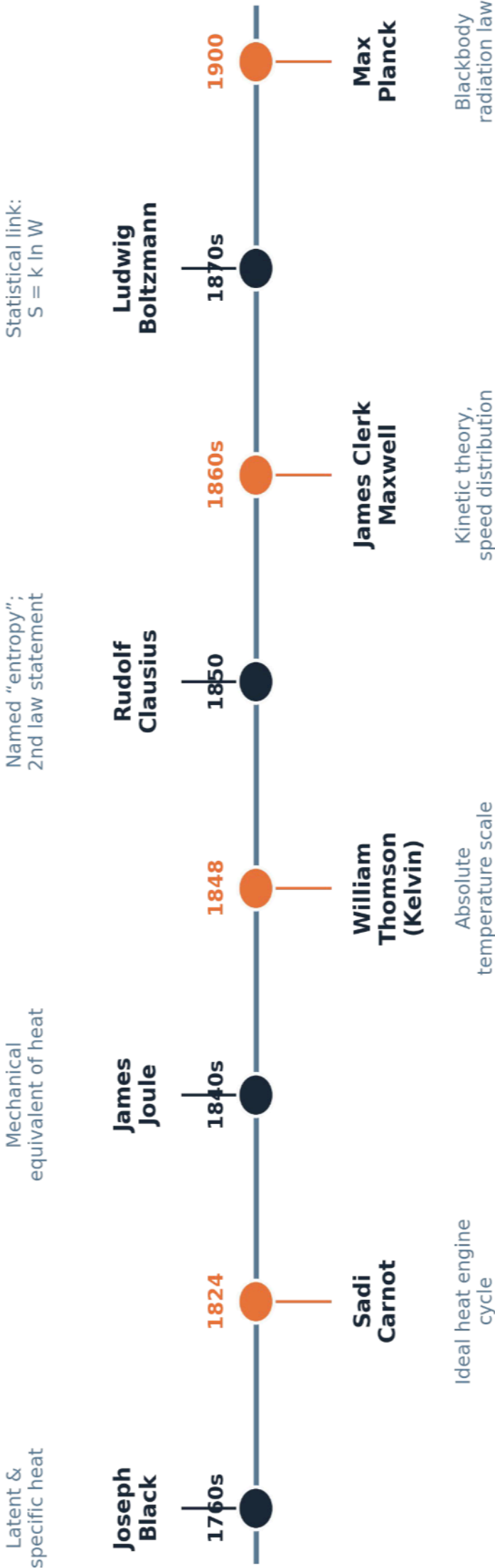
$$\Delta S_{\text{universe}} \geq 0$$

Entropy of an isolated system never decreases.

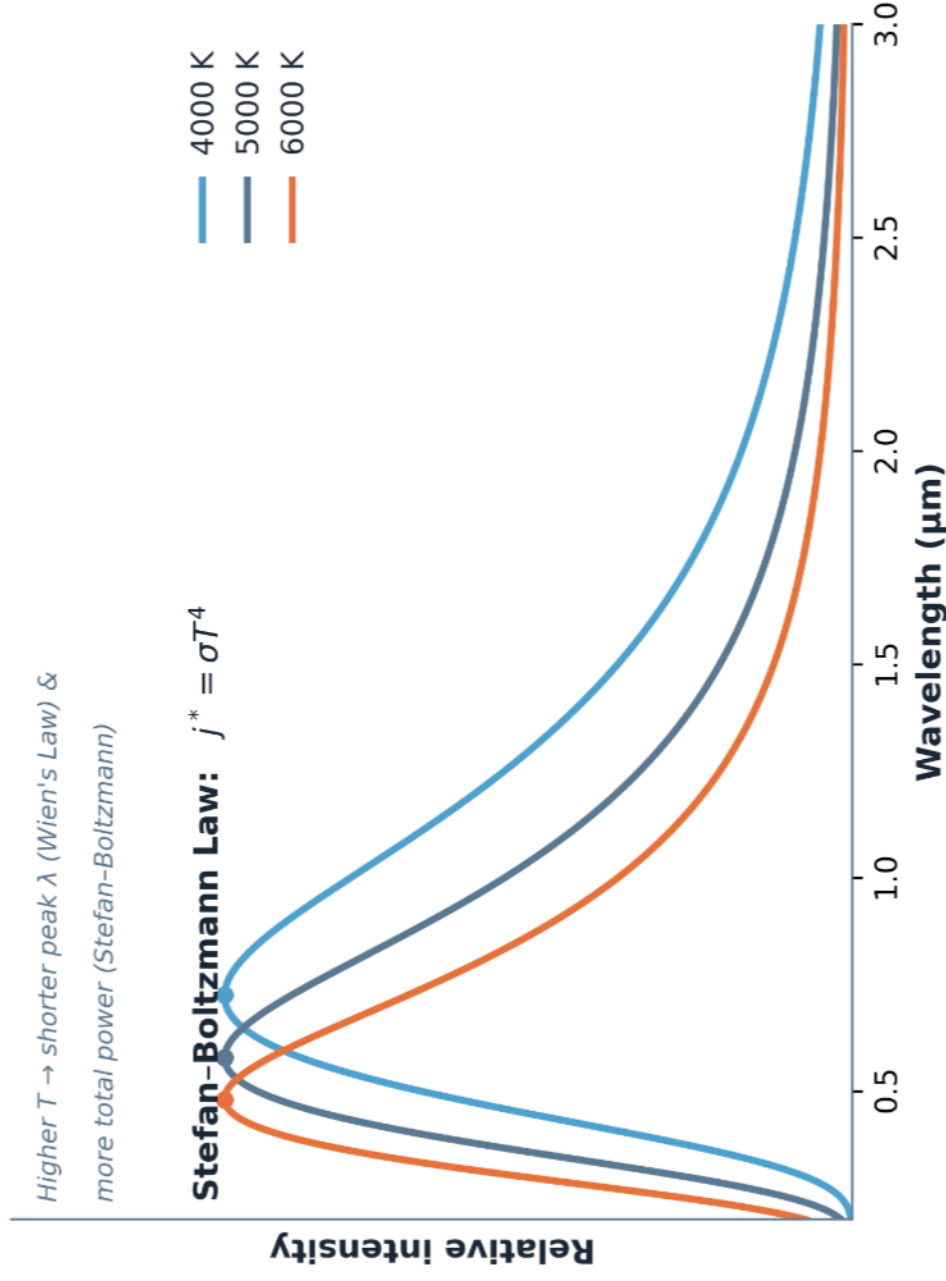
Heat flows spontaneously from hot to cold, never the reverse without external work (Clausius statement). No engine can convert heat completely into work (Kelvin-Planck statement) — 100% efficiency is impossible.



The History of Thermodynamics



Blackbody Radiation & the Third Law



Radiant exitance

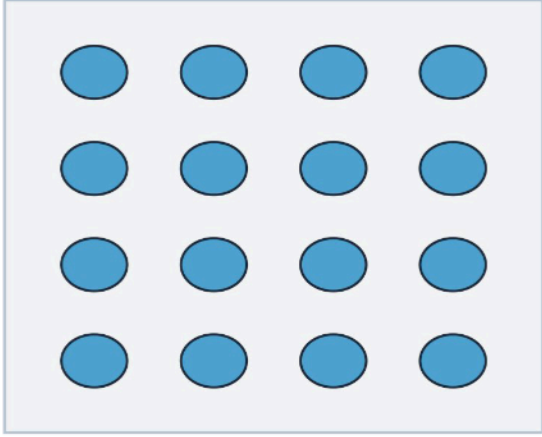
Power radiated per unit area of a blackbody's surface, j^* , governed by the Stefan-Boltzmann law $j^* = \sigma T^4$, where $\sigma = 5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \text{K}^4)$.

Third Law of Thermodynamics

As temperature approaches absolute zero (0 K), the entropy of a perfect crystal approaches a minimum, constant value (zero). Absolute zero itself is unreachable in a finite number of steps.

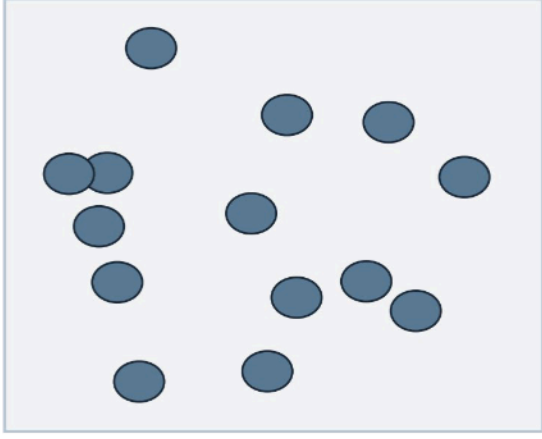
Entropy

SOLID



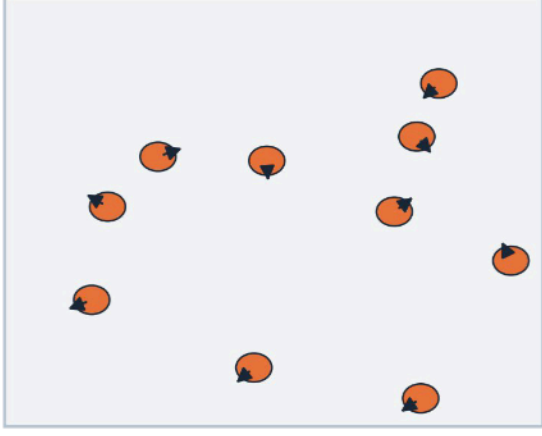
low entropy
ordered lattice

LIQUID



medium entropy
free to flow

GAS



high entropy
free, dispersed

What it measures

A measure of disorder, or the number of microscopic arrangements consistent with a system's macroscopic state.

Thermodynamic (reversible)

$$\Delta S = Q_{\text{rev}} / T$$

Statistical (Boltzmann)

$$S = k \ln W$$

Enthalpy

$$H = U + PV$$

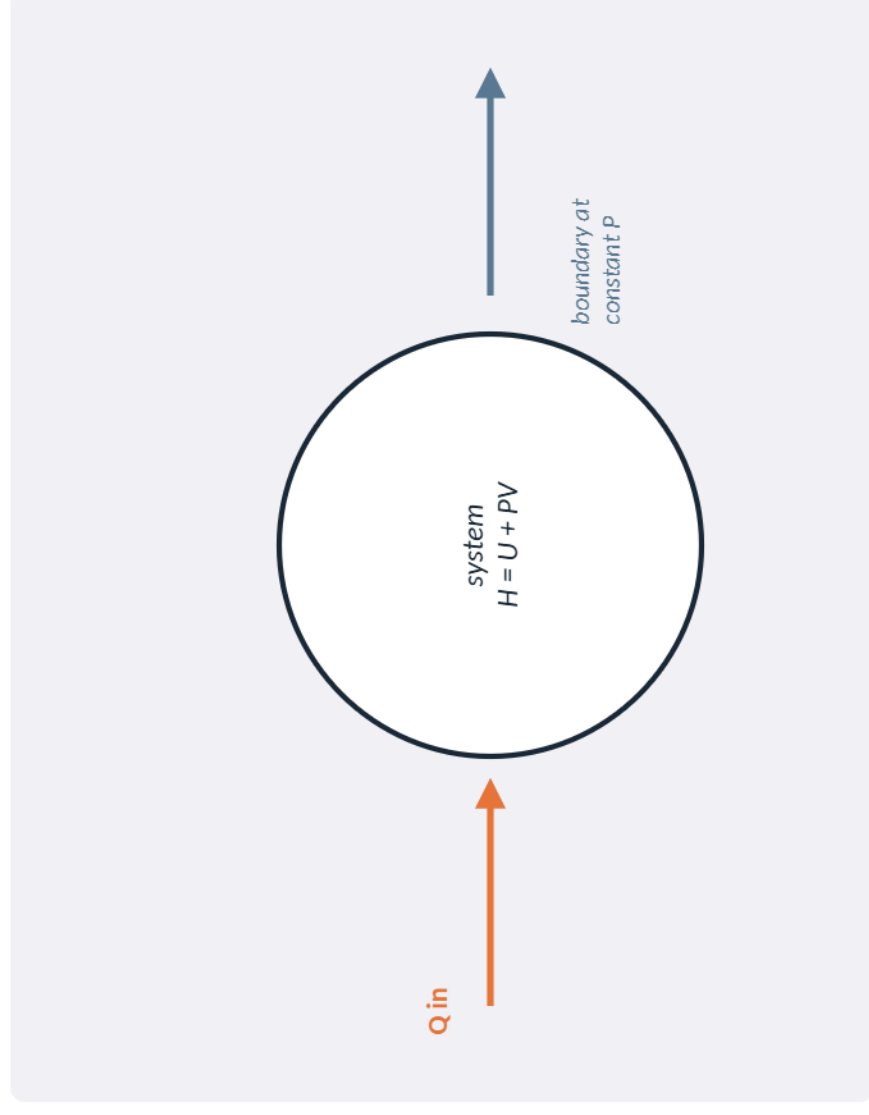
H total heat content of a system

U internal energy

P pressure

V volume

At constant pressure, ΔH equals the heat absorbed or released — $\Delta H = Q_p$. This is why chemists and engineers track enthalpy for reactions and flow processes run open to the atmosphere.



Math Skills — Rule 5.d & 5.e

The mathematical content allowed on written-test questions differs by division.

DIVISION B

- Standard arithmetic: ratios, exponents, absolute value.
- Simple algebra: solving one equation for one variable.
- Simple geometry: volume/area of common shapes.
- No trigonometry or calculus.

DIVISION C

- Standard arithmetic: ratios, exponents, absolute value.
- Algebra: multi-step derivations with multiple variables.
- Geometry: volume/area of common shapes.
- No trigonometry or calculus.

Quick-Reference Formula Sheet

$$K = ^\circ C + 273.15$$

$$^\circ F = ^\circ C \times 9/5 + 32$$

$$Q = mL$$

latent heat

$$\Delta U = Q - W$$

first law

$$j^* = \sigma T^4$$

Stefan-Boltzmann law

$$S = k \ln W$$

entropy (statistical)

$$Q = mc\Delta T$$

sensible heat

$$PV = nRT$$

ideal gas law

$$\eta = 1 - T_c/T_h$$

Carnot efficiency

$$\Delta S = Q_{rev}/T$$

entropy (thermo.)

$$H = U + PV$$

enthalpy

GOOD LUCK

Know your seven content areas, your unit conversions, and your formula sheet — and remember Part II rewards a good prediction as much as a hot cup of water.

THERMODYNAMICS B — REGIONAL EXAM

Science Olympiad — Division B (Middle School)

2027

Team Name / Number: _____

Team Members: _____

Score: _____ / 80 points

TEST DIRECTIONS

- *This exam contains 30 questions: 21 multiple choice, 4 multi-select, and 5 short answer, worth a total of 80 points.*
 - *For multiple choice questions, select the ONE best answer. For multi-select questions, select ALL choices that apply — there may be more than one correct answer.*
 - *For short answer questions, write your response in the space provided.*
 - *Five questions (#6, #11, #12, #20, and #26) ask you to analyze an accompanying figure. Figures appear directly below their associated question.*
 - *Unless otherwise noted, answers should use metric units and appropriate significant figures.*
 - *Calculators (Class III) and team notes may be used per Event Parameters.*
-

1. (2 pts - Systems & Temperature)

Thermometer B is held at a constant temperature. Objects A and C are each brought separately into equilibrium with B. What does the Zeroth Law allow you to conclude about A and C?

- A. Object A and Object C will always have different temperatures
- B. Object A and Object C are in thermal equilibrium with each other
- C. Object A and Object C cannot be measured with the same thermometer
- D. Object A and Object C must be made of the same material

2. (2 pts - Systems & Temperature)

A weather station reports an afternoon temperature of 35°C. Using $^{\circ}\text{F} = (9/5)(^{\circ}\text{C}) + 32$, which Fahrenheit reading should appear on its display?

- A. 63°F
- B. 95°F
- C. 67°F
- D. 99°F

3. (2 pts - Systems & Temperature)

Two samples of the same pure material have different sizes. Which listed property should remain unchanged when comparing the samples?

- A. Mass
- B. Volume
- C. Density
- D. Total thermal energy

4. (3 pts - Systems & Temperature)

A sample is divided into two equal portions without changing its composition. Select every listed property that should have the same value for each portion as for the original sample.

(Select ALL that apply)

- A. Temperature
- B. Mass
- C. Density
- D. Volume
- E. Boiling point
- F. Total heat content

5. (2 pts - Systems & Temperature)

One energy unit was historically based on warming a gram of water by one Celsius degree. Which unit is described?

- A. Joule
- B. Watt
- C. Calorie
- D. Kelvin

6. (3 pts - Systems & Temperature)

Use Figure 1 as a 0°C -to- 100°C interval. If Point X is four-tenths of the distance above the freezing mark, which labeled temperature matches it?

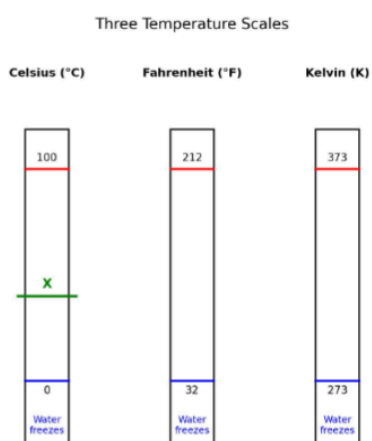


Figure 1: Three Temperature Scales

- A. 20°C
- B. 40°C
- C. 60°C
- D. 80°C

7. (2 pts - Phases & Gas Law)

Imagine equal numbers of particles in a crystal, a liquid, and a gas. Which sequence arranges the states from the most closely packed particles to the most widely separated?

- A. Gas, Liquid, Solid
- B. Solid, Gas, Liquid
- C. Solid, Liquid, Gas
- D. Liquid, Solid, Gas

8. (2 pts - Phases & Gas Law)

Ice absorbs energy while melting, yet a thermometer continues to read 0°C . How should the absorbed energy be classified?

- A. Sensible heat
- B. Latent heat
- C. Specific heat
- D. Radiant heat

9. (3 pts - Phases & Gas Law)

A sealed syringe contains gas at constant temperature. The plunger is pushed until the pressure becomes twice its original value. According to $PV = nRT$, how does the gas volume change?

- A. It doubles
- B. It is cut in half
- C. It stays the same
- D. It quadruples

10. (3 pts - Phases & Gas Law)

A class is sorting statements about melting, freezing, boiling, condensation, and sublimation. Select every scientifically correct statement.

(Select ALL that apply)

- A. Melting is the transition from solid to liquid
- B. Sublimation is the transition from solid directly to gas
- C. Condensation releases energy to the surroundings
- D. Boiling occurs at a single fixed temperature regardless of pressure
- E. Freezing is an endothermic process

11. (3 pts - Phases & Gas Law)

Locate Point X at 60°C and 1 atm in Figure 2. Which region of the diagram contains the point?

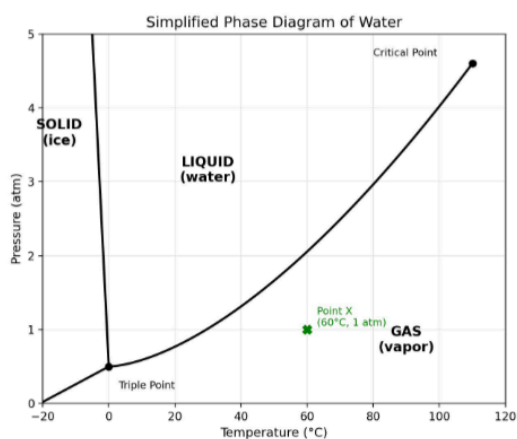


Figure 2: Simplified Phase Diagram of Water

- A. Solid
- B. Liquid
- C. Gas
- D. At the triple point

12. (4 pts - Phases & Gas Law)

Figure 3 shows water receiving energy along the horizontal segment D. Describe the molecular change taking place and account for the unchanged thermometer reading.

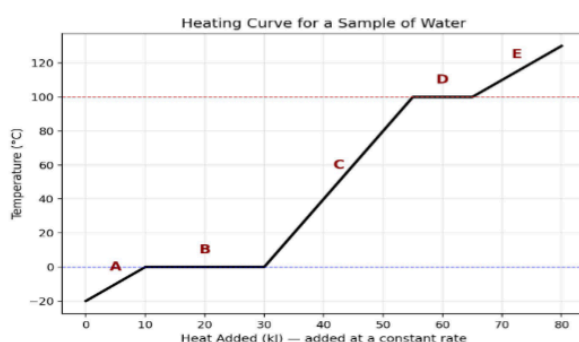


Figure 3: Heating Curve for a Sample of Water

13. (2 pts - Phases & Gas Law)

A table lists a substance's latent heat of fusion. What quantity could be calculated directly from that value and a sample's mass?

- A. The amount of heat needed to raise 1 gram of the substance by 1°C
- B. The amount of heat needed to melt 1 gram of the substance at its melting point
- C. The rate at which a substance conducts heat
- D. The pressure at which a substance boils

14. (2 pts - Heat Transfer)

Only one end of a spoon is immersed in hot soup, but energy reaches the handle through the solid metal. Which transfer mechanism is responsible?

- A. Convection
- B. Radiation
- C. Conduction
- D. Evaporation

15. (2 pts - Heat Transfer)

An engineer selects a material with a large value of thermal conductivity. What behavior should the engineer expect?

- A. Transfer heat slowly through itself
- B. Transfer heat quickly through itself
- C. Not transfer any heat
- D. Only transfer heat by radiation

16. (2 pts - Heat Transfer)

Suppose an entire object receives thermal energy and its temperature rises. What relationship is described by that object's heat capacity?

- A. The amount of heat required to raise the temperature of an entire object by 1°C
- B. The amount of heat required to raise the temperature of 1 gram of a substance by 1°C
- C. The maximum temperature an object can reach
- D. The rate of heat transfer through a material

17. (4 pts - Heat Transfer)

A 50 g water sample is warmed from 20°C to 45°C . With $c = 4.18 \text{ J}/(\text{g}\cdot^{\circ}\text{C})$, determine the energy supplied using $q = mc\Delta T$ and show the calculation.

18. (3 pts - Heat Transfer)

A cooking utensil must transfer energy rapidly from a burner. Select every material in the list that would generally perform well as a thermal conductor.

(Select ALL that apply)

- A. Copper
- B. Wood
- C. Aluminum
- D. Styrofoam
- E. Steel
- F. Air

19. (4 pts - Heat Transfer)

Two objects can have the same specific heat but different heat capacities. Explain how that can occur and distinguish the two quantities.

20. (3 pts - Heat Transfer)

Compare the conductivity values in Figure 4. Which listed substance would slow conductive heat flow most effectively?

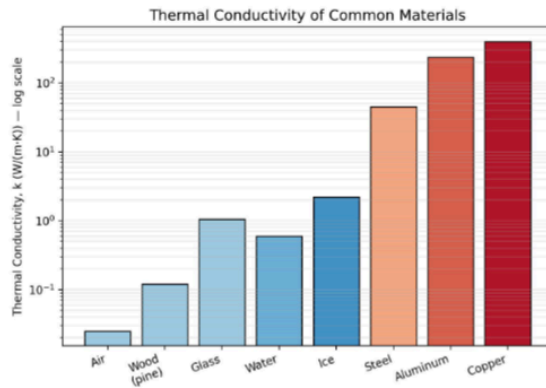


Figure 4: Thermal Conductivity of Common Materials

- A. Copper
- B. Steel
- C. Glass
- D. Air

21. (2 pts - Processes & Engines)

A rigid tank is heated without allowing its walls to move. What name is given to this constant-volume process?

- A. Isobaric
- B. Isothermal
- C. Isochoric
- D. Adiabatic

22. (2 pts - Processes & Engines)

During an experiment, thermal energy supplied to a device becomes stored energy and mechanical work. Which broad scientific principle underlies this accounting?

- A. Heat always flows from cold objects to hot objects
- B. Energy cannot be created or destroyed, only transferred or transformed
- C. The entropy of an isolated system always increases
- D. All matter has the same temperature at absolute zero

23. (2 pts - Processes & Engines)

A warm object cools in a room, but the reverse change never occurs spontaneously. Which statement best captures the thermodynamic rule illustrated?

- A. Heat naturally flows from a colder object to a hotter object on its own
- B. The total energy of an isolated system is always exactly conserved
- C. In any energy transfer, some usable energy becomes unusable heat, and the disorder (entropy) of an isolated system tends to increase
- D. Pressure and volume of a gas are always inversely proportional

24. (3 pts - Processes & Engines)

An engine receives 800 J from its hot reservoir and delivers 200 J of mechanical work. What percentage of the input becomes useful work?

- A. 20%
- B. 25%
- C. 40%
- D. 80%

25. (4 pts - Processes & Engines)

A gas in an operating engine repeatedly expands and contracts. Describe its condition after one complete cycle compared with its initial condition.

26. (3 pts - Processes & Engines)

Inspect the rectangular cycle in Figure 5. On which labeled leg is volume increasing while pressure remains fixed?

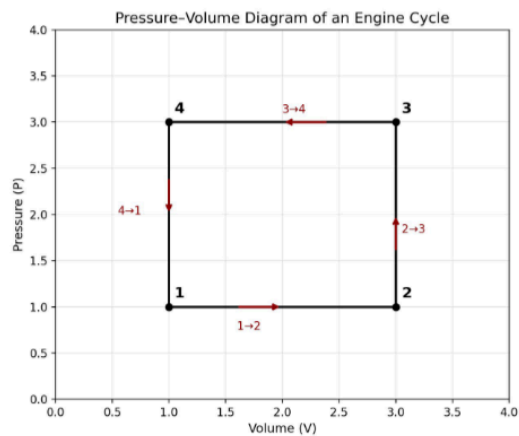


Figure 5: Pressure-Volume Diagram of an Engine Cycle

- A. 1→2
- B. 2→3
- C. 3→4
- D. 4→1

27. (2 pts - History)

William Thomson's temperature scale is commonly identified by the noble title he later received. Which title was it?

- A. Lord Kelvin
- B. Sir Isaac Newton
- C. Count Rumford
- D. Baron Fourier

28. (2 pts - History)

Which discovery associated with Joseph Black distinguished energy that changes temperature from energy involved in a phase change?

- A. The Second Law of Thermodynamics
- B. Latent heat and specific heat
- C. The Ideal Gas Law
- D. The Stefan-Boltzmann Law

29. (3 pts - History)

Review the scientist-and-contribution pairings. Select each pairing that accurately reflects the history of thermodynamics.

(Select ALL that apply)

- A. Rudolf Clausius helped formalize the concept of entropy and the Second Law
- B. James Joule established the mechanical equivalent of heat
- C. Ludwig Boltzmann contributed to the statistical explanation of entropy
- D. Sadi Carnot invented the modern electric refrigerator
- E. James Clerk Maxwell contributed to the kinetic theory of gases

30. (4 pts - History)

Why is Sadi Carnot central to the study of heat engines? Summarize his principal insight in one or two sentences.

THERMODYNAMICS B — REGIONAL EXAM

ANSWER KEY

Division B (Middle School) — Honors Level — 2027 Draft Rules, Section 3

1. (2 pts - Multiple Choice)

Thermometer B is held at a constant temperature. Objects A and C are each brought separately into equilibrium with B. What does the Zeroth Law allow you to conclude about A and C?

- A. Object A and Object C will always have different temperatures
- B. Object A and Object C are in thermal equilibrium with each other ✓ CORRECT**
- C. Object A and Object C cannot be measured with the same thermometer
- D. Object A and Object C must be made of the same material

Explanation: The Zeroth Law states that if two systems are each in thermal equilibrium with a third system, they are in thermal equilibrium with each other (and therefore at the same temperature).

2. (2 pts - Multiple Choice)

A weather station reports an afternoon temperature of 35°C. Using $^{\circ}\text{F} = (9/5)(^{\circ}\text{C}) + 32$, which Fahrenheit reading should appear on its display?

- A. 63°F
- B. 95°F ✓ CORRECT**
- C. 67°F
- D. 99°F

Explanation: $(9/5)(35) + 32 = 63 + 32 = 95^{\circ}\text{F}$.

3. (2 pts - Multiple Choice)

Two samples of the same pure material have different sizes. Which listed property should remain unchanged when comparing the samples?

- A. Mass
- B. Volume
- C. Density ✓ CORRECT**
- D. Total thermal energy

Explanation: Density is intensive — it is the same for a sample regardless of how much of the substance is present. Mass, volume, and total thermal energy are extensive properties that scale with the amount of matter.

4. (3 pts - Multi-Select)

A sample is divided into two equal portions without changing its composition. Select every listed property that should have the same value for each portion as for the original sample.

- A. Temperature ✓ CORRECT**

- B. Mass
- C. Density ✓ CORRECT**
- D. Volume
- E. Boiling point ✓ CORRECT**
- F. Total heat content

Explanation: Temperature, density, and boiling point do not depend on the amount of substance present. Mass, volume, and total heat content are extensive properties.

5. (2 pts - Multiple Choice)

One energy unit was historically based on warming a gram of water by one Celsius degree. Which unit is described?

- A. Joule
- B. Watt
- C. Calorie ✓ CORRECT**
- D. Kelvin

Explanation: This is the definition of a calorie. The joule is the SI unit of energy, the watt is a unit of power, and the kelvin is a unit of temperature.

6. (3 pts - Multiple Choice)

Use Figure 1 as a 0°C-to-100°C interval. If Point X is four-tenths of the distance above the freezing mark, which labeled temperature matches it?

- A. 20°C
- B. 40°C ✓ CORRECT**
- C. 60°C
- D. 80°C

Explanation: The freezing point is 0°C and the boiling point is 100°C, a 100-degree span. 40% of 100°C is 40°C, so Point X $\approx$ 40°C.

7. (2 pts - Multiple Choice)

Imagine equal numbers of particles in a crystal, a liquid, and a gas. Which sequence arranges the states from the most closely packed particles to the most widely separated?

- A. Gas, Liquid, Solid
- B. Solid, Gas, Liquid
- C. Solid, Liquid, Gas ✓ CORRECT**
- D. Liquid, Solid, Gas

Explanation: Particles are most tightly packed in a solid, farther apart in a liquid, and farthest apart in a gas.

8. (2 pts - Multiple Choice)

Ice absorbs energy while melting, yet a thermometer continues to read 0°C. How should the absorbed energy be classified?

- A. Sensible heat
- B. Latent heat ✓ CORRECT**
- C. Specific heat
- D. Radiant heat

Explanation: Latent heat is the heat absorbed or released during a phase change, without a change in temperature. Sensible heat causes a measurable temperature change.

9. (3 pts - Multiple Choice)

A sealed syringe contains gas at constant temperature. The plunger is pushed until the pressure becomes twice its original value. According to $PV = nRT$, how does the gas volume change?

- A. It doubles
- B. It is cut in half ✓ CORRECT**
- C. It stays the same
- D. It quadruples

Explanation: At constant n and T , PV is constant, so pressure and volume are inversely proportional. Doubling P cuts V in half.

10. (3 pts - Multi-Select)

A class is sorting statements about melting, freezing, boiling, condensation, and sublimation. Select every scientifically correct statement.

- A. Melting is the transition from solid to liquid ✓ CORRECT**
- B. Sublimation is the transition from solid directly to gas ✓ CORRECT**
- C. Condensation releases energy to the surroundings ✓ CORRECT**
- D. Boiling occurs at a single fixed temperature regardless of pressure
- E. Freezing is an endothermic process

Explanation: Melting (solid→liquid) and sublimation (solid→gas) are correctly described, and condensation is exothermic (releases energy). Boiling point depends on pressure, and freezing is exothermic, not endothermic — so those two statements are false.

11. (3 pts - Multiple Choice)

Locate Point X at 60°C and 1 atm in Figure 2. Which region of the diagram contains the point?

- A. Solid
- B. Liquid ✓ CORRECT**
- C. Gas
- D. At the triple point

Explanation: Point X (60°C , 1 atm) falls within the region of the diagram labeled LIQUID, between the solid-liquid boundary and the liquid-gas boundary.

12. (4 pts - Short Answer)

Figure 3 shows water receiving energy along the horizontal segment D. Describe the molecular change taking place and account for the unchanged thermometer reading.

Sample Full-Credit Answer: During segment D, the water is boiling – changing from the liquid phase to the gas phase. The heat energy added during this plateau is being used to overcome the attractive forces between water molecules (breaking them apart into vapor) rather than to increase the average kinetic energy of the molecules, so the temperature stays constant until the phase change is complete.

13. (2 pts - Multiple Choice)

A table lists a substance's latent heat of fusion. What quantity could be calculated directly from that value and a sample's mass?

- A. The amount of heat needed to raise 1 gram of the substance by 1°C
- B. The amount of heat needed to melt 1 gram of the substance at its melting point ✓ CORRECT**
- C. The rate at which a substance conducts heat
- D. The pressure at which a substance boils

Explanation: Specific latent heat of fusion is the energy required to melt one gram (or one kilogram) of a substance at constant temperature.

14. (2 pts - Multiple Choice)

Only one end of a spoon is immersed in hot soup, but energy reaches the handle through the solid metal. Which transfer mechanism is responsible?

- A. Convection
- B. Radiation
- C. Conduction ✓ CORRECT**
- D. Evaporation

Explanation: Conduction is the transfer of heat through direct contact between particles of a material, such as heat moving along the metal spoon.

15. (2 pts - Multiple Choice)

An engineer selects a material with a large value of thermal conductivity. What behavior should the engineer expect?

- A. Transfer heat slowly through itself
- B. Transfer heat quickly through itself ✓ CORRECT**
- C. Not transfer any heat
- D. Only transfer heat by radiation

Explanation: Thermal conductivity measures how readily heat passes through a material by conduction – a high value means heat is transferred quickly.

16. (2 pts - Multiple Choice)

Suppose an entire object receives thermal energy and its temperature rises. What relationship is described by that object's heat capacity?

A. The amount of heat required to raise the temperature of an entire object by 1 °C

✓ CORRECT

B. The amount of heat required to raise the temperature of 1 gram of a substance by 1 °C

C. The maximum temperature an object can reach

D. The rate of heat transfer through a material

Explanation: Heat capacity applies to a specific object (depends on its total mass), while specific heat (option B) applies per gram of a substance.

17. (4 pts - Short Answer)

A 50 g water sample is warmed from 20 °C to 45 °C. With $c = 4.18 \text{ J}/(\text{g} \cdot ^\circ\text{C})$, determine the energy supplied using $q = mc\Delta T$ and show the calculation.

Sample Full-Credit Answer: $\Delta T = 45^\circ\text{C} - 20^\circ\text{C} = 25^\circ\text{C}$. $q = mc\Delta T = (50 \text{ g})(4.18 \text{ J}/(\text{g} \cdot ^\circ\text{C}))(25^\circ\text{C}) = 5,225 \text{ J}$ (5.225 kJ). Full credit requires the correct setup, ΔT , and final numeric answer with units.

18. (3 pts - Multi-Select)

A cooking utensil must transfer energy rapidly from a burner. Select every material in the list that would generally perform well as a thermal conductor.

A. Copper ✓ CORRECT

B. Wood

C. Aluminum ✓ CORRECT

D. Styrofoam

E. Steel ✓ CORRECT

F. Air

Explanation: Copper, aluminum, and steel are metals with relatively high thermal conductivity. Wood, styrofoam, and air are common thermal insulators (poor conductors).

19. (4 pts - Short Answer)

Two objects can have the same specific heat but different heat capacities. Explain how that can occur and distinguish the two quantities.

Sample Full-Credit Answer: Heat capacity is the amount of heat needed to raise the temperature of an entire object (of whatever mass it has) by 1 °C, while specific heat is the amount of heat needed to raise the temperature of exactly 1 gram (or 1 kg) of a particular substance by 1 °C. Specific heat is a property of the material itself, whereas heat capacity depends on both the material and the total mass of the object.

20. (3 pts - Multiple Choice)

Compare the conductivity values in Figure 4. Which listed substance would slow conductive heat flow most effectively?

A. Copper

B. Steel

C. Glass

D. Air ✓ CORRECT

Explanation: Air has by far the lowest thermal conductivity value shown on the chart, making it the best insulator of the choices listed.

21. (2 pts - Multiple Choice)

A rigid tank is heated without allowing its walls to move. What name is given to this constant-volume process?

- A. Isobaric
- B. Isothermal
- C. **Isochoric** ✓ CORRECT
- D. Adiabatic

Explanation: Isochoric (constant volume) – isobaric is constant pressure, isothermal is constant temperature, and adiabatic means no heat is exchanged with the surroundings.

22. (2 pts - Multiple Choice)

During an experiment, thermal energy supplied to a device becomes stored energy and mechanical work. Which broad scientific principle underlies this accounting?

- A. Heat always flows from cold objects to hot objects
- B. **Energy cannot be created or destroyed, only transferred or transformed** ✓ CORRECT
- C. The entropy of an isolated system always increases
- D. All matter has the same temperature at absolute zero

Explanation: The First Law is a statement of conservation of energy: the change in a system's internal energy equals the heat added minus the work done by the system.

23. (2 pts - Multiple Choice)

A warm object cools in a room, but the reverse change never occurs spontaneously. Which statement best captures the thermodynamic rule illustrated?

- A. Heat naturally flows from a colder object to a hotter object on its own
- B. The total energy of an isolated system is always exactly conserved
- C. **In any energy transfer, some usable energy becomes unusable heat, and the disorder (entropy) of an isolated system tends to increase** ✓ CORRECT
- D. Pressure and volume of a gas are always inversely proportional

Explanation: The Second Law describes the natural direction of processes: heat flows from hot to cold on its own, and entropy tends to increase, meaning no engine can be perfectly efficient.

24. (3 pts - Multiple Choice)

An engine receives 800 J from its hot reservoir and delivers 200 J of mechanical work. What percentage of the input becomes useful work?

- A. 20%
- B. **25%** ✓ CORRECT
- C. 40%
- D. 80%

Explanation: $\text{Efficiency} = 200 \text{ J} \div 800 \text{ J} \times 100\% = 25\%$.

25. (4 pts - Short Answer)

A gas in an operating engine repeatedly expands and contracts. Describe its condition after one complete cycle compared with its initial condition.

Sample Full-Credit Answer: Over one complete cycle, the working substance goes through a series of processes (such as expansion, compression, heating, and cooling) and returns to its original pressure, volume, and temperature by the end of the cycle. In doing so, the engine converts some of the heat absorbed into net useful work, while exhausting the remaining heat to the surroundings.

26. (3 pts - Multiple Choice)

Inspect the rectangular cycle in Figure 5. On which labeled leg is volume increasing while pressure remains fixed?

- A. 1→2 ✓ CORRECT
- B. 2→3
- C. 3→4
- D. 4→1

Explanation: During 1→2, the volume increases while the pressure stays constant (isobaric expansion), so the gas does positive work on its surroundings. 2→3 and 4→1 occur at constant volume (no work), and 3→4 is a compression (work done ON the gas).

27. (2 pts - Multiple Choice)

William Thomson's temperature scale is commonly identified by the noble title he later received. Which title was it?

- A. Lord Kelvin ✓ CORRECT
- B. Sir Isaac Newton
- C. Count Rumford
- D. Baron Fourier

Explanation: William Thomson was granted the title Lord Kelvin, and the absolute temperature scale is named in his honor.

28. (2 pts - Multiple Choice)

Which discovery associated with Joseph Black distinguished energy that changes temperature from energy involved in a phase change?

- A. The Second Law of Thermodynamics
- B. Latent heat and specific heat ✓ CORRECT
- C. The Ideal Gas Law
- D. The Stefan-Boltzmann Law

Explanation: Joseph Black's experiments in the 1750s-60s led to his identification of latent heat and specific heat capacity.

29. (3 pts - Multi-Select)

Review the scientist-and-contribution pairings. Select each pairing that accurately reflects the history of thermodynamics.

A. Rudolf Clausius helped formalize the concept of entropy and the Second Law ✓
CORRECT

B. James Joule established the mechanical equivalent of heat ✓ CORRECT

C. Ludwig Boltzmann contributed to the statistical explanation of entropy ✓
CORRECT

D. Sadi Carnot invented the modern electric refrigerator

E. James Clerk Maxwell contributed to the kinetic theory of gases ✓ CORRECT

Explanation: Clausius, Joule, Boltzmann, and Maxwell statements are correct. Sadi Carnot did not invent the electric refrigerator — he is known for describing the idealized Carnot heat-engine cycle and the theoretical limit on engine efficiency.

30. (4 pts - Short Answer)

Why is Sadi Carnot central to the study of heat engines? Summarize his principal insight in one or two sentences.

Sample Full-Credit Answer: Sadi Carnot developed the concept of an idealized heat engine cycle (the Carnot cycle) and showed that there is a maximum possible efficiency for any heat engine operating between two given temperatures. His work laid an important foundation for what became the Second Law of Thermodynamics.

THERMODYNAMICS C — REGIONAL EXAM

Science Olympiad — Division C (High School)

2027

Team Name / Number: _____

Team Members: _____

Score: _____ / 89 points

TEST DIRECTIONS

- *This exam contains 30 questions: 21 multiple choice, 4 multi-select, and 5 short answer, worth a total of 89 points.*
- *For multiple choice questions, select the ONE best answer. For multi-select questions, select ALL choices that apply — there may be more than one correct answer.*
- *For short answer questions, write your response — and show all calculation steps where relevant — in the space provided.*
- *Five questions (#6, #11, #12, #20, and #26) ask you to analyze an accompanying figure. Figures appear directly below their associated question.*
- *Unless otherwise noted, answers should use metric units and appropriate significant figures.*
- *Calculators (Class III) and team notes may be used per Event Parameters. Show your work for full credit on calculation-based questions.*

1. (2 pts - Systems & Temperature)

Object Q is maintained at a fixed reference temperature. Samples P and R each separately reach equilibrium with Q. Which law guarantees that P and R are also in thermal equilibrium, and what measurement principle does it establish?

- A. The First Law; it shows that energy is conserved between P, Q, and R
- B. The Zeroth Law; it establishes that thermal equilibrium is a transitive relationship, which is what allows temperature to be defined and measured with a thermometer
- C. The Second Law; it shows that entropy is equal among all three objects
- D. The Third Law; it proves that P, Q, and R can never reach absolute zero

2. (3 pts - Systems & Temperature)

A biological sample is maintained at 98.6°F. Convert this value first to Celsius and then to kelvin using the relationships provided. Which result is correct?

- A. 273.15 K
- B. 310.15 K
- C. 371.75 K
- D. 37.0 K

3. (2 pts - Systems & Temperature)

A chemist doubles the quantity of gas while keeping its temperature and pressure fixed. Which listed system property must increase with the amount of gas?

- A. Temperature
- B. Specific heat
- C. Total internal energy
- D. Pressure

4. (3 pts - Systems & Temperature)

Select every listed unit that measures transferred or stored energy rather than temperature, pressure, or power.

(Select ALL that apply)

- A. Joule
- B. Watt
- C. Calorie
- D. British Thermal Unit (BTU)
- E. Kelvin
- F. Pascal

5. (3 pts - Systems & Temperature)

Why can a stable thermometer reading be accepted as the temperature of the liquid surrounding the thermometer bulb? Identify the relevant law.

- A. The First Law of Thermodynamics
- B. Conservation of mass
- C. The Zeroth Law of Thermodynamics
- D. Boyle's Law

6. (3 pts - Systems & Temperature)

Figure 1 locates X 55% of the way from water's Fahrenheit freezing point to its boiling point. Convert that position to an absolute temperature and choose the nearest kelvin value.

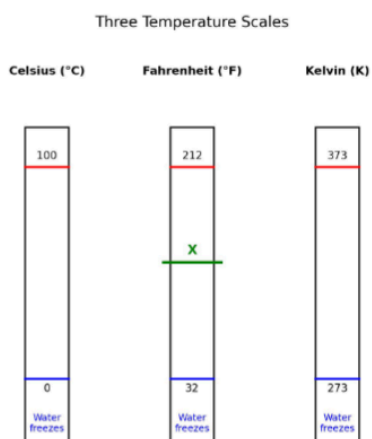


Figure 1: Three Temperature Scales

- A. 301 K
- B. 328 K
- C. 355 K
- D. 386 K

7. (2 pts - Phases & Gas Law)

Which particle-level description accounts for a gas occupying far more volume than the same number of particles in a liquid?

- A. Gas particles have lost their electrons
- B. Gas particles have enough kinetic energy to overcome intermolecular attractive forces almost entirely
- C. Gas particles are chemically different from liquid particles
- D. Gas particles have no mass

8. (3 pts - Phases & Gas Law)

At its boiling point, a 200 g water sample receives 226 kJ while $L_v = 2.260$ kJ/g. What portion of the original liquid becomes vapor?

- A. 25%
- B. 50%
- C. 75%
- D. 100%

9. (3 pts - Phases & Gas Law)

A gas begins at 1.0 atm, 2.0 L, and 300 K, then reaches 0.5 L and 600 K. Apply the combined gas law to determine its final pressure.

- A. 2.0 atm
- B. 4.0 atm
- C. 8.0 atm
- D. 16.0 atm

10. (3 pts - Phases & Gas Law)

Evaluate the proposed consequences and assumptions of $PV = nRT$. Select every statement that is valid for an ideal gas.

(Select ALL that apply)

- A. At constant temperature and moles, pressure and volume are inversely proportional
- B. At constant volume and moles, pressure is directly proportional to Kelvin temperature
- C. The ideal gas law can be used with Celsius temperatures without conversion
- D. Increasing the number of moles of gas at constant P and T increases the volume
- E. The ideal gas law assumes gas particles have significant volume and strong intermolecular forces

11. (3 pts - Phases & Gas Law)

Follow the constant-temperature pressure path from Y in Figure 2. Because water's fusion boundary has a negative slope, how does added pressure shift the melting temperature?

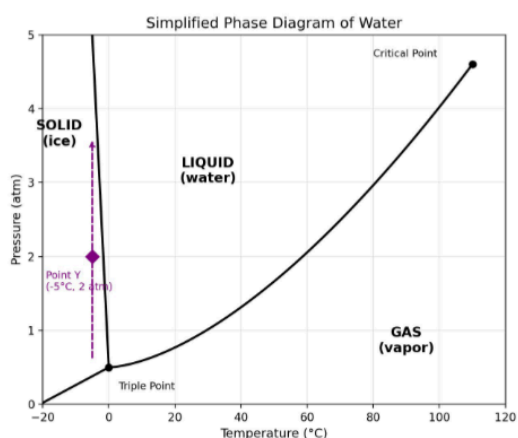


Figure 2: Simplified Phase Diagram of Water, with Point Y and a constant-temperature pressure increase shown

- A. The melting point increases significantly
- B. The melting point decreases slightly
- C. The melting point is completely unaffected by pressure
- D. Water cannot exist as a solid above 1 atm

12. (5 pts - Phases & Gas Law)

For the 100 g sample represented in Figure 3, calculate separately the energy that warms the ice from -20°C to 0°C and the energy that melts it. Report their sum.

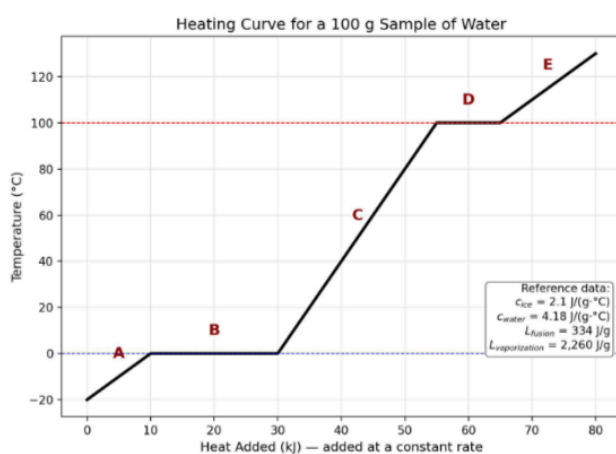


Figure 3: Heating Curve for a 100 g Sample of Water (with reference data)

13. (2 pts - Phases & Gas Law)

Which listed change of state transfers energy from the substance to its surroundings?

- A. Melting
- B. Vaporization
- C. Sublimation
- D. Condensation

14. (2 pts - Heat Transfer)

Energy from the Sun crosses nearly empty space before reaching Earth. Which heat-transfer process can operate without matter?

- A. Conduction
- B. Convection
- C. Radiation
- D. Advection

15. (3 pts - Heat Transfer)

In $Q/t = kA\Delta T/d$, only the slab thickness is doubled. What happens to the conductive transfer rate?

- A. Double the rate of heat loss
- B. Cut the rate of heat loss in half
- C. Have no effect on the rate of heat loss
- D. Quadruple the rate of heat loss

16. (2 pts - Heat Transfer)

Which combination of material amount and material-specific behavior determines an object's total heat capacity?

- A. Only the material it is made of
- B. Only its temperature
- C. Both the material and the total mass of the object
- D. Only its shape

17. (5 pts - Heat Transfer)

Convert 0.50 kg of aluminum to grams and calculate the energy absorbed as it warms from 20°C to 150°C when $c = 0.90 \text{ J}/(\text{g} \cdot ^\circ\text{C})$.

18. (3 pts - Heat Transfer)

Select all claims that correctly distinguish a material's thermal conductivity from an object's heat capacity.

(Select ALL that apply)

- A. A material's thermal conductivity is an intensive property
- B. A larger object always has a higher thermal conductivity than a smaller object made of the same material
- C. Metals generally have higher thermal conductivity than gases
- D. Heat capacity increases as the mass of an object increases, for a given material
- E. Thermal conductivity has SI units of $\text{W}/(\text{m}\cdot\text{K})$

19. (4 pts - Heat Transfer)

Account for copper's much greater conductivity than air by comparing particle interactions and the role of mobile electrons.

20. (4 pts - Heat Transfer)

Using the glass conductivity in Figure 4 and the supplied SI conversions, apply Fourier's law to estimate the power conducted through the window.

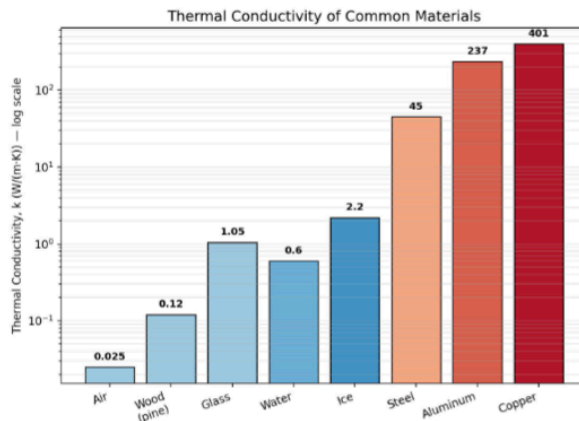


Figure 4: Thermal Conductivity of Common Materials (with k values labeled)

- A. 63 W
- B. 315 W
- C. 630 W
- D. 6,300 W

21. (2 pts - Processes & Engines)

A gas is thermally insulated while it expands. Which statement must be true for this adiabatic change?

- A. No work is done on or by the system
- B. No heat is exchanged between the system and its surroundings
- C. The temperature of the system remains constant
- D. The pressure of the system remains constant

22. (3 pts - Processes & Engines)

A system takes in 500 J as heat and performs 200 J of work. Use $\Delta U = Q - W$ to determine its internal-energy change.

- A. 300 J
- B. 700 J
- C. -300 J
- D. 100 J

23. (2 pts - Processes & Engines)

Which everyday observation demonstrates that spontaneous energy transfers have a preferred direction?

- A. A perpetual motion machine that runs forever with no energy input is possible

- B. Heat spontaneously flows from a cold object to a hot object
- C. No heat engine can convert 100% of the heat it absorbs into useful work
- D. Energy can be created from nothing

24. (2 pts - Processes & Engines)

A Carnot loop contains two constant-temperature legs. What type of process describes each of its remaining two legs?

- A. Two isobaric processes
- B. Two adiabatic processes
- C. Two isochoric processes
- D. Two isenthalpic processes

25. (5 pts - Processes & Engines)

Compare a frictionless reversible engine with a real engine operating between identical reservoirs. Explain which sets the efficiency ceiling and why the other cannot reach it.

26. (4 pts - Processes & Engines)

The engine in Figure 5 works between 600 K and 300 K. Calculate the reversible upper limit on efficiency using $1 - T_c/T_h$.

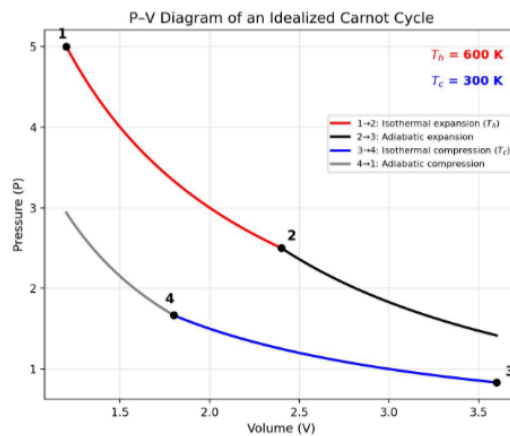


Figure 5: P-V Diagram of an Idealized Carnot Cycle

- A. 25%
- B. 50%
- C. 75%
- D. 100%

27. (2 pts - History)

Which theoretical development by Rudolf Clausius gave a quantitative name to the directionality expressed by the Second Law?

- A. Discovering latent heat
- B. Formulating a mathematical statement of the Second Law of Thermodynamics and introducing the concept of entropy
- C. Establishing the mechanical equivalent of heat
- D. Developing the kinetic theory of gases

28. (2 pts - History)

Which microscopic model of gas behavior is most closely connected with James Clerk Maxwell?

- A. The invention of the steam engine
- B. Describing the statistical distribution of molecular speeds in a gas (part of the kinetic theory of gases)
- C. The discovery of the Zeroth Law
- D. The construction of the first working refrigerator

29. (3 pts - History)

Select each historical statement that correctly connects a researcher with a thermodynamic advance.

- A. James Joule's experiments established the numerical relationship between mechanical work and heat
- B. Max Planck's early work on blackbody radiation laid groundwork that would later connect to thermodynamics
- C. Ludwig Boltzmann related entropy to the statistical behavior of particles
- D. Sadi Carnot proved that a heat engine's efficiency depends only on the type of working fluid used, not on temperature
- E. Lord Kelvin proposed an absolute temperature scale with a lowest possible temperature

30. (4 pts - History)

Explain why the maximum efficiency predicted by Carnot depends on reservoir temperatures but not on the chemical identity of the working fluid.

THERMODYNAMICS C — REGIONAL EXAM

ANSWER KEY

Division C (High School) — Honors Level — 2027 Draft Rules, Section 3

1. (2 pts - Multiple Choice)

Object Q is maintained at a fixed reference temperature. Samples P and R each separately reach equilibrium with Q. Which law guarantees that P and R are also in thermal equilibrium, and what measurement principle does it establish?

- A. The First Law; it shows that energy is conserved between P, Q, and R
- B. The Zeroth Law; it establishes that thermal equilibrium is a transitive relationship, which is what allows temperature to be defined and measured with a thermometer ✓ CORRECT**
- C. The Second Law; it shows that entropy is equal among all three objects
- D. The Third Law; it proves that P, Q, and R can never reach absolute zero

Explanation: The Zeroth Law establishes the transitive property of thermal equilibrium (if A-B and B-C, then A-C), which is the logical basis for using a thermometer to compare and define temperature.

2. (3 pts - Multiple Choice)

A biological sample is maintained at 98.6°F. Convert this value first to Celsius and then to kelvin using the relationships provided. Which result is correct?

- A. 273.15 K
- B. 310.15 K ✓ CORRECT**
- C. 371.75 K
- D. 37.0 K

Explanation: $(5/9)(98.6 - 32) = (5/9)(66.6) = 37.0^{\circ}\text{C}$. Then $37.0 + 273.15 = 310.15\text{ K}$.

3. (2 pts - Multiple Choice)

A chemist doubles the quantity of gas while keeping its temperature and pressure fixed. Which listed system property must increase with the amount of gas?

- A. Temperature
- B. Specific heat
- C. Total internal energy ✓ CORRECT**
- D. Pressure

Explanation: Total internal energy depends on the amount of matter in the system, so it is extensive. Temperature, specific heat, and pressure are all intensive.

4. (3 pts - Multi-Select)

Select every listed unit that measures transferred or stored energy rather than temperature, pressure, or power.

- A. Joule ✓ CORRECT
- B. Watt
- C. Calorie ✓ CORRECT
- D. British Thermal Unit (BTU) ✓ CORRECT
- E. Kelvin
- F. Pascal

Explanation: Joule, calorie, and BTU are all units of energy/heat. Watt is a unit of power, Kelvin is a unit of temperature, and Pascal is a unit of pressure.

5. (3 pts - Multiple Choice)

Why can a stable thermometer reading be accepted as the temperature of the liquid surrounding the thermometer bulb? Identify the relevant law.

- A. The First Law of Thermodynamics
- B. Conservation of mass
- C. The Zeroth Law of Thermodynamics ✓ CORRECT
- D. Boyle's Law

Explanation: Once the thermometer and water reach thermal equilibrium, the Zeroth Law guarantees the thermometer's reading accurately reflects the water's temperature.

6. (3 pts - Multiple Choice)

Figure 1 locates X 55% of the way from water's Fahrenheit freezing point to its boiling point. Convert that position to an absolute temperature and choose the nearest kelvin value.

- A. 301 K
- B. 328 K ✓ CORRECT
- C. 355 K
- D. 386 K

Explanation: The Fahrenheit range is $212 - 32 = 180^{\circ}\text{F}$. 55% of $180^{\circ}\text{F} = 99^{\circ}\text{F}$, so $X = 32 + 99 = 131^{\circ}\text{F}$. Converting: $^{\circ}\text{C} = (5/9)(131 - 32) = 55^{\circ}\text{C}$. $\text{K} = 55 + 273.15 \approx 328 \text{ K}$.

7. (2 pts - Multiple Choice)

Which particle-level description accounts for a gas occupying far more volume than the same number of particles in a liquid?

- A. Gas particles have lost their electrons
- B. Gas particles have enough kinetic energy to overcome intermolecular attractive forces almost entirely ✓ CORRECT
- C. Gas particles are chemically different from liquid particles
- D. Gas particles have no mass

Explanation: In the gas phase, particles possess enough kinetic energy to largely overcome the attractive intermolecular forces that hold particles close together in a liquid.

8. (3 pts - Multiple Choice)

At its boiling point, a 200 g water sample receives 226 kJ while $L_v = 2.260 \text{ kJ/g}$. What portion of the original liquid becomes vapor?

- A. 25%
- B. 50% ✓ CORRECT**
- C. 75%
- D. 100%

Explanation: $\text{Mass vaporized} = 226,000 \text{ J} \div 2,260 \text{ J/g} = 100 \text{ g}$. $\text{Fraction} = 100 \text{ g} \div 200 \text{ g} = 0.50$, or 50%.

9. (3 pts - Multiple Choice)

A gas begins at 1.0 atm, 2.0 L, and 300 K, then reaches 0.5 L and 600 K. Apply the combined gas law to determine its final pressure.

- A. 2.0 atm
- B. 4.0 atm
- C. 8.0 atm ✓ CORRECT**
- D. 16.0 atm

Explanation: $P_2 = P_1 V_1 T_2 / (T_1 V_2) = (1.0 \text{ atm})(2.0 \text{ L})(600 \text{ K}) / [(300 \text{ K})(0.5 \text{ L})] = 1200 / 150 = 8.0 \text{ atm}$.

10. (3 pts - Multi-Select)

Evaluate the proposed consequences and assumptions of $PV = nRT$. Select every statement that is valid for an ideal gas.

- A. At constant temperature and moles, pressure and volume are inversely proportional ✓ CORRECT**
- B. At constant volume and moles, pressure is directly proportional to Kelvin temperature ✓ CORRECT**
- C. The ideal gas law can be used with Celsius temperatures without conversion
- D. Increasing the number of moles of gas at constant P and T increases the volume ✓ CORRECT**
- E. The ideal gas law assumes gas particles have significant volume and strong intermolecular forces

Explanation: Statements 1, 2, and 4 correctly describe relationships within $PV = nRT$. Temperature must always be converted to Kelvin (statement 3 is false), and the ideal gas model assumes negligible particle volume and no intermolecular forces (statement 5 is false).

11. (3 pts - Multiple Choice)

Follow the constant-temperature pressure path from Y in Figure 2. Because water's fusion boundary has a negative slope, how does added pressure shift the melting temperature?

- A. The melting point increases significantly
- B. The melting point decreases slightly ✓ CORRECT**
- C. The melting point is completely unaffected by pressure
- D. Water cannot exist as a solid above 1 atm

Explanation: Because the solid-liquid line has a negative slope, increasing pressure at a constant sub-zero temperature can cross from the solid region into the liquid region — meaning water's melting point decreases slightly as pressure increases (unlike most substances).

12. (5 pts - Short Answer)

For the 100 g sample represented in Figure 3, calculate separately the energy that warms the ice from -20°C to 0°C and the energy that melts it. Report their sum.

Sample Full-Credit Answer: Segment A (warming ice from -20°C to 0°C): $q_1 = mc\Delta T = (100\text{ g})(2.1\text{ J/(g}\cdot^{\circ}\text{C)})(20^{\circ}\text{C}) = 4,200\text{ J}$. Segment B (melting at 0°C): $q_2 = mL_{\text{fusion}} = (100\text{ g})(334\text{ J/g}) = 33,400\text{ J}$. Total heat = $q_1 + q_2 = 4,200\text{ J} + 33,400\text{ J} = 37,600\text{ J}$ (37.6 kJ). Full credit requires both segment calculations shown separately and a correct total.

13. (2 pts - Multiple Choice)

Which listed change of state transfers energy from the substance to its surroundings?

- A. Melting
- B. Vaporization
- C. Sublimation
- D. Condensation ✓ CORRECT**

Explanation: Condensation (gas $\rightarrow$ liquid) releases energy as intermolecular bonds form. Melting, vaporization, and sublimation are all endothermic — they absorb energy.

14. (2 pts - Multiple Choice)

Energy from the Sun crosses nearly empty space before reaching Earth. Which heat-transfer process can operate without matter?

- A. Conduction
- B. Convection
- C. Radiation ✓ CORRECT**
- D. Advection

Explanation: Radiation transfers energy via electromagnetic waves and can travel through a vacuum, unlike conduction, convection, and advection, which all require matter.

15. (3 pts - Multiple Choice)

In $Q/t = kA\Delta T/d$, only the slab thickness is doubled. What happens to the conductive transfer rate?

- A. Double the rate of heat loss
- B. Cut the rate of heat loss in half ✓ CORRECT**
- C. Have no effect on the rate of heat loss
- D. Quadruple the rate of heat loss

Explanation: Since Q/t is inversely proportional to thickness d , doubling d cuts the rate of heat transfer in half.

16. (2 pts - Multiple Choice)

Which combination of material amount and material-specific behavior determines an object's total heat capacity?

- A. Only the material it is made of
- B. Only its temperature
- C. Both the material and the total mass of the object ✓ CORRECT**
- D. Only its shape

Explanation: Heat capacity is an extensive property – it scales with both the specific heat of the material and the total mass of the object.

17. (5 pts - Short Answer)

Convert 0.50 kg of aluminum to grams and calculate the energy absorbed as it warms from 20°C to 150°C when $c = 0.90 \text{ J}/(\text{g} \cdot ^\circ\text{C})$.

Sample Full-Credit Answer: First convert mass to grams: $0.50 \text{ kg} = 500 \text{ g}$. $\Delta T = 150^\circ\text{C} - 20^\circ\text{C} = 130^\circ\text{C}$. $q = mc\Delta T = (500 \text{ g})(0.90 \text{ J}/(\text{g} \cdot ^\circ\text{C}))(130^\circ\text{C}) = 58,500 \text{ J}$ (58.5 kJ). Full credit requires the unit conversion, correct setup, and final numeric answer.

18. (3 pts - Multi-Select)

Select all claims that correctly distinguish a material's thermal conductivity from an object's heat capacity.

- A. A material's thermal conductivity is an intensive property ✓ CORRECT**
- B. A larger object always has a higher thermal conductivity than a smaller object made of the same material
- C. Metals generally have higher thermal conductivity than gases ✓ CORRECT**
- D. Heat capacity increases as the mass of an object increases, for a given material ✓ CORRECT**
- E. Thermal conductivity has SI units of $\text{W}/(\text{m} \cdot \text{K})$ ✓ CORRECT**

Explanation: Thermal conductivity (k) is intensive – it does not depend on the size of the object, so statement 2 is false. Statements 1, 3, 4, and 5 are all correct.

19. (4 pts - Short Answer)

Account for copper's much greater conductivity than air by comparing particle interactions and the role of mobile electrons.

Sample Full-Credit Answer: In metals, atoms are packed closely together, and free electrons can move readily throughout the material, rapidly transferring kinetic energy from hotter regions to cooler regions through both particle collisions and electron movement. In gases, particles are far apart and collide much less frequently, so kinetic energy is transferred far more slowly, making gases poor conductors (good insulators) compared to metals.

20. (4 pts - Multiple Choice)

Using the glass conductivity in Figure 4 and the supplied SI conversions, apply Fourier's law to estimate the power conducted through the window.

- A. 63 W
- B. 315 W

C. 630 W ✓ CORRECT

D. 6,300 W

Explanation: $Q/t = kA\Delta T/d = (1.05 \text{ W/(m}\cdot\text{K)})(0.20 \text{ m}^2)(15^\circ\text{C}) / (0.0050 \text{ m}) = 3.15 / 0.0050 = 630 \text{ W}.$

21. (2 pts - Multiple Choice)

A gas is thermally insulated while it expands. Which statement must be true for this adiabatic change?

A. No work is done on or by the system

B. No heat is exchanged between the system and its surroundings ✓ CORRECT

C. The temperature of the system remains constant

D. The pressure of the system remains constant

Explanation: Adiabatic means $Q = 0$ — the system is thermally insulated so no heat enters or leaves, though work and temperature can still change.

22. (3 pts - Multiple Choice)

A system takes in 500 J as heat and performs 200 J of work. Use $\Delta U = Q - W$ to determine its internal-energy change.

A. 300 J ✓ CORRECT

B. 700 J

C. -300 J

D. 100 J

Explanation: $\Delta U = Q - W = 500 \text{ J} - 200 \text{ J} = 300 \text{ J}.$ The internal energy of the system increases by 300 J.

23. (2 pts - Multiple Choice)

Which everyday observation demonstrates that spontaneous energy transfers have a preferred direction?

A. A perpetual motion machine that runs forever with no energy input is possible

B. Heat spontaneously flows from a cold object to a hot object

C. No heat engine can convert 100% of the heat it absorbs into useful work ✓ CORRECT

D. Energy can be created from nothing

Explanation: The Second Law implies that some energy is always lost as unusable heat in any real process, so no heat engine can be perfectly (100%) efficient.

24. (2 pts - Multiple Choice)

A Carnot loop contains two constant-temperature legs. What type of process describes each of its remaining two legs?

A. Two isobaric processes

B. Two adiabatic processes ✓ CORRECT

C. Two isochoric processes

D. Two isenthalpic processes

Explanation: The idealized Carnot cycle consists of two isothermal processes (one at T_h , one at T_c) connected by two adiabatic processes.

25. (5 pts - Short Answer)

Compare a frictionless reversible engine with a real engine operating between identical reservoirs. Explain which sets the efficiency ceiling and why the other cannot reach it.

Sample Full-Credit Answer: The idealized Carnot engine (Engine 2) will always have a higher (or, at best, equal) efficiency than the real engine, because the reversible Carnot cycle represents the theoretical maximum efficiency possible between two given temperature reservoirs. Real engines have irreversible losses, such as friction and unwanted heat transfer, which the Second Law of Thermodynamics guarantees will always keep their efficiency below the Carnot limit.

26. (4 pts - Multiple Choice)

The engine in Figure 5 works between 600 K and 300 K. Calculate the reversible upper limit on efficiency using $1 - T_c/T_h$.

- A. 25%
- B. 50% ✓ CORRECT
- C. 75%
- D. 100%

Explanation: $\eta = 1 - (300 \text{ K} / 600 \text{ K}) = 1 - 0.5 = 0.50$, or 50%.

27. (2 pts - Multiple Choice)

Which theoretical development by Rudolf Clausius gave a quantitative name to the directionality expressed by the Second Law?

- A. Discovering latent heat
- B. Formulating a mathematical statement of the Second Law of Thermodynamics and introducing the concept of entropy ✓ CORRECT
- C. Establishing the mechanical equivalent of heat
- D. Developing the kinetic theory of gases

Explanation: Clausius formalized the Second Law and is credited with introducing the term and concept of entropy.

28. (2 pts - Multiple Choice)

Which microscopic model of gas behavior is most closely connected with James Clerk Maxwell?

- A. The invention of the steam engine
- B. Describing the statistical distribution of molecular speeds in a gas (part of the kinetic theory of gases) ✓ CORRECT
- C. The discovery of the Zeroth Law
- D. The construction of the first working refrigerator

Explanation: Maxwell developed the statistical distribution describing the range of molecular speeds in a gas at a given temperature, a cornerstone of the kinetic theory of gases.

29. (3 pts - Multi-Select)

Select each historical statement that correctly connects a researcher with a thermodynamic advance.

A. James Joule's experiments established the numerical relationship between mechanical work and heat ✓ CORRECT

B. Max Planck's early work on blackbody radiation laid groundwork that would later connect to thermodynamics ✓ CORRECT

C. Ludwig Boltzmann related entropy to the statistical behavior of particles ✓ CORRECT

D. Sadi Carnot proved that a heat engine's efficiency depends only on the type of working fluid used, not on temperature

E. Lord Kelvin proposed an absolute temperature scale with a lowest possible temperature ✓ CORRECT

Explanation: Statements 1, 2, 3, and 5 are correct. Statement 4 is false – Carnot showed that an idealized engine's maximum efficiency depends only on the temperatures of the hot and cold reservoirs, NOT on the type of working fluid used.

30. (4 pts - Short Answer)

Explain why the maximum efficiency predicted by Carnot depends on reservoir temperatures but not on the chemical identity of the working fluid.

Sample Full-Credit Answer: Carnot's finding showed that there is a fundamental theoretical limit on how efficient any heat engine can be, based solely on the temperatures it operates between ($\eta = 1 - T_c/T_h$), regardless of the engine's design or working fluid. This was significant because it set an upper bound that no real engine could ever exceed, and it helped lay the theoretical foundation for the Second Law of Thermodynamics.

THERMODYNAMICS B — STATE EXAM

Science Olympiad — Division B (Middle School)

2027

Team Name / Number: _____

Team Members: _____

Score: _____ / 128 points

TEST DIRECTIONS

- *This exam contains 50 questions: 35 multiple choice, 5 multi-select, and 10 short answer, worth a total of 128 points.*
- *For multiple choice questions, select the ONE best answer. For multi-select questions, select ALL choices that apply — there may be more than one correct answer.*
- *For short answer questions, write your response — and show all calculation steps where relevant — in the space provided.*
- *8 questions (#5, #12, #13, #22, #33, #45, #46, and #48) ask you to analyze an accompanying figure. Figures appear directly below their associated question.*
- *This exam includes content on radiant exitance, blackbody radiation, the Stefan-Boltzmann Law, and the Third Law of Thermodynamics (Questions 44-50), which is assessed only at the State and National level.*
- *Unless otherwise noted, answers should use metric units and appropriate significant figures.*
- *Calculators (Class III) and team notes may be used per Event Parameters. Show your work for full credit on calculation-based questions.*

1. (2 pts - Systems & Temperature)

Object B is maintained at a fixed temperature. Objects A and C are each separately allowed to reach thermal equilibrium with B. What relationship must then hold between A and C?

- A. Object A and Object C will always have different temperatures
- B. Object A and Object C are in thermal equilibrium with each other
- C. Object A and Object C cannot be measured with the same thermometer
- D. Object A and Object C must be made of the same material

2. (2 pts - Systems & Temperature)

A classroom is maintained at 20°C. What value should a correctly converted Fahrenheit thermostat display? Use $^{\circ}\text{F} = (9/5)(^{\circ}\text{C}) + 32$.

- A. 52°F
- B. 68°F
- C. 36°F
- D. 72°F

3. (2 pts - Systems & Temperature)

A large copper bar is cut into three pieces. Which listed characteristic of the copper does not change because of the cut?

- A. Mass
- B. Volume
- C. Density
- D. Total thermal energy

4. (2 pts - Systems & Temperature)

A food label uses an older unit based on the energy needed to warm a small amount of water. Which listed unit fits that definition?

- A. Joule
- B. Watt
- C. Calorie
- D. Kelvin

5. (3 pts - Systems & Temperature)

In Figure 1, treat the Celsius scale between water's fixed points as a 100-degree interval. Which answer gives the reading located 65% above the lower fixed point?

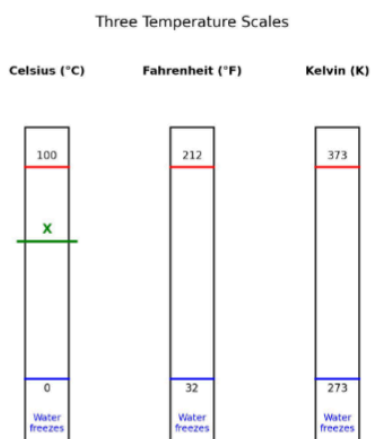


Figure 1: Three Temperature Scales

- A. 35°C
- B. 50°C
- C. 65°C
- D. 80°C

6. (2 pts - Systems & Temperature)

A snack transfers 5 calories of energy. Using 4.18 joules per calorie, which option is the closest equivalent energy?

- A. 4.18 J
- B. 9.0 J
- C. 20.9 J
- D. 41.8 J

7. (3 pts - Systems & Temperature)

A technician increases the amount of a pure substance while leaving its state unchanged. Select every property whose value would not scale with the amount added.

(Select ALL that apply)

- A. Temperature
- B. Mass
- C. Density
- D. Volume
- E. Boiling point
- F. Total heat content

8. (3 pts - Systems & Temperature)

A hot, massive object may contain more transferred energy than a hotter but tiny object. Use this idea to distinguish temperature from heat.

9. (2 pts - Phases & Gas Law)

Arrange solid, liquid, and gas according to the typical separation between neighboring particles, beginning with the smallest separation.

- A. Gas, Liquid, Solid
- B. Solid, Gas, Liquid
- C. Solid, Liquid, Gas
- D. Liquid, Solid, Gas

10. (2 pts - Phases & Gas Law)

A frozen sample changes to liquid at its melting point while its measured temperature is steady. Which category describes the energy absorbed?

- A. Sensible heat
- B. Latent heat
- C. Specific heat
- D. Radiant heat

11. (3 pts - Phases & Gas Law)

Gas in a flexible container remains at one temperature while its pressure rises to two times the starting value. What volume change follows from the ideal gas relationship?

- A. It doubles
- B. It is cut in half
- C. It stays the same
- D. It quadruples

12. (3 pts - Phases & Gas Law)

Use the boundaries in Figure 2 to classify water at the marked coordinate of 60°C and 1 atmosphere.

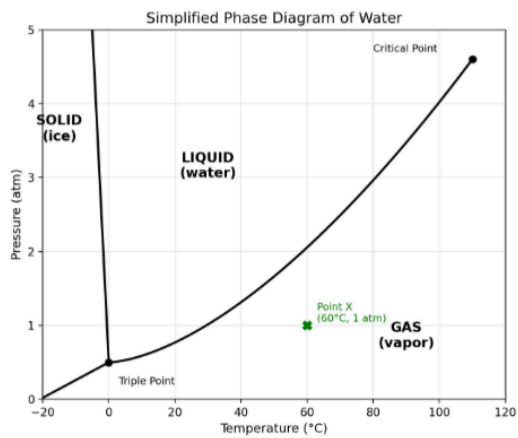


Figure 2: Simplified Phase Diagram of Water

- A. Solid
- B. Liquid
- C. Gas
- D. At the triple point

13. (4 pts - Phases & Gas Law)

On Figure 3, energy continues entering the sample during segment D. Explain both the rearrangement of particles and the reason the temperature stays at 100°C.

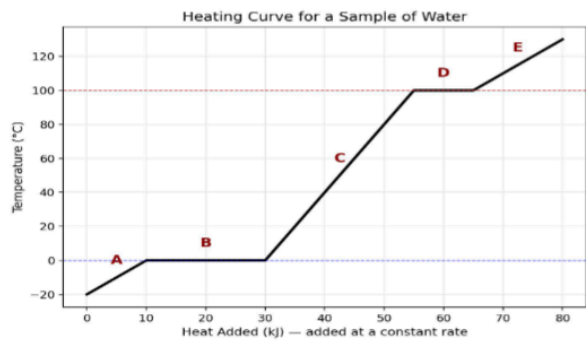


Figure 3: Heating Curve for a Sample of Water

14. (2 pts - Phases & Gas Law)

What does multiplying a material's latent heat of fusion by the mass undergoing melting determine?

- A. The amount of heat needed to raise 1 gram of the substance by 1°C
- B. The amount of heat needed to melt 1 gram of the substance at its melting point
- C. The rate at which a substance conducts heat
- D. The pressure at which a substance boils

15. (2 pts - Phases & Gas Law)

A pressure-temperature graph contains one coordinate at which the solid, liquid, and vapor regions meet. What is true at this coordinate?

- A. Only the solid and liquid phases exist
- B. All three phases (solid, liquid, and gas) coexist in equilibrium
- C. The substance is at its critical temperature
- D. The substance cannot be a solid

16. (3 pts - Phases & Gas Law)

Evaluate the proposed descriptions of phase changes and select every statement consistent with energy transfer and state changes.

(Select ALL that apply)

- A. Melting is the transition from solid to liquid
- B. Sublimation is the transition from solid directly to gas
- C. Condensation releases energy to the surroundings
- D. Boiling occurs at a single fixed temperature regardless of pressure
- E. Freezing is an endothermic process

17. (2 pts - Phases & Gas Law)

A block of solid carbon dioxide disappears into the air without forming liquid. Which named phase change has occurred?

- A. Melting
- B. Sublimation
- C. Condensation
- D. Deposition

18. (3 pts - Phases & Gas Law)

Determine the energy needed to melt 50 g of ice already at 0°C when $L_f = 334 \text{ J/g}$. Include the equation and substitution.

19. (2 pts - Heat Transfer)

Energy travels along the length of a metal utensil from its immersed tip toward your hand. Which mode of heat transfer dominates within the utensil?

- A. Convection
- B. Radiation
- C. Conduction
- D. Evaporation

20. (2 pts - Heat Transfer)

What does a high numerical thermal conductivity reveal about the rate at which a material passes thermal energy?

- A. Transfer heat slowly through itself
- B. Transfer heat quickly through itself
- C. Not transfer any heat
- D. Only transfer heat by radiation

21. (2 pts - Heat Transfer)

Which description relates the total energy absorbed by a particular object to its resulting temperature change?

- A. The amount of heat required to raise the temperature of an entire object by 1°C
- B. The amount of heat required to raise the temperature of 1 gram of a substance by 1°C
- C. The maximum temperature an object can reach
- D. The rate of heat transfer through a material

22. (3 pts - Heat Transfer)

From the materials compared in Figure 4, identify the one that offers the greatest resistance to conduction.

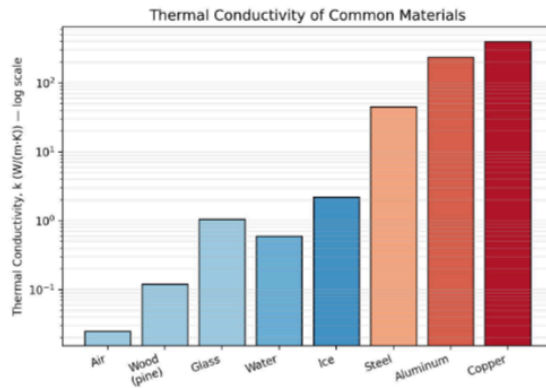


Figure 4: Thermal Conductivity of Common Materials

- A. Copper
- B. Steel
- C. Glass
- D. Air

23. (2 pts - Heat Transfer)

Circulating currents develop in heated water because warmer portions rise and cooler portions fall. How is this transfer classified?

- A. Conduction
- B. Convection
- C. Radiation
- D. Sublimation

24. (2 pts - Heat Transfer)

A person standing away from a fire receives energy across the intervening space. Which heat-transfer mechanism makes this possible?

- A. Conduction
- B. Convection
- C. Radiation
- D. Evaporation

25. (3 pts - Heat Transfer)

Select every listed material whose mobile electrons or structure generally allow energy to conduct readily.

(Select ALL that apply)

- A. Copper
- B. Wood
- C. Aluminum
- D. Styrofoam
- E. Steel
- F. Air

26. (4 pts - Heat Transfer)

Using $q = mc\Delta T$, find the energy required for 50 g of water to warm by 25°C when $c = 4.18 \text{ J/(g}\cdot^\circ\text{C)}$. Show each step.

27. (2 pts - Heat Transfer)

When no device supplies work, what direction of thermal-energy transfer is spontaneous between objects at unequal temperatures?

- A. From cold objects to hot objects
- B. From hot objects to cold objects
- C. Heat does not flow without work being done
- D. Heat flows equally in both directions

28. (3 pts - Heat Transfer)

Explain why doubling the mass of an otherwise identical sample doubles its heat capacity but leaves its specific heat unchanged.

29. (2 pts - Processes & Engines)

A gas is heated inside a strong, sealed cylinder whose volume cannot change. Which thermodynamic process name applies?

- A. Isobaric
- B. Isothermal
- C. Isochoric
- D. Adiabatic

30. (2 pts - Processes & Engines)

A closed system receives energy as heat and can return some as work. Which law supplies the energy-balance rule for the system?

- A. Heat always flows from cold objects to hot objects
- B. Energy cannot be created or destroyed, only transferred or transformed
- C. Entropy of an isolated system always increases
- D. All matter has the same temperature at absolute zero

31. (2 pts - Processes & Engines)

Which proposed statement accounts for the preferred direction of natural processes and the tendency for entropy to increase?

- A. Heat naturally flows from a colder object to a hotter object
- B. The total energy of an isolated system is always exactly conserved
- C. In any energy transfer, some usable energy becomes unusable heat, and no engine can be perfectly efficient
- D. Pressure and volume of a gas are always inversely proportional

32. (3 pts - Processes & Engines)

A device converts 150 J of a 600 J thermal input to work. Calculate its efficiency as a percentage.

- A. 15%
- B. 25%
- C. 40%
- D. 60%

33. (3 pts - Processes & Engines)

Follow the path in Figure 5 and identify the constant-pressure segment on which the system's volume grows.

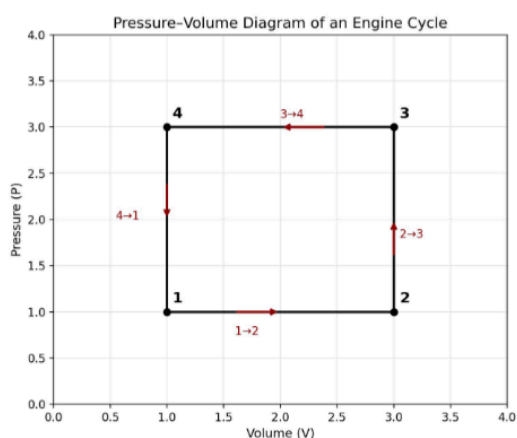


Figure 5: Pressure-Volume Diagram of an Engine Cycle

- A. 1→2
- B. 2→3
- C. 3→4
- D. 4→1

34. (2 pts - Processes & Engines)

After an engine completes a closed loop on a state diagram, which statement describes the final state of its working gas?

- A. Has more internal energy than at the start
- B. Has less internal energy than at the start
- C. Returns to its original state (same pressure, volume, and temperature)
- D. Is completely converted into work

35. (3 pts - Processes & Engines)

Select every claim that correctly describes heat-engine inputs, outputs, cycling, and efficiency limits.

(Select ALL that apply)

- A. No heat engine can be 100% efficient
- B. All the heat absorbed by an engine is converted into useful work
- C. A heat engine requires a temperature difference between a hot and a cold reservoir to do net work
- D. Increasing an engine's efficiency means less waste heat is produced per unit of work
- E. Engines violate the First Law of Thermodynamics

36. (4 pts - Processes & Engines)

Compare a working substance before and after a complete engine cycle. State what returns to its starting value even though energy has crossed the system boundary.

37. (3 pts - Processes & Engines)

Use energy conservation to explain why a self-contained machine cannot continuously deliver more energy than it receives.

38. (2 pts - History)

Which honor attached to William Thomson became the name of the absolute-temperature unit and scale?

- A. Lord Kelvin
- B. Sir Isaac Newton
- C. Count Rumford
- D. Baron Fourier

39. (2 pts - History)

Joseph Black's experiments established two related thermal quantities. Which answer names them?

- A. The Second Law of Thermodynamics
- B. Latent heat and specific heat
- C. The Ideal Gas Law
- D. The Stefan-Boltzmann Law

40. (2 pts - History)

What quantitative connection between mechanical work and heat was demonstrated by James Joule?

- A. The Ideal Gas Law
- B. The mechanical equivalent of heat (the numerical relationship between work and heat)
- C. The Second Law of Thermodynamics
- D. The concept of absolute zero

41. (2 pts - History)

Which ideal engine analysis established an upper limit on efficiency based on reservoir temperatures?

- A. The first working steam engine
- B. An idealized, maximally efficient heat engine cycle
- C. The kinetic theory of gases
- D. The law of conservation of mass

42. (2 pts - History)

Whose statistical treatment of microscopic particle arrangements gave entropy a molecular interpretation?

- A. James Clerk Maxwell
- B. Rudolf Clausius
- C. Ludwig Boltzmann
- D. Joseph Black

43. (3 pts - History)

Explain how Carnot's reversible cycle provides a benchmark against which real heat engines can be judged.

44. (2 pts - Radiation & Third Law)

Which description captures the absorption and emission behavior of the ideal surface physicists call a blackbody?

- A. Reflects all radiation that strikes it
- B. Absorbs and emits all wavelengths of electromagnetic radiation perfectly (with no reflection)
- C. Is always black in visible color, regardless of temperature
- D. Emits radiation only in the visible light spectrum

45. (3 pts - Radiation & Third Law)

Study the three spectral curves in Figure 6. Which curve's peak position and intensity indicate the greatest absolute temperature?

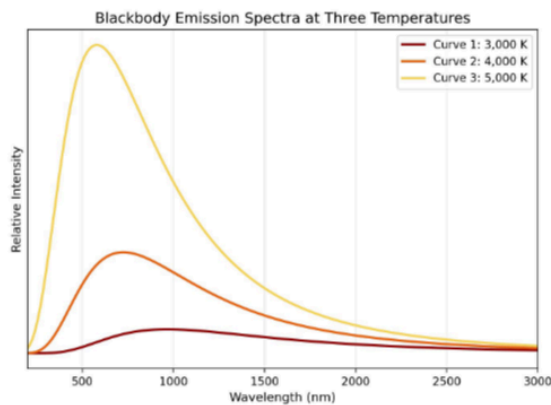


Figure 6: Blackbody Emission Spectra at Three Temperatures

- A. Curve 1
- B. Curve 2
- C. Curve 3
- D. All three curves represent the same temperature

46. (4 pts - Radiation & Third Law)

Use the T^4 relationship illustrated in Figure 7 to compare the marked radiant-exittance values at 200 K and 400 K.

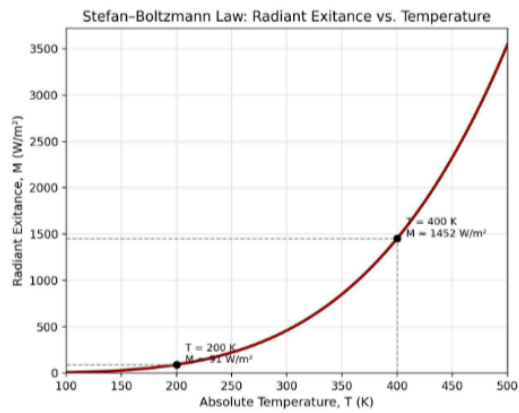


Figure 7: Stefan-Boltzmann Law – Radiant Exitance vs. Temperature

- A. 2 times
- B. 4 times
- C. 8 times
- D. 16 times

47. (3 pts - Radiation & Third Law)

Select every statement that correctly links blackbody temperature, emitted power, spectrum, and the Stefan-Boltzmann relationship.

(Select ALL that apply)

- A. Hotter objects emit more total radiant energy than cooler objects
- B. Radiant exitance is directly (linearly) proportional to Kelvin temperature
- C. All real objects are perfect blackbodies
- D. The Stefan-Boltzmann Law relates radiated power to the fourth power of absolute temperature
- E. Blackbody radiation can travel through the vacuum of space

48. (4 pts - Radiation & Third Law)

As the curve in Figure 8 approaches 0 K, describe the entropy trend and connect it to the behavior predicted for a perfect crystal.

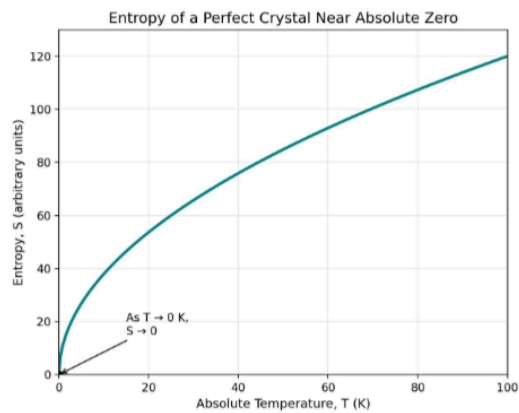


Figure 8: Entropy of a Perfect Crystal Near Absolute Zero

49. (2 pts - Radiation & Third Law)

Which statement most accurately expresses the limiting behavior of entropy as a perfect crystal approaches absolute zero?

- A. Energy cannot be created or destroyed, only transformed
- B. Heat naturally flows from hot objects to cold objects
- C. As the temperature of a perfect crystal approaches absolute zero, its entropy approaches a minimum (zero) value, and absolute zero itself cannot actually be reached
- D. Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other

50. (3 pts - Radiation & Third Law)

What change in the scientific treatment of thermal radiation resulted from Max Planck's introduction of discrete energy packets?

THERMODYNAMICS B — STATE EXAM

ANSWER KEY

Division B (Middle School) — Honors Level — 2027 Draft Rules, Section 3

1. (2 pts - Multiple Choice)

Object B is maintained at a fixed temperature. Objects A and C are each separately allowed to reach thermal equilibrium with B. What relationship must then hold between A and C?

- A. Object A and Object C will always have different temperatures
- B. Object A and Object C are in thermal equilibrium with each other ✓ CORRECT**
- C. Object A and Object C cannot be measured with the same thermometer
- D. Object A and Object C must be made of the same material

Explanation: The Zeroth Law states that if two systems are each in thermal equilibrium with a third system, they are in thermal equilibrium with each other.

2. (2 pts - Multiple Choice)

A classroom is maintained at 20°C. What value should a correctly converted Fahrenheit thermostat display? Use $^{\circ}\text{F} = (9/5)(^{\circ}\text{C}) + 32$.

- A. 52°F
- B. 68°F ✓ CORRECT**
- C. 36°F
- D. 72°F

Explanation: $(9/5)(20) + 32 = 36 + 32 = 68^{\circ}\text{F}$.

3. (2 pts - Multiple Choice)

A large copper bar is cut into three pieces. Which listed characteristic of the copper does not change because of the cut?

- A. Mass
- B. Volume
- C. Density ✓ CORRECT**
- D. Total thermal energy

Explanation: Density does not change with the amount of substance present, so it is intensive.

4. (2 pts - Multiple Choice)

A food label uses an older unit based on the energy needed to warm a small amount of water. Which listed unit fits that definition?

- A. Joule
- B. Watt
- C. Calorie ✓ CORRECT**
- D. Kelvin

Explanation: This is the definition of a calorie.

5. (3 pts - Multiple Choice)

In Figure 1, treat the Celsius scale between water's fixed points as a 100-degree interval. Which answer gives the reading located 65% above the lower fixed point?

- A. 35°C
- B. 50°C
- C. 65°C ✓ CORRECT**
- D. 80°C

Explanation: The freezing and boiling points of water are 0°C and 100°C, a 100-degree span. 65% of 100°C = 65°C.

6. (2 pts - Multiple Choice)

A snack transfers 5 calories of energy. Using 4.18 joules per calorie, which option is the closest equivalent energy?

- A. 4.18 J
- B. 9.0 J
- C. 20.9 J ✓ CORRECT**
- D. 41.8 J

Explanation: $5 \times 4.18 \text{ J} = 20.9 \text{ J}$.

7. (3 pts - Multi-Select)

A technician increases the amount of a pure substance while leaving its state unchanged. Select every property whose value would not scale with the amount added.

- A. Temperature ✓ CORRECT**
- B. Mass
- C. Density ✓ CORRECT**
- D. Volume
- E. Boiling point ✓ CORRECT**
- F. Total heat content

Explanation: Temperature, density, and boiling point do not depend on the amount of substance present. Mass, volume, and total heat content are extensive.

8. (3 pts - Short Answer)

A hot, massive object may contain more transferred energy than a hotter but tiny object. Use this idea to distinguish temperature from heat.

Sample Full-Credit Answer: Heat is the transfer of thermal energy between objects or systems because of a temperature difference, while temperature is a measure of the average kinetic energy of the particles within a substance. Heat is energy in transit (measured in joules), whereas temperature is a state property that indicates how hot or cold something is (measured in degrees or kelvin).

9. (2 pts - Multiple Choice)

Arrange solid, liquid, and gas according to the typical separation between neighboring particles, beginning with the smallest separation.

- A. Gas, Liquid, Solid
- B. Solid, Gas, Liquid
- C. Solid, Liquid, Gas ✓ CORRECT
- D. Liquid, Solid, Gas

Explanation: Particles are closest together in a solid, farther apart in a liquid, and farthest apart in a gas.

10. (2 pts - Multiple Choice)

A frozen sample changes to liquid at its melting point while its measured temperature is steady. Which category describes the energy absorbed?

- A. Sensible heat
- B. Latent heat ✓ CORRECT
- C. Specific heat
- D. Radiant heat

Explanation: Latent heat is absorbed or released during a phase change, without a change in temperature.

11. (3 pts - Multiple Choice)

Gas in a flexible container remains at one temperature while its pressure rises to two times the starting value. What volume change follows from the ideal gas relationship?

- A. It doubles
- B. It is cut in half ✓ CORRECT
- C. It stays the same
- D. It quadruples

Explanation: At constant n and T , pressure and volume are inversely proportional.

12. (3 pts - Multiple Choice)

Use the boundaries in Figure 2 to classify water at the marked coordinate of 60°C and 1 atmosphere.

- A. Solid
- B. Liquid ✓ CORRECT
- C. Gas
- D. At the triple point

Explanation: Point X (60°C , 1 atm) falls within the region of the diagram labeled LIQUID.

13. (4 pts - Short Answer)

On Figure 3, energy continues entering the sample during segment D. Explain both the rearrangement of particles and the reason the temperature stays at 100°C .

Sample Full-Credit Answer: During segment D, the water is boiling — changing from the liquid phase to the gas phase. The heat energy added is being used to overcome the attractive forces between water molecules (breaking them apart into vapor) rather than increasing the average kinetic energy of the molecules, so the temperature stays constant until the phase change is complete.

14. (2 pts - Multiple Choice)

What does multiplying a material's latent heat of fusion by the mass undergoing melting determine?

- A. The amount of heat needed to raise 1 gram of the substance by 1°C
- B. The amount of heat needed to melt 1 gram of the substance at its melting point ✓ CORRECT**
- C. The rate at which a substance conducts heat
- D. The pressure at which a substance boils

Explanation: Specific latent heat of fusion is the energy required to melt one gram of a substance at constant temperature.

15. (2 pts - Multiple Choice)

A pressure-temperature graph contains one coordinate at which the solid, liquid, and vapor regions meet. What is true at this coordinate?

- A. Only the solid and liquid phases exist
- B. All three phases (solid, liquid, and gas) coexist in equilibrium ✓ CORRECT**
- C. The substance is at its critical temperature
- D. The substance cannot be a solid

Explanation: The triple point is the unique combination of temperature and pressure at which the solid, liquid, and gas phases all coexist in equilibrium.

16. (3 pts - Multi-Select)

Evaluate the proposed descriptions of phase changes and select every statement consistent with energy transfer and state changes.

- A. Melting is the transition from solid to liquid ✓ CORRECT**
- B. Sublimation is the transition from solid directly to gas ✓ CORRECT**
- C. Condensation releases energy to the surroundings ✓ CORRECT**
- D. Boiling occurs at a single fixed temperature regardless of pressure
- E. Freezing is an endothermic process

Explanation: Boiling point depends on pressure, and freezing is exothermic (not endothermic), so those two statements are false.

17. (2 pts - Multiple Choice)

A block of solid carbon dioxide disappears into the air without forming liquid. Which named phase change has occurred?

- A. Melting
- B. Sublimation ✓ CORRECT**

- C. Condensation
- D. Deposition

Explanation: Sublimation is the direct transition from solid to gas.

18. (3 pts - Short Answer)

Determine the energy needed to melt 50 g of ice already at 0°C when $L_f = 334 \text{ J/g}$. Include the equation and substitution.

Sample Full-Credit Answer: $q = mL = (50 \text{ g})(334 \text{ J/g}) = 16,700 \text{ J}$.

19. (2 pts - Multiple Choice)

Energy travels along the length of a metal utensil from its immersed tip toward your hand. Which mode of heat transfer dominates within the utensil?

- A. Convection
- B. Radiation
- C. Conduction ✓ CORRECT
- D. Evaporation

Explanation: Conduction is heat transfer through direct contact between particles of a material.

20. (2 pts - Multiple Choice)

What does a high numerical thermal conductivity reveal about the rate at which a material passes thermal energy?

- A. Transfer heat slowly through itself
- B. Transfer heat quickly through itself ✓ CORRECT
- C. Not transfer any heat
- D. Only transfer heat by radiation

Explanation: A high thermal conductivity value means heat is conducted quickly through the material.

21. (2 pts - Multiple Choice)

Which description relates the total energy absorbed by a particular object to its resulting temperature change?

- A. The amount of heat required to raise the temperature of an entire object by 1°C ✓ CORRECT
- B. The amount of heat required to raise the temperature of 1 gram of a substance by 1°C
- C. The maximum temperature an object can reach
- D. The rate of heat transfer through a material

Explanation: Heat capacity applies to a specific object and depends on its total mass, unlike specific heat (per gram).

22. (3 pts - Multiple Choice)

From the materials compared in Figure 4, identify the one that offers the greatest resistance to conduction.

- A. Copper
- B. Steel
- C. Glass
- D. Air ✓ CORRECT**

Explanation: Air has by far the lowest thermal conductivity shown, making it the best insulator.

23. (2 pts - Multiple Choice)

Circulating currents develop in heated water because warmer portions rise and cooler portions fall. How is this transfer classified?

- A. Conduction
- B. Convection ✓ CORRECT**
- C. Radiation
- D. Sublimation

Explanation: Convection is heat transfer through the bulk movement of a fluid, driven by density differences.

24. (2 pts - Multiple Choice)

A person standing away from a fire receives energy across the intervening space. Which heat-transfer mechanism makes this possible?

- A. Conduction
- B. Convection
- C. Radiation ✓ CORRECT**
- D. Evaporation

Explanation: Radiation transfers energy as electromagnetic waves and does not require a medium.

25. (3 pts - Multi-Select)

Select every listed material whose mobile electrons or structure generally allow energy to conduct readily.

- A. Copper ✓ CORRECT**
- B. Wood
- C. Aluminum ✓ CORRECT**
- D. Styrofoam
- E. Steel ✓ CORRECT**
- F. Air

Explanation: Copper, aluminum, and steel are metals with relatively high thermal conductivity; wood, styrofoam, and air are common insulators.

26. (4 pts - Short Answer)

Using $q = mc\Delta T$, find the energy required for 50 g of water to warm by 25°C when $c = 4.18 \text{ J}/(\text{g}\cdot^\circ\text{C})$. Show each step.

Sample Full-Credit Answer: $\Delta T = 45 - 20 = 25^\circ\text{C}$. $q = mc\Delta T = (50 \text{ g})(4.18 \text{ J}/(\text{g}\cdot^\circ\text{C}))(25^\circ\text{C}) = 5,225 \text{ J}$.

27. (2 pts - Multiple Choice)

When no device supplies work, what direction of thermal-energy transfer is spontaneous between objects at unequal temperatures?

- A. From cold objects to hot objects
- B. From hot objects to cold objects ✓ CORRECT**
- C. Heat does not flow without work being done
- D. Heat flows equally in both directions

Explanation: Heat spontaneously flows from higher-temperature objects to lower-temperature objects.

28. (3 pts - Short Answer)

Explain why doubling the mass of an otherwise identical sample doubles its heat capacity but leaves its specific heat unchanged.

Sample Full-Credit Answer: Heat capacity is the amount of heat needed to raise the temperature of an entire object (of whatever mass) by 1°C , while specific heat is the amount of heat needed to raise the temperature of exactly 1 gram of a particular substance by 1°C . Specific heat is a property of the material itself, whereas heat capacity depends on both the material and the total mass of the object.

29. (2 pts - Multiple Choice)

A gas is heated inside a strong, sealed cylinder whose volume cannot change. Which thermodynamic process name applies?

- A. Isobaric
- B. Isothermal
- C. Isochoric ✓ CORRECT**
- D. Adiabatic

Explanation: Isochoric means constant volume.

30. (2 pts - Multiple Choice)

A closed system receives energy as heat and can return some as work. Which law supplies the energy-balance rule for the system?

- A. Heat always flows from cold objects to hot objects
- B. Energy cannot be created or destroyed, only transferred or transformed ✓ CORRECT**
- C. Entropy of an isolated system always increases
- D. All matter has the same temperature at absolute zero

Explanation: The First Law is a statement of conservation of energy.

31. (2 pts - Multiple Choice)

Which proposed statement accounts for the preferred direction of natural processes and the tendency for entropy to increase?

- A. Heat naturally flows from a colder object to a hotter object
- B. The total energy of an isolated system is always exactly conserved
- C. In any energy transfer, some usable energy becomes unusable heat, and no engine can be perfectly efficient ✓ CORRECT
- D. Pressure and volume of a gas are always inversely proportional

Explanation: The Second Law implies that some energy is always lost as unusable heat, meaning no real process (or engine) can be perfectly efficient.

32. (3 pts - Multiple Choice)

A device converts 150 J of a 600 J thermal input to work. Calculate its efficiency as a percentage.

- A. 15%
- B. 25% ✓ CORRECT
- C. 40%
- D. 60%

Explanation: Efficiency = $150 \text{ J} \div 600 \text{ J} \times 100\% = 25\%$.

33. (3 pts - Multiple Choice)

Follow the path in Figure 5 and identify the constant-pressure segment on which the system's volume grows.

- A. 1→2 ✓ CORRECT
- B. 2→3
- C. 3→4
- D. 4→1

Explanation: During 1→2, the volume increases at constant pressure (isobaric expansion), so the gas does positive work on its surroundings.

34. (2 pts - Multiple Choice)

After an engine completes a closed loop on a state diagram, which statement describes the final state of its working gas?

- A. Has more internal energy than at the start
- B. Has less internal energy than at the start
- C. Returns to its original state (same pressure, volume, and temperature) ✓ CORRECT
- D. Is completely converted into work

Explanation: A complete cycle returns the working substance to its original state, even though net work has been done.

35. (3 pts - Multi-Select)

Select every claim that correctly describes heat-engine inputs, outputs, cycling, and efficiency limits.

- A. No heat engine can be 100% efficient ✓ CORRECT
- B. All the heat absorbed by an engine is converted into useful work
- C. A heat engine requires a temperature difference between a hot and a cold reservoir to do net work ✓ CORRECT
- D. Increasing an engine's efficiency means less waste heat is produced per unit of work ✓ CORRECT
- E. Engines violate the First Law of Thermodynamics

Explanation: Statements 1, 3, and 4 are true. Statement 2 is false (some heat is always exhausted, not converted to work), and statement 5 is false (engines obey, not violate, the First Law).

36. (4 pts - Short Answer)

Compare a working substance before and after a complete engine cycle. State what returns to its starting value even though energy has crossed the system boundary.

Sample Full-Credit Answer: Over one complete cycle, the working substance undergoes a series of processes (such as expansion and compression, heating and cooling) and returns to its original pressure, volume, and temperature by the end of the cycle. In doing so, the engine converts some of the absorbed heat into net useful work, while exhausting the remaining heat to the surroundings.

37. (3 pts - Short Answer)

Use energy conservation to explain why a self-contained machine cannot continuously deliver more energy than it receives.

Sample Full-Credit Answer: Such a machine would violate the First Law of Thermodynamics, which states that energy cannot be created or destroyed – a machine cannot produce more energy output than the energy put into it. In addition, the Second Law guarantees that some energy is always lost as unusable heat in any real process, making a perfectly efficient (let alone energy-creating) machine impossible.

38. (2 pts - Multiple Choice)

Which honor attached to William Thomson became the name of the absolute-temperature unit and scale?

- A. Lord Kelvin ✓ CORRECT
- B. Sir Isaac Newton
- C. Count Rumford
- D. Baron Fourier

Explanation: William Thomson was granted the title Lord Kelvin.

39. (2 pts - Multiple Choice)

Joseph Black's experiments established two related thermal quantities. Which answer names them?

- A. The Second Law of Thermodynamics
- B. Latent heat and specific heat ✓ CORRECT

- C. The Ideal Gas Law
- D. The Stefan-Boltzmann Law

Explanation: Joseph Black's experiments led to his identification of latent heat and specific heat capacity.

40. (2 pts - Multiple Choice)

What quantitative connection between mechanical work and heat was demonstrated by James Joule?

- A. The Ideal Gas Law
- B. The mechanical equivalent of heat (the numerical relationship between work and heat) ✓ CORRECT**
- C. The Second Law of Thermodynamics
- D. The concept of absolute zero

Explanation: Joule's experiments quantified the relationship between mechanical work and the heat it produces.

41. (2 pts - Multiple Choice)

Which ideal engine analysis established an upper limit on efficiency based on reservoir temperatures?

- A. The first working steam engine
- B. An idealized, maximally efficient heat engine cycle ✓ CORRECT**
- C. The kinetic theory of gases
- D. The law of conservation of mass

Explanation: Carnot developed the concept of an idealized, reversible heat engine cycle that sets the theoretical maximum efficiency limit.

42. (2 pts - Multiple Choice)

Whose statistical treatment of microscopic particle arrangements gave entropy a molecular interpretation?

- A. James Clerk Maxwell
- B. Rudolf Clausius
- C. Ludwig Boltzmann ✓ CORRECT**
- D. Joseph Black

Explanation: Ludwig Boltzmann developed the statistical interpretation connecting entropy to the number of possible microscopic arrangements of particles.

43. (3 pts - Short Answer)

Explain how Carnot's reversible cycle provides a benchmark against which real heat engines can be judged.

Sample Full-Credit Answer: Sadi Carnot developed the concept of an idealized heat engine cycle (the Carnot cycle) and showed that there is a maximum possible efficiency for any heat engine

operating between two temperatures. His work laid an important foundation for what became the Second Law of Thermodynamics.

44. (2 pts - Multiple Choice)

Which description captures the absorption and emission behavior of the ideal surface physicists call a blackbody?

- A. Reflects all radiation that strikes it
- B. Absorbs and emits all wavelengths of electromagnetic radiation perfectly (with no reflection) ✓ CORRECT**
- C. Is always black in visible color, regardless of temperature
- D. Emits radiation only in the visible light spectrum

Explanation: A blackbody is a theoretical perfect absorber and emitter of radiation at all wavelengths. It is not necessarily visually black – for example, the Sun behaves approximately like a blackbody but appears bright.

45. (3 pts - Multiple Choice)

Study the three spectral curves in Figure 6. Which curve's peak position and intensity indicate the greatest absolute temperature?

- A. Curve 1
- B. Curve 2
- C. Curve 3 ✓ CORRECT**
- D. All three curves represent the same temperature

Explanation: Curve 3 has both the greatest overall intensity and a peak shifted to the shortest wavelength, both of which indicate it belongs to the hottest object.

46. (4 pts - Multiple Choice)

Use the T^4 relationship illustrated in Figure 7 to compare the marked radiant-exitance values at 200 K and 400 K.

- A. 2 times
- B. 4 times
- C. 8 times
- D. 16 times ✓ CORRECT**

Explanation: Since $M \propto T^4$, doubling the temperature (200 K $\rightarrow$ 400 K) increases the radiant exitance by a factor of $2^4 = 16$, which matches the graph (about 91 W/m² at 200 K vs. about 1,452 W/m² at 400 K).

47. (3 pts - Multi-Select)

Select every statement that correctly links blackbody temperature, emitted power, spectrum, and the Stefan-Boltzmann relationship.

- A. Hotter objects emit more total radiant energy than cooler objects ✓ CORRECT**
- B. Radiant exitance is directly (linearly) proportional to Kelvin temperature
- C. All real objects are perfect blackbodies

D. The Stefan-Boltzmann Law relates radiated power to the fourth power of absolute temperature ✓ CORRECT

E. Blackbody radiation can travel through the vacuum of space ✓ CORRECT

Explanation: Statements 1, 4, and 5 are correct. Statement 2 is false – radiant exitance is proportional to T^4 , not T . Statement 3 is false – real objects only approximate blackbody behavior; none are perfect blackbodies.

48. (4 pts - Short Answer)

As the curve in Figure 8 approaches 0 K, describe the entropy trend and connect it to the behavior predicted for a perfect crystal.

Sample Full-Credit Answer: The graph shows that as the temperature of a perfect crystal approaches absolute zero, its entropy also approaches zero. This illustrates the Third Law of Thermodynamics, which states that the entropy of a perfect crystal at a temperature of absolute zero is exactly zero, and that absolute zero itself can never actually be reached through any finite process.

49. (2 pts - Multiple Choice)

Which statement most accurately expresses the limiting behavior of entropy as a perfect crystal approaches absolute zero?

A. Energy cannot be created or destroyed, only transformed

B. Heat naturally flows from hot objects to cold objects

C. As the temperature of a perfect crystal approaches absolute zero, its entropy approaches a minimum (zero) value, and absolute zero itself cannot actually be reached ✓ CORRECT

D. Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other

Explanation: Option A restates the First Law, option B and D restate other laws (Second Law and Zeroth Law, respectively). Option C correctly states the Third Law.

50. (3 pts - Short Answer)

What change in the scientific treatment of thermal radiation resulted from Max Planck's introduction of discrete energy packets?

Sample Full-Credit Answer: Max Planck proposed that energy is emitted and absorbed by matter in discrete packets called quanta, rather than continuously, which allowed him to correctly derive the mathematical relationship describing the spectrum of blackbody radiation. This idea marked the beginning of quantum theory in physics.

THERMODYNAMICS C — STATE EXAM

Science Olympiad — Division C (High School)

2027

Team Name / Number: _____

Team Members: _____

Score: _____ / 144 points

TEST DIRECTIONS

- This exam contains 50 questions: 35 multiple choice, 5 multi-select, and 10 short answer, worth a total of 144 points.
- For multiple choice questions, select the ONE best answer. For multi-select questions, select ALL choices that apply — there may be more than one correct answer.
- For short answer questions, write your response — and show all calculation steps where relevant — in the space provided.
- 8 questions (#5, #12, #15, #20, #30, #40, #41, #47) ask you to analyze an accompanying figure. Figures appear directly below their associated question.
- This exam includes content on radiant exitance, blackbody radiation, the Stefan-Boltzmann Law, and the Third Law of Thermodynamics (Questions 39-44), as well as entropy and enthalpy (Questions 45-50), which are assessed only at the State and National level.
- Unless otherwise noted, answers should use metric units and appropriate significant figures.
- Calculators (Class III) and team notes may be used per Event Parameters. Show your work for full credit on calculation-based questions.

1. (2 pts - Systems & Temperature)

Object Q remains at a fixed reference temperature while samples P and R each separately equilibrate with it. Which law establishes the resulting relationship between P and R and makes temperature comparison possible?

- A. The First Law; it shows that energy is conserved between P, Q, and R
- B. The Zeroth Law; it establishes that thermal equilibrium is a transitive relationship, which is what allows temperature to be defined and measured with a thermometer
- C. The Second Law; it shows that entropy is equal among all three objects
- D. The Third Law; it proves that P, Q, and R can never reach absolute zero

2. (3 pts - Systems & Temperature)

A laboratory is held at 68°F. Convert the setting to Celsius and then add 273.15 to obtain the corresponding absolute temperature.

- A. 293.15 K

- B. 253.15 K
- C. 310.15 K
- D. 200.15 K

3. (2 pts - Systems & Temperature)

A closed vessel is replaced by another containing twice as much of the same substance in the same state. Which listed property scales with the amount present?

- A. Temperature
- B. Specific heat
- C. Total internal energy
- D. Pressure

4. (2 pts - Systems & Temperature)

Which option has the dimensions of energy and is therefore appropriate for reporting a measured heat transfer?

- A. Joule
- B. Watt
- C. Pascal
- D. Newton

5. (3 pts - Systems & Temperature)

Point X in Figure 1 is 30 K above water's freezing point. Express that location on the Fahrenheit scale.

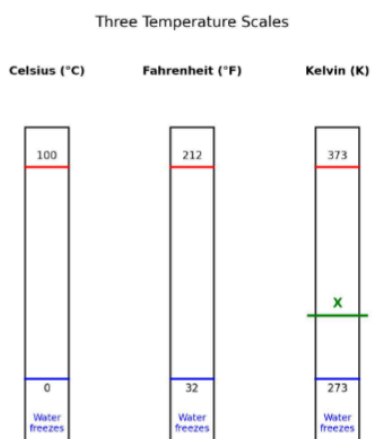


Figure 1: Three Temperature Scales

- A. 76° F
- B. 86° F
- C. 96° F
- D. 106° F

6. (3 pts - Systems & Temperature)

Separate the energy units from the units of power, temperature, and pressure. Select every valid energy unit.

(Select ALL that apply)

- A. Joule
- B. Watt
- C. Calorie
- D. British Thermal Unit (BTU)
- E. Kelvin
- F. Pascal

7. (3 pts - Systems & Temperature)

Explain how the transitive nature of thermal equilibrium permits a thermometer to compare objects that never touch one another.

8. (2 pts - Phases & Gas Law)

At the molecular level, why can a fixed mass of gas expand to fill a container while the corresponding liquid occupies a nearly fixed volume?

- A. Gas particles have lost their electrons
- B. Gas particles have enough kinetic energy to overcome intermolecular attractive forces almost entirely
- C. Gas particles are chemically different from liquid particles
- D. Gas particles have no mass

9. (3 pts - Phases & Gas Law)

A 150 g sample at 100°C absorbs 169.5 kJ entirely as latent heat. With $L_v = 2.260$ kJ/g, determine the fraction vaporized.

- A. 25%
- B. 50%
- C. 75%
- D. 100%

10. (3 pts - Phases & Gas Law)

Use the combined gas law for a sample changing from 2.0 atm, 4.0 L, 250 K to 10.0 L, 500 K. Which final pressure is obtained?

- A. 0.8 atm
- B. 1.0 atm
- C. 1.6 atm
- D. 3.2 atm

11. (3 pts - Phases & Gas Law)

Select every statement that follows from the variables, proportionalities, and assumptions represented in the ideal gas equation.

- A. At constant temperature and moles, pressure and volume are inversely proportional
- B. At constant volume and moles, pressure is directly proportional to Kelvin temperature
- C. The ideal gas law can be used with Celsius temperatures without conversion
- D. Increasing the number of moles of gas at constant P and T increases the volume
- E. The ideal gas law assumes gas particles have significant volume and strong intermolecular forces

12. (3 pts - Phases & Gas Law)

In Figure 2, increasing pressure at constant temperature crosses water's negatively sloped solid-liquid boundary. What trend does this reveal for the melting point?

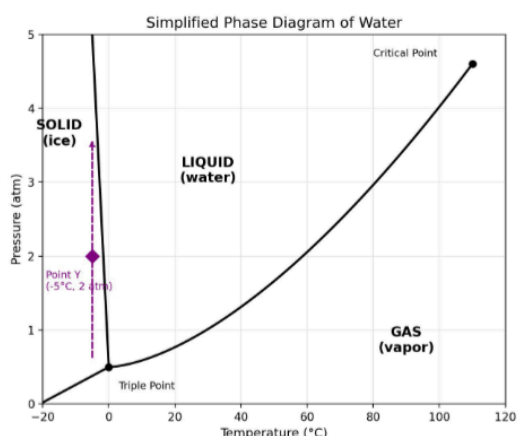


Figure 2: Simplified Phase Diagram of Water, with Point Y and a constant-temperature pressure increase shown

- A. The melting point increases significantly
- B. The melting point decreases slightly
- C. The melting point is completely unaffected by pressure
- D. Water cannot exist as a solid above 1 atm

13. (2 pts - Phases & Gas Law)

Which phase transition decreases the substance's energy and releases heat to the environment?

- A. Melting
- B. Vaporization
- C. Sublimation
- D. Condensation

14. (2 pts - Phases & Gas Law)

What special equilibrium condition exists at the single pressure-temperature coordinate where all three phase regions touch?

- A. Only the solid and liquid phases exist
- B. All three phases (solid, liquid, and gas) coexist in equilibrium
- C. The substance is at its critical temperature
- D. The substance cannot be a solid

15. (5 pts - Phases & Gas Law)

For the path from liquid water at 0°C through vapor at 100°C in Figure 3, compute the sensible-heating contribution and vaporization contribution before adding them.

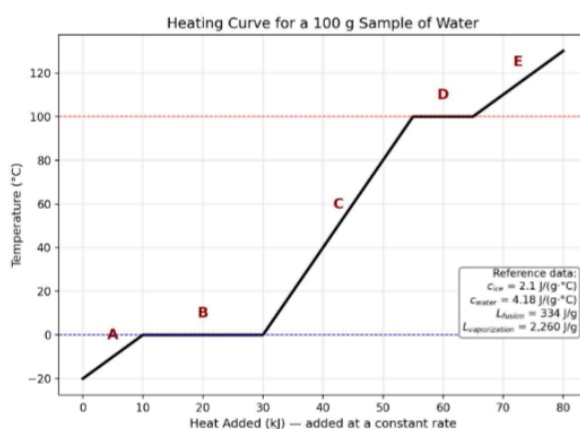


Figure 3: Heating Curve for a 100 g Sample of Water (with reference data)

16. (5 pts - Phases & Gas Law)

Find the total energy needed first to warm 75 g of ice from -15°C to 0°C and then melt it, using the provided heat capacity and latent heat.

17. (2 pts - Heat Transfer)

A temperature gradient along a solid metal utensil transfers energy from its hot end to its cool end. Which mechanism describes this process?

- A. Convection
- B. Radiation
- C. Conduction
- D. Evaporation

18. (3 pts - Heat Transfer)

A wall is rebuilt with twice its original thickness while k , area, and temperature difference are fixed. Use Fourier's law to predict the new heat-loss rate.

- A. Double the rate of heat loss
- B. Cut the rate of heat loss in half
- C. Have no effect on the rate of heat loss
- D. Quadruple the rate of heat loss

19. (2 pts - Heat Transfer)

Which factors must be combined to obtain the number of joules required to raise a whole object's temperature by one degree?

- A. Only the material it is made of
- B. Only its temperature
- C. Both the material and the total mass of the object
- D. Only its shape

20. (4 pts - Heat Transfer)

Convert the plate dimensions in the prompt to SI units, take copper's k from Figure 4, and calculate the conducted power from $kA\Delta T/d$.

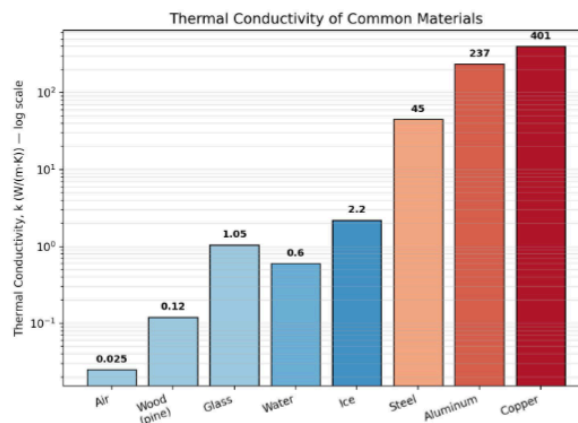


Figure 4: Thermal Conductivity of Common Materials (with k values labeled)

- A. 8,020 W
- B. 40,100 W
- C. 80,200 W
- D. 160,400 W

21. (2 pts - Heat Transfer)

Two bodies at different temperatures are placed in an insulated enclosure. Without external work, which direction of net energy exchange is permitted?

- A. From cold objects to hot objects
- B. From hot objects to cold objects
- C. Heat does not flow without work being done
- D. Heat flows equally in both directions

22. (2 pts - Heat Transfer)

A distant radiant heater warms a detector without direct contact or bulk fluid circulation. Which transfer mode dominates?

- A. Conduction
- B. Convection
- C. Radiation
- D. Evaporation

23. (3 pts - Heat Transfer)

Select each accurate statement about how conductivity and heat capacity depend on material, geometry, and sample size.

(Select ALL that apply)

- A. A material's thermal conductivity is an intensive property
- B. A larger object always has a higher thermal conductivity than a smaller object made of the same material
- C. Metals generally have higher thermal conductivity than gases
- D. Heat capacity increases as the mass of an object increases, for a given material
- E. Thermal conductivity has SI units of $\text{W}/(\text{m}\cdot\text{K})$

24. (5 pts - Heat Transfer)

For a 500 g aluminum block with $c = 0.90 \text{ J}/(\text{g}\cdot^{\circ}\text{C})$, calculate q for a rise from 20°C to 150°C and retain correct units.

25. (4 pts - Heat Transfer)

Explain why tightly coupled atoms and delocalized electrons transport thermal energy through copper more effectively than widely separated air molecules do.

26. (2 pts - Processes & Engines)

A piston-cylinder is insulated so that no thermal energy crosses its boundary. Which thermodynamic label applies to its process?

- A. No work is done on or by the system
- B. No heat is exchanged between the system and its surroundings
- C. The temperature of the system remains constant
- D. The pressure of the system remains constant

27. (3 pts - Processes & Engines)

Apply the sign convention in $\Delta U = Q - W$ when 750 J enters as heat and the gas delivers 300 J of work.

- A. 450 J
- B. 1,050 J
- C. -450 J
- D. 300 J

28. (2 pts - Processes & Engines)

Which observation best reflects the fact that total entropy does not spontaneously decrease?

- A. A perpetual motion machine that runs forever with no energy input is possible
- B. Heat spontaneously flows from a cold object to a hot object
- C. No heat engine can convert 100% of the heat it absorbs into useful work
- D. Energy can be created from nothing

29. (2 pts - Processes & Engines)

Besides its two isotherms, what two thermally insulated paths close a reversible Carnot cycle?

- A. Two isobaric processes
- B. Two adiabatic processes
- C. Two isochoric processes
- D. Two isenthalpic processes

30. (4 pts - Processes & Engines)

For the reservoirs shown in Figure 5, compute $1 - 200/800$ and interpret the result as the maximum possible efficiency.

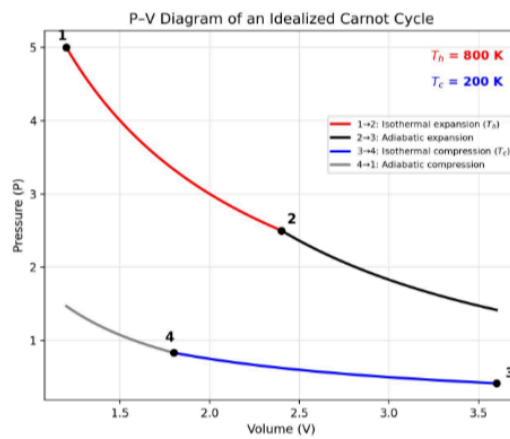


Figure 5: P-V Diagram of an Idealized Carnot Cycle

- A. 25%
- B. 50%
- C. 75%
- D. 90%

31. (2 pts - Processes & Engines)

A working gas traces a closed P-V path and returns to its starting coordinates. What must therefore be true of its thermodynamic state?

- A. Has more internal energy than at the start
- B. Has less internal energy than at the start
- C. Returns to its original state (same pressure, volume, and temperature)
- D. Is completely converted into work

32. (3 pts - Processes & Engines)

Select every statement consistent with the energy flow and theoretical limits of a cyclic heat engine.

(Select ALL that apply)

- A. No heat engine can be 100% efficient
- B. All the heat absorbed by an engine is converted into useful work
- C. A heat engine requires a temperature difference between a hot and a cold reservoir to do net work
- D. Increasing an engine's efficiency means less waste heat is produced per unit of work
- E. Engines violate the First Law of Thermodynamics

33. (5 pts - Processes & Engines)

Both engines use the same hot and cold reservoirs, but only one is reversible. Explain why the Carnot device establishes the upper efficiency and why friction lowers the real device's value.

34. (2 pts - History)

Which concept and law did Clausius help formalize when analyzing irreversible heat flow?

- A. Discovering latent heat
- B. Formulating a mathematical statement of the Second Law of Thermodynamics and introducing the concept of entropy
- C. Establishing the mechanical equivalent of heat
- D. Developing the kinetic theory of gases

35. (2 pts - History)

Which contribution of Maxwell connected probability distributions with molecular speeds in a gas?

- A. The invention of the steam engine
- B. Describing the statistical distribution of molecular speeds in a gas (part of the kinetic theory of gases)
- C. The discovery of the Zeroth Law
- D. The construction of the first working refrigerator

36. (2 pts - History)

Which researcher expressed entropy in terms of the number of accessible microscopic arrangements?

- A. James Clerk Maxwell
- B. Rudolf Clausius
- C. Ludwig Boltzmann
- D. Joseph Black

37. (2 pts - History)

Planck proposed discrete exchanges of energy to resolve what failure of classical predictions?

- A. The photoelectric effect
- B. The spectrum of blackbody radiation
- C. The structure of the atom
- D. The theory of relativity

38. (3 pts - History)

Summarize how Carnot used an ideal reversible cycle to relate engine performance to hot- and cold-reservoir temperatures.

39. (2 pts - Radiation & Third Law)

Which idealized surface absorbs all incident electromagnetic radiation and emits a temperature-dependent spectrum?

- A. Reflects all radiation that strikes it
- B. Absorbs and emits all wavelengths of electromagnetic radiation perfectly (with no reflection)
- C. Is always black in visible color, regardless of temperature
- D. Emits radiation only in the visible light spectrum

40. (3 pts - Radiation & Third Law)

Use both peak location and curve height in Figure 6 to identify the spectrum belonging to the hottest source.

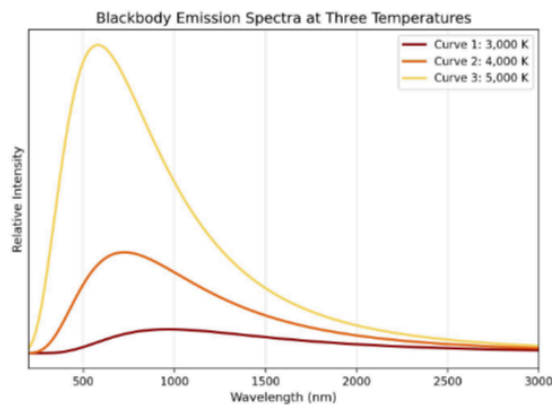


Figure 6: Blackbody Emission Spectra at Three Temperatures

- A. Curve 1
- B. Curve 2
- C. Curve 3
- D. All three curves represent the same temperature

41. (5 pts - Radiation & Third Law)

Substitute 300 K into $M = \sigma T^4$ with $\sigma = 5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$, using Figure 7 only as context, and calculate M .

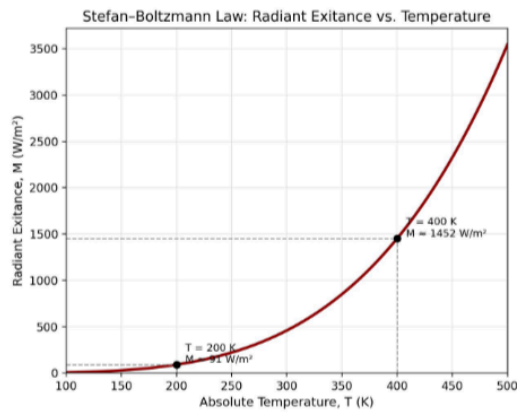


Figure 7: Stefan-Boltzmann Law – Radiant Exitance vs. Temperature

- A. 46 W/m²
- B. 459 W/m²
- C. 4,590 W/m²
- D. 45,900 W/m²

42. (3 pts - Radiation & Third Law)

Select every accurate consequence of M proportional to T^4 and of the temperature dependence of a blackbody spectrum.

(Select ALL that apply)

- A. Hotter objects emit more total radiant energy than cooler objects
- B. Radiant exitance is directly (linearly) proportional to Kelvin temperature
- C. All real objects are perfect blackbodies
- D. The Stefan-Boltzmann Law relates radiated power to the fourth power of absolute temperature
- E. Blackbody radiation can travel through the vacuum of space

43. (2 pts - Radiation & Third Law)

Which option correctly describes the entropy limit for a perfect crystal as temperature tends toward 0 K?

- A. Energy cannot be created or destroyed, only transformed
- B. Heat naturally flows from hot objects to cold objects
- C. As the temperature of a perfect crystal approaches absolute zero, its entropy approaches a minimum (zero) value, and absolute zero itself cannot actually be reached
- D. Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other

44. (3 pts - Radiation & Third Law)

Clarify the practical meaning of saying absolute zero is unattainable, including what happens as successive cooling steps approach it.

45. (2 pts - Entropy & Enthalpy)

Which description best connects entropy with the number of microscopic arrangements compatible with a macroscopic state?

- A. A measure of the total energy of a system
- B. A measure of the disorder, or the number of possible microscopic arrangements, of a system
- C. The heat content of a system at constant pressure
- D. The rate of heat transfer through a material

46. (2 pts - Entropy & Enthalpy)

Which thermodynamic state function equals $U + PV$ and is especially useful for constant-pressure energy accounting?

- A. A measure of disorder in a system
- B. The total kinetic energy of a system's particles
- C. A thermodynamic quantity equal to a system's internal energy plus the product of its pressure and volume, often used to describe heat content at constant pressure
- D. The temperature at which a system's entropy is zero

47. (4 pts - Entropy & Enthalpy)

The curve in Figure 8 contains entropy jumps at melting and boiling. Which labeled transition produces the greatest jump?

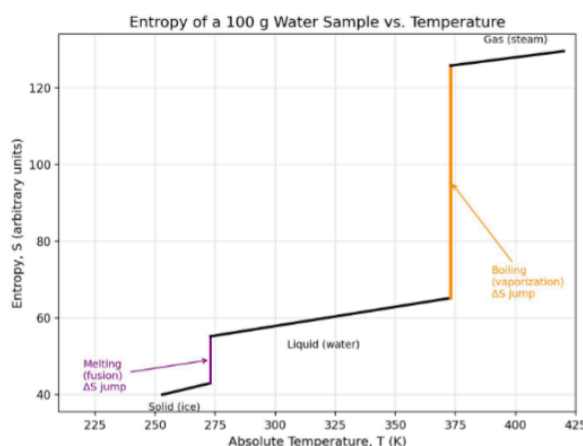


Figure 8: Entropy of a 100 g Water Sample vs. Temperature

- A. The gradual rise while heating solid ice
- B. The vertical jump at the melting point
- C. The gradual rise while heating liquid water
- D. The vertical jump at the boiling point

48. (2 pts - Entropy & Enthalpy)

For a spontaneous change in an isolated system, which sign or limiting value is permitted for the system's entropy change?

- A. ΔS is always negative
- B. ΔS is always exactly zero
- C. ΔS is always positive or zero
- D. ΔS depends only on the system's temperature

49. (5 pts - Entropy & Enthalpy)

A 20 g ice sample melts reversibly at 273 K. Calculate Q from mL_f and then use $\Delta S = Q/T$.

50. (4 pts - Entropy & Enthalpy)

Explain why the heat exchanged at constant pressure is represented by ΔH and how that makes enthalpy useful for analyzing physical or chemical changes.

THERMODYNAMICS C — STATE EXAM

ANSWER KEY

Division C (High School) — Honors Level — 2027 Draft Rules, Section 3

1. (2 pts - Multiple Choice)

Object Q remains at a fixed reference temperature while samples P and R each separately equilibrate with it. Which law establishes the resulting relationship between P and R and makes temperature comparison possible?

- A. The First Law; it shows that energy is conserved between P, Q, and R
- B. The Zeroth Law; it establishes that thermal equilibrium is a transitive relationship, which is what allows temperature to be defined and measured with a thermometer ✓ CORRECT**
- C. The Second Law; it shows that entropy is equal among all three objects
- D. The Third Law; it proves that P, Q, and R can never reach absolute zero

Explanation: The Zeroth Law establishes the transitive property of thermal equilibrium, which is the logical basis for using a thermometer to compare and define temperature.

2. (3 pts - Multiple Choice)

A laboratory is held at 68°F. Convert the setting to Celsius and then add 273.15 to obtain the corresponding absolute temperature.

- A. 293.15 K ✓ CORRECT**
- B. 253.15 K
- C. 310.15 K
- D. 200.15 K

Explanation: $(5/9)(68 - 32) = (5/9)(36) = 20.0^{\circ}\text{C}$. Then $20.0 + 273.15 = 293.15\text{ K}$.

3. (2 pts - Multiple Choice)

A closed vessel is replaced by another containing twice as much of the same substance in the same state. Which listed property scales with the amount present?

- A. Temperature
- B. Specific heat
- C. Total internal energy ✓ CORRECT**
- D. Pressure

Explanation: Total internal energy scales with the amount of matter in a system, so it is extensive. The others are all intensive.

4. (2 pts - Multiple Choice)

Which option has the dimensions of energy and is therefore appropriate for reporting a measured heat transfer?

- A. Joule ✓ CORRECT**

- B. Watt
- C. Pascal
- D. Newton

Explanation: The joule is the SI unit of energy, including heat. Watt is power, pascal is pressure, and newton is force.

5. (3 pts - Multiple Choice)

Point X in Figure 1 is 30 K above water's freezing point. Express that location on the Fahrenheit scale.

- A. 76 °F
- B. 86 °F ✓ CORRECT**
- C. 96 °F
- D. 106 °F

Explanation: 30% of the 100 K span above 273 K gives $X = 273 + 30 = 303$ K, i.e. 30 °C. Converting to Fahrenheit: $^{\circ}\text{F} = (9/5)(30) + 32 = 54 + 32 = 86^{\circ}\text{F}$.

6. (3 pts - Multi-Select)

Separate the energy units from the units of power, temperature, and pressure. Select every valid energy unit.

- A. Joule ✓ CORRECT**
- B. Watt
- C. Calorie ✓ CORRECT**
- D. British Thermal Unit (BTU) ✓ CORRECT**
- E. Kelvin
- F. Pascal

Explanation: Joule, calorie, and BTU are all units of energy/heat. Watt is power, Kelvin is temperature, and Pascal is pressure.

7. (3 pts - Short Answer)

Explain how the transitive nature of thermal equilibrium permits a thermometer to compare objects that never touch one another.

Sample Full-Credit Answer: Without the Zeroth Law, there would be no logical basis for comparing the temperatures of two objects that are not in direct contact with each other. The law establishes that thermal equilibrium is transitive, which is what allows a thermometer (acting as a third object) to be used to indirectly compare and assign temperature values to other objects.

8. (2 pts - Multiple Choice)

At the molecular level, why can a fixed mass of gas expand to fill a container while the corresponding liquid occupies a nearly fixed volume?

- A. Gas particles have lost their electrons
- B. Gas particles have enough kinetic energy to overcome intermolecular attractive forces almost entirely ✓ CORRECT**

- C. Gas particles are chemically different from liquid particles
- D. Gas particles have no mass

Explanation: In the gas phase, particles possess enough kinetic energy to largely overcome the attractive intermolecular forces that hold particles close together in a liquid.

9. (3 pts - Multiple Choice)

A 150 g sample at 100°C absorbs 169.5 kJ entirely as latent heat. With $L_v = 2.260$ kJ/g, determine the fraction vaporized.

- A. 25%
- B. 50% ✓ CORRECT
- C. 75%
- D. 100%

Explanation: Mass vaporized = $169,500 \text{ J} \div 2,260 \text{ J/g} = 75 \text{ g}$. Fraction = $75 \text{ g} \div 150 \text{ g} = 0.50$, or 50%.

10. (3 pts - Multiple Choice)

Use the combined gas law for a sample changing from 2.0 atm, 4.0 L, 250 K to 10.0 L, 500 K. Which final pressure is obtained?

- A. 0.8 atm
- B. 1.0 atm
- C. 1.6 atm ✓ CORRECT
- D. 3.2 atm

Explanation: $P_2 = P_1 V_1 T_2 / (T_1 V_2) = (2.0 \text{ atm})(4.0 \text{ L})(500 \text{ K}) / [(250 \text{ K})(10.0 \text{ L})] = 4,000 / 2,500 = 1.6 \text{ atm}$.

11. (3 pts - Multi-Select)

Select every statement that follows from the variables, proportionalities, and assumptions represented in the ideal gas equation.

- A. At constant temperature and moles, pressure and volume are inversely proportional ✓ CORRECT
- B. At constant volume and moles, pressure is directly proportional to Kelvin temperature ✓ CORRECT
- C. The ideal gas law can be used with Celsius temperatures without conversion
- D. Increasing the number of moles of gas at constant P and T increases the volume ✓ CORRECT
- E. The ideal gas law assumes gas particles have significant volume and strong intermolecular forces

Explanation: Statements 1, 2, and 4 correctly describe relationships within $PV = nRT$. Temperature must always be converted to Kelvin (statement 3 is false), and the ideal gas model assumes negligible particle volume and no intermolecular forces (statement 5 is false).

12. (3 pts - Multiple Choice)

In Figure 2, increasing pressure at constant temperature crosses water's negatively sloped solid-liquid boundary. What trend does this reveal for the melting point?

- A. The melting point increases significantly
- B. The melting point decreases slightly ✓ CORRECT**
- C. The melting point is completely unaffected by pressure
- D. Water cannot exist as a solid above 1 atm

Explanation: Because the solid-liquid line has a negative slope, increasing pressure at a constant sub-zero temperature can cross from the solid region into the liquid region – meaning water's melting point decreases slightly as pressure increases.

13. (2 pts - Multiple Choice)

Which phase transition decreases the substance's energy and releases heat to the environment?

- A. Melting
- B. Vaporization
- C. Sublimation
- D. Condensation ✓ CORRECT**

Explanation: Condensation (gas → liquid) releases energy as intermolecular bonds form. Melting, vaporization, and sublimation are all endothermic.

14. (2 pts - Multiple Choice)

What special equilibrium condition exists at the single pressure-temperature coordinate where all three phase regions touch?

- A. Only the solid and liquid phases exist
- B. All three phases (solid, liquid, and gas) coexist in equilibrium ✓ CORRECT**
- C. The substance is at its critical temperature
- D. The substance cannot be a solid

Explanation: The triple point is the unique combination of temperature and pressure at which the solid, liquid, and gas phases all coexist in equilibrium.

15. (5 pts - Short Answer)

For the path from liquid water at 0°C through vapor at 100°C in Figure 3, compute the sensible-heating contribution and vaporization contribution before adding them.

Sample Full-Credit Answer: Segment C (warming liquid water from 0°C to 100°C): $q_1 = mc\Delta T = (100\text{ g})(4.18\text{ J/(g}\cdot^\circ\text{C)})(100^\circ\text{C}) = 41,800\text{ J}$. Segment D (vaporizing at 100°C): $q_2 = m\Delta_{\text{vaporization}} = (100\text{ g})(2,260\text{ J/g}) = 226,000\text{ J}$. Total heat = $q_1 + q_2 = 41,800\text{ J} + 226,000\text{ J} = 267,800\text{ J}$ (267.8 kJ).

16. (5 pts - Short Answer)

Find the total energy needed first to warm 75 g of ice from -15°C to 0°C and then melt it, using the provided heat capacity and latent heat.

Sample Full-Credit Answer: Step 1 (warming ice from -15°C to 0°C): $q_1 = mc\Delta T = (75\text{ g})(2.1\text{ J/(g}\cdot^{\circ}\text{C)})(15^{\circ}\text{C}) = 2,362.5\text{ J}$. Step 2 (melting at 0°C): $q_2 = mL_{\text{fusion}} = (75\text{ g})(334\text{ J/g}) = 25,050\text{ J}$. Total heat = $2,362.5\text{ J} + 25,050\text{ J} = 27,412.5\text{ J}$ ($\approx 27,413\text{ J}$).

17. (2 pts - Multiple Choice)

A temperature gradient along a solid metal utensil transfers energy from its hot end to its cool end. Which mechanism describes this process?

- A. Convection
- B. Radiation
- C. Conduction ✓ CORRECT
- D. Evaporation

Explanation: Conduction is the transfer of heat through direct contact between particles of a material.

18. (3 pts - Multiple Choice)

A wall is rebuilt with twice its original thickness while k , area, and temperature difference are fixed. Use Fourier's law to predict the new heat-loss rate.

- A. Double the rate of heat loss
- B. Cut the rate of heat loss in half ✓ CORRECT
- C. Have no effect on the rate of heat loss
- D. Quadruple the rate of heat loss

Explanation: Since Q/t is inversely proportional to thickness d , doubling d cuts the rate of heat transfer in half.

19. (2 pts - Multiple Choice)

Which factors must be combined to obtain the number of joules required to raise a whole object's temperature by one degree?

- A. Only the material it is made of
- B. Only its temperature
- C. Both the material and the total mass of the object ✓ CORRECT
- D. Only its shape

Explanation: Heat capacity is an extensive property – it scales with both the specific heat of the material and the total mass of the object.

20. (4 pts - Multiple Choice)

Convert the plate dimensions in the prompt to SI units, take copper's k from Figure 4, and calculate the conducted power from $kA\Delta T/d$.

- A. 8,020 W
- B. 40,100 W
- C. 80,200 W ✓ CORRECT
- D. 160,400 W

Explanation: $Q/t = kA\Delta T/d = (401 \text{ W/(m}\cdot\text{K)})(0.050 \text{ m}^2)(8^\circ\text{C}) / (0.0020 \text{ m}) = 160.4 / 0.0020 = 80,200 \text{ W}$.

21. (2 pts - Multiple Choice)

Two bodies at different temperatures are placed in an insulated enclosure. Without external work, which direction of net energy exchange is permitted?

- A. From cold objects to hot objects
- B. From hot objects to cold objects ✓ CORRECT**
- C. Heat does not flow without work being done
- D. Heat flows equally in both directions

Explanation: Heat spontaneously flows from higher-temperature objects to lower-temperature objects.

22. (2 pts - Multiple Choice)

A distant radiant heater warms a detector without direct contact or bulk fluid circulation. Which transfer mode dominates?

- A. Conduction
- B. Convection
- C. Radiation ✓ CORRECT**
- D. Evaporation

Explanation: Radiation transfers energy as electromagnetic waves and does not require a medium.

23. (3 pts - Multi-Select)

Select each accurate statement about how conductivity and heat capacity depend on material, geometry, and sample size.

- A. A material's thermal conductivity is an intensive property ✓ CORRECT**
- B. A larger object always has a higher thermal conductivity than a smaller object made of the same material
- C. Metals generally have higher thermal conductivity than gases ✓ CORRECT**
- D. Heat capacity increases as the mass of an object increases, for a given material ✓ CORRECT**
- E. Thermal conductivity has SI units of W/(m·K) ✓ CORRECT**

Explanation: Thermal conductivity (k) is intensive — it does not depend on object size, so statement 2 is false. Statements 1, 3, 4, and 5 are all correct.

24. (5 pts - Short Answer)

For a 500 g aluminum block with $c = 0.90 \text{ J/(g}\cdot^\circ\text{C)}$, calculate q for a rise from 20°C to 150°C and retain correct units.

Sample Full-Credit Answer: First convert mass to grams: $0.50 \text{ kg} = 500 \text{ g}$. $\Delta T = 150^\circ\text{C} - 20^\circ\text{C} = 130^\circ\text{C}$. $q = mc\Delta T = (500 \text{ g})(0.90 \text{ J/(g}\cdot^\circ\text{C)})(130^\circ\text{C}) = 58,500 \text{ J}$ (58.5 kJ).

25. (4 pts - Short Answer)

Explain why tightly coupled atoms and delocalized electrons transport thermal energy through copper more effectively than widely separated air molecules do.

Sample Full-Credit Answer: In metals, atoms are packed closely together, and free electrons can move readily throughout the material, rapidly transferring kinetic energy from hotter regions to cooler regions through both particle collisions and electron movement. In gases, particles are far apart and collide much less frequently, so kinetic energy is transferred far more slowly, making gases poor conductors (good insulators) compared to metals.

26. (2 pts - Multiple Choice)

A piston-cylinder is insulated so that no thermal energy crosses its boundary. Which thermodynamic label applies to its process?

- A. No work is done on or by the system
- B. No heat is exchanged between the system and its surroundings ✓ CORRECT**
- C. The temperature of the system remains constant
- D. The pressure of the system remains constant

Explanation: Adiabatic means $Q = 0$ — no heat enters or leaves the system, though work and temperature can still change.

27. (3 pts - Multiple Choice)

Apply the sign convention in $\Delta U = Q - W$ when 750 J enters as heat and the gas delivers 300 J of work.

- A. 450 J ✓ CORRECT**
- B. 1,050 J
- C. -450 J
- D. 300 J

Explanation: $\Delta U = Q - W = 750 \text{ J} - 300 \text{ J} = 450 \text{ J}$.

28. (2 pts - Multiple Choice)

Which observation best reflects the fact that total entropy does not spontaneously decrease?

- A. A perpetual motion machine that runs forever with no energy input is possible
- B. Heat spontaneously flows from a cold object to a hot object
- C. No heat engine can convert 100% of the heat it absorbs into useful work ✓ CORRECT**
- D. Energy can be created from nothing

Explanation: The Second Law implies that some energy is always lost as unusable heat, so no heat engine can be perfectly (100%) efficient.

29. (2 pts - Multiple Choice)

Besides its two isotherms, what two thermally insulated paths close a reversible Carnot cycle?

- A. Two isobaric processes
- B. Two adiabatic processes ✓ CORRECT**

- C. Two isochoric processes
- D. Two isenthalpic processes

Explanation: The idealized Carnot cycle consists of two isothermal processes connected by two adiabatic processes.

30. (4 pts - Multiple Choice)

For the reservoirs shown in Figure 5, compute $1 - 200/800$ and interpret the result as the maximum possible efficiency.

- A. 25%
- B. 50%
- C. 75% ✓ CORRECT**
- D. 90%

Explanation: $\eta = 1 - (200\text{ K} / 800\text{ K}) = 1 - 0.25 = 0.75$, or 75%.

31. (2 pts - Multiple Choice)

A working gas traces a closed P-V path and returns to its starting coordinates. What must therefore be true of its thermodynamic state?

- A. Has more internal energy than at the start
- B. Has less internal energy than at the start
- C. Returns to its original state (same pressure, volume, and temperature) ✓ CORRECT**
- D. Is completely converted into work

Explanation: A complete cycle returns the working substance to its original state, even though net work has been done.

32. (3 pts - Multi-Select)

Select every statement consistent with the energy flow and theoretical limits of a cyclic heat engine.

- A. No heat engine can be 100% efficient ✓ CORRECT**
- B. All the heat absorbed by an engine is converted into useful work
- C. A heat engine requires a temperature difference between a hot and a cold reservoir to do net work ✓ CORRECT**
- D. Increasing an engine's efficiency means less waste heat is produced per unit of work ✓ CORRECT**
- E. Engines violate the First Law of Thermodynamics

Explanation: Statements 1, 3, and 4 are true. Statement 2 is false (some heat is always exhausted, not converted to work), and statement 5 is false (engines obey, not violate, the First Law).

33. (5 pts - Short Answer)

Both engines use the same hot and cold reservoirs, but only one is reversible. Explain why the Carnot device establishes the upper efficiency and why friction lowers the real device's value.

Sample Full-Credit Answer: The idealized Carnot engine (Engine 2) will always have a higher (or, at best, equal) efficiency than the real engine, because the reversible Carnot cycle represents the theoretical maximum efficiency possible between two given temperature reservoirs. Real engines have irreversible losses, such as friction and unwanted heat transfer, which the Second Law of Thermodynamics guarantees will always keep their efficiency below the Carnot limit.

34. (2 pts - Multiple Choice)

Which concept and law did Clausius help formalize when analyzing irreversible heat flow?

- A. Discovering latent heat
- B. Formulating a mathematical statement of the Second Law of Thermodynamics and introducing the concept of entropy ✓ CORRECT**
- C. Establishing the mechanical equivalent of heat
- D. Developing the kinetic theory of gases

Explanation: Clausius formalized the Second Law and is credited with introducing the term and concept of entropy.

35. (2 pts - Multiple Choice)

Which contribution of Maxwell connected probability distributions with molecular speeds in a gas?

- A. The invention of the steam engine
- B. Describing the statistical distribution of molecular speeds in a gas (part of the kinetic theory of gases) ✓ CORRECT**
- C. The discovery of the Zeroth Law
- D. The construction of the first working refrigerator

Explanation: Maxwell developed the statistical distribution describing the range of molecular speeds in a gas at a given temperature.

36. (2 pts - Multiple Choice)

Which researcher expressed entropy in terms of the number of accessible microscopic arrangements?

- A. James Clerk Maxwell
- B. Rudolf Clausius
- C. Ludwig Boltzmann ✓ CORRECT**
- D. Joseph Black

Explanation: Ludwig Boltzmann developed the statistical interpretation connecting entropy to the number of possible microscopic arrangements of particles.

37. (2 pts - Multiple Choice)

Planck proposed discrete exchanges of energy to resolve what failure of classical predictions?

- A. The photoelectric effect
- B. The spectrum of blackbody radiation ✓ CORRECT**

- C. The structure of the atom
- D. The theory of relativity

Explanation: Planck proposed that energy is emitted and absorbed in discrete quanta to correctly derive the observed spectrum of blackbody radiation.

38. (3 pts - Short Answer)

Summarize how Carnot used an ideal reversible cycle to relate engine performance to hot- and cold-reservoir temperatures.

Sample Full-Credit Answer: Sadi Carnot developed the concept of an idealized heat engine cycle (the Carnot cycle) and showed that there is a maximum possible efficiency for any heat engine operating between two given temperatures. His work laid an important foundation for what became the Second Law of Thermodynamics.

39. (2 pts - Multiple Choice)

Which idealized surface absorbs all incident electromagnetic radiation and emits a temperature-dependent spectrum?

- A. Reflects all radiation that strikes it
- B. Absorbs and emits all wavelengths of electromagnetic radiation perfectly (with no reflection) ✓ CORRECT**
- C. Is always black in visible color, regardless of temperature
- D. Emits radiation only in the visible light spectrum

Explanation: A blackbody is a theoretical perfect absorber and emitter of radiation at all wavelengths. It is not necessarily visually black — the Sun, for example, behaves approximately like a blackbody but appears bright.

40. (3 pts - Multiple Choice)

Use both peak location and curve height in Figure 6 to identify the spectrum belonging to the hottest source.

- A. Curve 1
- B. Curve 2
- C. Curve 3 ✓ CORRECT**
- D. All three curves represent the same temperature

Explanation: Curve 3 has both the greatest overall intensity and a peak shifted to the shortest wavelength, both of which indicate it belongs to the hottest object.

41. (5 pts - Multiple Choice)

Substitute 300 K into $M = \sigma T^4$ with $\sigma = 5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$, using Figure 7 only as context, and calculate M.

- A. 46 W/m²
- B. 459 W/m² ✓ CORRECT**
- C. 4,590 W/m²
- D. 45,900 W/m²

Explanation: $M = \sigma T^4 = (5.67 \times 10^{-8})(300)^4 = (5.67 \times 10^{-8})(8.1 \times 10^9) \approx 459 \text{ W/m}^2$.

42. (3 pts - Multi-Select)

Select every accurate consequence of M proportional to T^4 and of the temperature dependence of a blackbody spectrum.

- A. Hotter objects emit more total radiant energy than cooler objects ✓ CORRECT**
- B. Radiant exitance is directly (linearly) proportional to Kelvin temperature
- C. All real objects are perfect blackbodies
- D. The Stefan-Boltzmann Law relates radiated power to the fourth power of absolute temperature ✓ CORRECT**
- E. Blackbody radiation can travel through the vacuum of space ✓ CORRECT**

Explanation: Statements 1, 4, and 5 are correct. Statement 2 is false — radiant exitance is proportional to T^4 , not T . Statement 3 is false — real objects only approximate blackbody behavior.

43. (2 pts - Multiple Choice)

Which option correctly describes the entropy limit for a perfect crystal as temperature tends toward 0 K?

- A. Energy cannot be created or destroyed, only transformed
- B. Heat naturally flows from hot objects to cold objects
- C. As the temperature of a perfect crystal approaches absolute zero, its entropy approaches a minimum (zero) value, and absolute zero itself cannot actually be reached ✓ CORRECT**
- D. Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other

Explanation: Option A restates the First Law, option B restates part of the Second Law, and option D restates the Zeroth Law. Option C correctly states the Third Law.

44. (3 pts - Short Answer)

Clarify the practical meaning of saying absolute zero is unattainable, including what happens as successive cooling steps approach it.

Sample Full-Credit Answer: The Third Law implies that while a system's entropy can get arbitrarily close to its minimum value as its temperature approaches absolute zero, it is impossible to actually cool any real system to exactly 0 K using a finite number of steps or processes. This makes absolute zero a theoretical limiting value rather than a temperature that can actually be reached.

45. (2 pts - Multiple Choice)

Which description best connects entropy with the number of microscopic arrangements compatible with a macroscopic state?

- A. A measure of the total energy of a system
- B. A measure of the disorder, or the number of possible microscopic arrangements, of a system ✓ CORRECT**
- C. The heat content of a system at constant pressure

D. The rate of heat transfer through a material

Explanation: Entropy is a measure of a system's disorder or the number of ways its particles can be microscopically arranged while producing the same macroscopic state.

46. (2 pts - Multiple Choice)

Which thermodynamic state function equals $U + PV$ and is especially useful for constant-pressure energy accounting?

A. A measure of disorder in a system

B. The total kinetic energy of a system's particles

C. A thermodynamic quantity equal to a system's internal energy plus the product of its pressure and volume, often used to describe heat content at constant pressure
✓ CORRECT

D. The temperature at which a system's entropy is zero

Explanation: Enthalpy ($H = U + PV$) is a convenient thermodynamic quantity because, at constant pressure, the change in enthalpy equals the heat absorbed or released by a system.

47. (4 pts - Multiple Choice)

The curve in Figure 8 contains entropy jumps at melting and boiling. Which labeled transition produces the greatest jump?

A. The gradual rise while heating solid ice

B. The vertical jump at the melting point

C. The gradual rise while heating liquid water

D. The vertical jump at the boiling point ✓ CORRECT

Explanation: The vertical jump at the boiling point (vaporization) is by far the largest entropy increase, since $\Delta S = \Delta H/T$ and the latent heat of vaporization is much larger than the latent heat of fusion.

48. (2 pts - Multiple Choice)

For a spontaneous change in an isolated system, which sign or limiting value is permitted for the system's entropy change?

A. ΔS is always negative

B. ΔS is always exactly zero

C. ΔS is always positive or zero ✓ CORRECT

D. ΔS depends only on the system's temperature

Explanation: The Second Law states that the entropy of an isolated system undergoing a spontaneous process never decreases — $\Delta S \geq 0$.

49. (5 pts - Short Answer)

A 20 g ice sample melts reversibly at 273 K. Calculate Q from mL_f and then use $\Delta S = Q/T$.

Sample Full-Credit Answer: $Q = mL = (20 \text{ g})(334 \text{ J/g}) = 6,680 \text{ J}$. $\Delta S = Q/T = 6,680 \text{ J} \div 273 \text{ K} \approx 24.5 \text{ J/K}$.

50. (4 pts - Short Answer)

Explain why the heat exchanged at constant pressure is represented by ΔH and how that makes enthalpy useful for analyzing physical or chemical changes.

Sample Full-Credit Answer: At constant pressure, the change in a system's enthalpy (ΔH) is equal to the heat absorbed or released by the system ($q_p = \Delta H$). This makes enthalpy a convenient quantity for tracking heat flow in processes that occur at constant pressure — such as most everyday physical and chemical changes occurring in open containers — without needing to separately account for pressure-volume work.

THERMODYNAMICS B — NATIONAL EXAM

Science Olympiad — Division B (Middle School)

2027

Team Name / Number: _____

Team Members: _____

Score: _____ / 214 points

TEST DIRECTIONS

- *This exam contains 80 questions: 60 multiple choice, 5 multi-select, 10 short answer, and 5 long answer, worth a total of 214 points.*
- *For multiple choice questions, select the ONE best answer. For multi-select questions, select ALL choices that apply — there may be more than one correct answer.*
- *For short answer questions, write a brief response (one or two sentences, plus any calculation work) in the space provided. For long answer questions, write a more complete response (three to four sentences) that fully addresses every part of the prompt.*
- *10 questions (#5, #17, #18, #33, #40, #50, #55, #71, #72, #74) ask you to analyze an accompanying figure. Figures appear directly below their associated question.*
- *This exam includes content on radiant exitance, blackbody radiation, the Stefan-Boltzmann Law, and the Third Law of Thermodynamics (Questions 70-80), which is assessed only at the State and National level.*
- *Unless otherwise noted, answers should use metric units and appropriate significant figures.*
- *Calculators (Class III) and team notes may be used per Event Parameters. Show your work for full credit on calculation-based questions.*

1. (2 pts - Systems & Temperature)

According to the Zeroth Law of Thermodynamics, if Object A is in thermal equilibrium with Object B, and Object B is in thermal equilibrium with Object C, what can be concluded about Object A and Object C?

- A. Object A and Object C will always have different temperatures
- B. Object A and Object C are in thermal equilibrium with each other
- C. Object A and Object C cannot be measured with the same thermometer
- D. Object A and Object C must be made of the same material

2. (2 pts - Systems & Temperature)

The formula for converting Celsius to Fahrenheit is $^{\circ}\text{F} = (9/5)(^{\circ}\text{C}) + 32$. What is the Fahrenheit temperature equivalent to 20°C ?

- A. 52°F
- B. 68°F
- C. 36°F
- D. 72°F

3. (2 pts - Systems & Temperature)

Which property of a system is classified as an intensive property (does NOT depend on the amount of matter present)?

- A. Mass
- B. Volume
- C. Density
- D. Total thermal energy

4. (2 pts - Systems & Temperature)

Which unit is defined as the amount of heat required to raise the temperature of 1 gram of water by 1°C ?

- A. Joule
- B. Watt
- C. Calorie
- D. Kelvin

5. (3 pts - Systems & Temperature)

Refer to Figure 1. Point X marks a temperature that is 65% of the way up the Celsius column, measured from water's freezing point to water's boiling point. What is the approximate Celsius temperature at Point X?

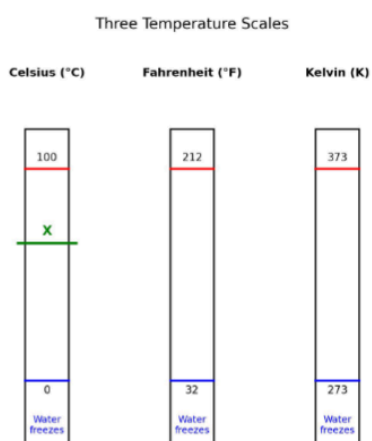


Figure 1: Three Temperature Scales

- A. 35° C
- B. 50° C
- C. 65° C
- D. 80° C

6. (2 pts - Systems & Temperature)

Approximately how many joules are equivalent to 5 calories? (1 calorie $\approx$ 4.18 J)

- A. 4.18 J
- B. 9.0 J
- C. 20.9 J
- D. 41.8 J

7. (3 pts - Systems & Temperature)

Select ALL of the following that are examples of INTENSIVE properties of a system.

(Select ALL that apply)

- A. Temperature
- B. Mass
- C. Density
- D. Volume
- E. Boiling point
- F. Total heat content

8. (3 pts - Systems & Temperature)

In one or two sentences, explain the difference between heat and temperature.

9. (2 pts - Systems & Temperature)

What is the Kelvin equivalent of 25°C? ($K = ^\circ C + 273$)

- A. 248 K
- B. 298 K
- C. 300 K
- D. 325 K

10. (2 pts - Systems & Temperature)

Two objects that are in thermal equilibrium with each other must have the same:

- A. Mass
- B. Volume
- C. Temperature
- D. Density

11. (2 pts - Systems & Temperature)

Which of the following is an example of an EXTENSIVE property (a property that DOES depend on the amount of matter present)?

- A. Temperature
- B. Density
- C. Mass
- D. Boiling point

12. (2 pts - Systems & Temperature)

The definition of a British Thermal Unit (BTU) relates to:

- A. The amount of heat needed to raise the temperature of 1 pound of water by 1 °F
- B. The amount of work needed to lift 1 kg by 1 meter
- C. The speed of sound in air
- D. The pressure exerted by 1 atmosphere

13. (2 pts - Systems & Temperature)

If Object A has a higher temperature than Object B, and the two are placed in contact, heat will flow:

- A. From B to A
- B. From A to B
- C. Equally in both directions
- D. Not at all

14. (2 pts - Phases & Gas Law)

Which of the following correctly lists the three common phases of matter in order of INCREASING average particle spacing?

- A. Gas, Liquid, Solid
- B. Solid, Gas, Liquid
- C. Solid, Liquid, Gas
- D. Liquid, Solid, Gas

15. (2 pts - Phases & Gas Law)

A sample of ice at 0°C is heated until it becomes liquid water still at 0°C, with no change in temperature during the process. What type of heat was added to the ice?

- A. Sensible heat
- B. Latent heat
- C. Specific heat
- D. Radiant heat

16. (3 pts - Phases & Gas Law)

Using the ideal gas law ($PV = nRT$), if the pressure of a fixed amount of gas is doubled while the temperature is held constant, what happens to the volume?

- A. It doubles
- B. It is cut in half
- C. It stays the same
- D. It quadruples

17. (3 pts - Phases & Gas Law)

Refer to Figure 2. Based on the location of Point X (60°C, 1 atm) on the diagram, what phase is the water in at that point?

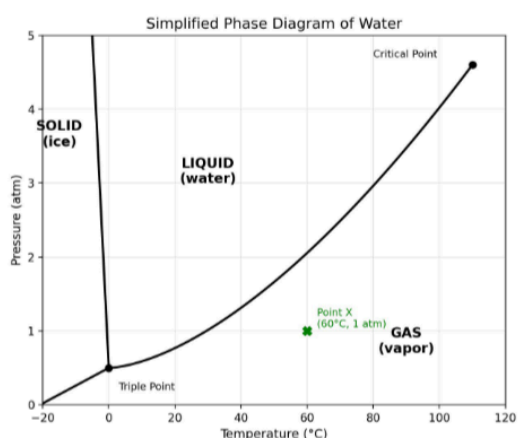


Figure 2: Simplified Phase Diagram of Water

- A. Solid
- B. Liquid
- C. Gas
- D. At the triple point

18. (4 pts - Phases & Gas Law)

Refer to Figure 3. Segment D on the graph is a flat plateau at 100°C . In one or two sentences, explain what is physically happening to the water molecules during segment D, and why the temperature does not increase even though heat is still being added.

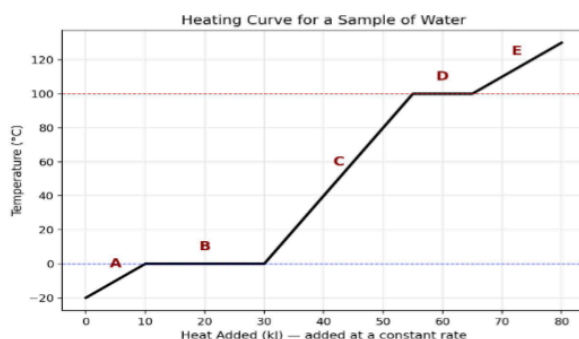


Figure 3: Heating Curve for a Sample of Water

19. (2 pts - Phases & Gas Law)

The specific latent heat of fusion for a substance describes:

- A. The amount of heat needed to raise 1 gram of the substance by 1°C
- B. The amount of heat needed to melt 1 gram of the substance at its melting point
- C. The rate at which a substance conducts heat
- D. The pressure at which a substance boils

20. (2 pts - Phases & Gas Law)

At the triple point of a substance on a phase diagram, what is true?

- A. Only the solid and liquid phases exist
- B. All three phases (solid, liquid, and gas) coexist in equilibrium
- C. The substance is at its critical temperature
- D. The substance cannot be a solid

21. (3 pts - Phases & Gas Law)

Select ALL of the following statements that are TRUE about phase transitions.

(Select ALL that apply)

- A. Melting is the transition from solid to liquid
- B. Sublimation is the transition from solid directly to gas
- C. Condensation releases energy to the surroundings
- D. Boiling occurs at a single fixed temperature regardless of pressure
- E. Freezing is an endothermic process

22. (2 pts - Phases & Gas Law)

Dry ice (solid carbon dioxide) turning directly into carbon dioxide gas without becoming a liquid is an example of:

- A. Melting
- B. Sublimation
- C. Condensation
- D. Deposition

23. (3 pts - Phases & Gas Law)

The latent heat of fusion of water is 334 J/g. Calculate the amount of heat, in joules, needed to melt 50 grams of ice at 0°C. Show your work.

24. (2 pts - Phases & Gas Law)

In the ideal gas law $PV = nRT$, if volume and the number of moles are held constant, pressure is directly proportional to:

- A. Volume
- B. Kelvin temperature
- C. Mass
- D. Density

25. (2 pts - Phases & Gas Law)

The process of a gas turning directly into a solid without becoming a liquid is called:

- A. Sublimation
- B. Deposition
- C. Condensation
- D. Fusion

26. (2 pts - Phases & Gas Law)

The latent heat of vaporization of a substance is always ____ its latent heat of fusion.

- A. greater than
- B. less than
- C. equal to
- D. unrelated to

27. (2 pts - Phases & Gas Law)

On a phase diagram, the line separating the liquid and gas regions represents:

- A. Melting points
- B. Boiling/condensation points
- C. Sublimation points
- D. Triple points

28. (3 pts - Phases & Gas Law)

A fixed amount of gas at 2.0 atm and 4.0 L is compressed to 2.0 L at constant temperature. Using Boyle's Law ($P_1V_1 = P_2V_2$), what is the new pressure?

- A. 1.0 atm
- B. 2.0 atm
- C. 4.0 atm
- D. 8.0 atm

29. (6 pts - Phases & Gas Law)

In three to four sentences, describe the difference between latent heat and sensible heat, and explain how each relates to a substance's heating curve. Include an example of each in your answer.

30. (2 pts - Heat Transfer)

A metal spoon left resting in a hot bowl of soup becomes warm at the handle, even though only the tip of the spoon is touching the soup. This is an example of which type of heat transfer?

- A. Convection
- B. Radiation
- C. Conduction
- D. Evaporation

31. (2 pts - Heat Transfer)

A material with a HIGH thermal conductivity will:

- A. Transfer heat slowly through itself
- B. Transfer heat quickly through itself
- C. Not transfer any heat
- D. Only transfer heat by radiation

32. (2 pts - Heat Transfer)

Heat capacity is best defined as:

- A. The amount of heat required to raise the temperature of an entire object by 1°C
- B. The amount of heat required to raise the temperature of 1 gram of a substance by 1°C
- C. The maximum temperature an object can reach
- D. The rate of heat transfer through a material

33. (3 pts - Heat Transfer)

Refer to Figure 4. Based on the chart, which material would make the BEST insulator (the poorest conductor of heat)?

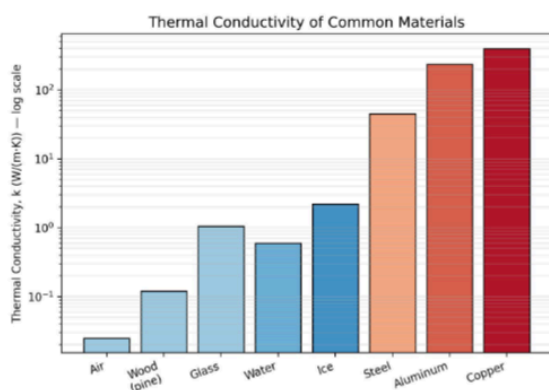


Figure 4: Thermal Conductivity of Common Materials

- A. Copper
- B. Steel
- C. Glass
- D. Air

34. (2 pts - Heat Transfer)

A pot of water boiling on a stove transfers heat throughout the water mainly as warmer, less dense water rises and cooler, denser water sinks. This is an example of:

- A. Conduction
- B. Convection
- C. Radiation
- D. Sublimation

35. (2 pts - Heat Transfer)

You feel the warmth of a campfire on your skin from several feet away, even though the air between you and the fire is not especially hot. This warming occurs mainly through:

- A. Conduction
- B. Convection
- C. Radiation
- D. Evaporation

36. (3 pts - Heat Transfer)

Select ALL of the following materials that are generally considered GOOD conductors of heat.

(Select ALL that apply)

- A. Copper
- B. Wood
- C. Aluminum
- D. Styrofoam
- E. Steel
- F. Air

37. (4 pts - Heat Transfer)

The specific heat of water is $4.18 \text{ J}/(\text{g} \cdot ^\circ\text{C})$. Using $q = mc\Delta T$, calculate the amount of heat (in joules) required to raise the temperature of 50 grams of water from 20°C to 45°C . Show your work.

38. (2 pts - Heat Transfer)

Heat naturally flows in which direction, without any additional energy input?

- A. From cold objects to hot objects
- B. From hot objects to cold objects
- C. Heat does not flow without work being done
- D. Heat flows equally in both directions

39. (3 pts - Heat Transfer)

In one or two sentences, explain the difference between heat capacity and specific heat.

40. (4 pts - Heat Transfer)

Refer to Figure 5. Based on the chart, which mechanism accounts for the GREATEST fraction of a typical house's winter heat loss?

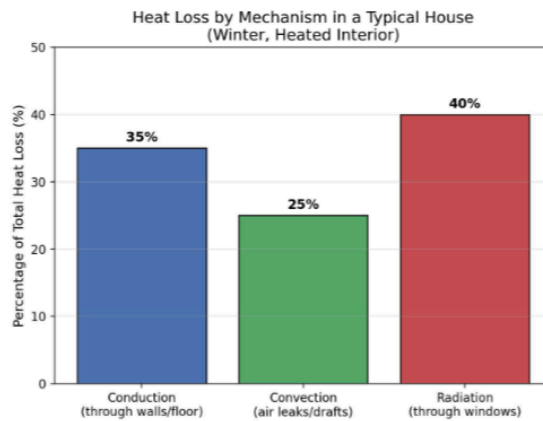


Figure 5: Heat Loss by Mechanism in a Typical House

- A. Conduction
- B. Convection
- C. Radiation
- D. All three are equal

41. (2 pts - Heat Transfer)

Styrofoam is commonly used as home insulation because it:

- A. Has high thermal conductivity
- B. Has low thermal conductivity due to trapped air pockets
- C. Conducts electricity poorly
- D. Has a high specific heat

42. (2 pts - Heat Transfer)

A thermos bottle keeps liquids hot primarily by reducing heat loss through:

- A. Conduction and convection (using a vacuum layer)
- B. Radiation only
- C. Sublimation
- D. Latent heat

43. (2 pts - Heat Transfer)

Which everyday object is specifically designed to have LOW thermal conductivity?

- A. Copper wire
- B. Cast iron skillet

- C. Oven mitt
- D. Aluminum foil

44. (2 pts - Heat Transfer)

The specific heat of a substance describes how much heat is needed to change the temperature of:

- A. The entire object, regardless of its mass
- B. Exactly 1 gram of the substance by 1°C
- C. 1 liter of any liquid
- D. The surrounding air

45. (6 pts - Heat Transfer)

In three to four sentences, explain how conduction, convection, and radiation differ from one another, and give a real-world example of each.

46. (2 pts - Processes & Engines)

A thermodynamic process in which a system's volume remains constant while its pressure and temperature may change is called:

- A. Isobaric
- B. Isothermal
- C. Isochoric
- D. Adiabatic

47. (2 pts - Processes & Engines)

The First Law of Thermodynamics is most closely related to which principle?

- A. Heat always flows from cold objects to hot objects
- B. Energy cannot be created or destroyed, only transferred or transformed
- C. Entropy of an isolated system always increases
- D. All matter has the same temperature at absolute zero

48. (2 pts - Processes & Engines)

Which statement best describes the Second Law of Thermodynamics?

- A. Heat naturally flows from a colder object to a hotter object
- B. The total energy of an isolated system is always exactly conserved
- C. In any energy transfer, some usable energy becomes unusable heat, and no engine can be perfectly efficient
- D. Pressure and volume of a gas are always inversely proportional

49. (3 pts - Processes & Engines)

A heat engine takes in 600 J of heat energy and performs 150 J of useful work. What is the efficiency of the engine, expressed as a percentage? (Efficiency = $\text{Work Output} \div \text{Heat Input} \times 100\%$)

- A. 15%
- B. 25%
- C. 40%
- D. 60%

50. (3 pts - Processes & Engines)

Refer to Figure 6. During which labeled process does the gas do positive work on its surroundings by expanding at constant pressure?

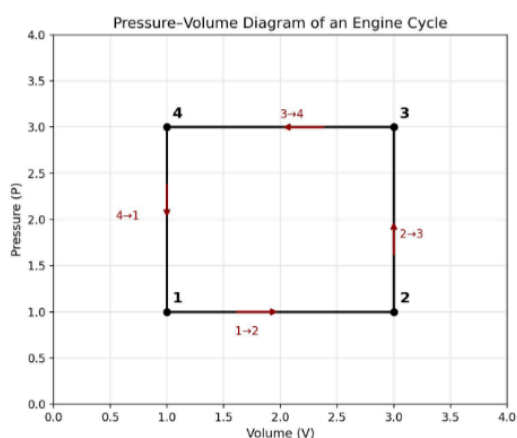


Figure 6: Pressure-Volume Diagram of an Engine Cycle

- A. 1→2
- B. 2→3
- C. 3→4
- D. 4→1

51. (2 pts - Processes & Engines)

At the end of one complete thermodynamic cycle, a heat engine's working substance:

- A. Has more internal energy than at the start
- B. Has less internal energy than at the start
- C. Returns to its original state (same pressure, volume, and temperature)
- D. Is completely converted into work

52. (3 pts - Processes & Engines)

Select ALL of the following statements that are TRUE about heat engines.

(Select ALL that apply)

- A. No heat engine can be 100% efficient
- B. All the heat absorbed by an engine is converted into useful work
- C. A heat engine requires a temperature difference between a hot and a cold reservoir to do net work
- D. Increasing an engine's efficiency means less waste heat is produced per unit of work
- E. Engines violate the First Law of Thermodynamics

53. (4 pts - Processes & Engines)

In one or two sentences, describe what happens to the working substance (such as a gas) over the course of one complete thermodynamic cycle in a heat engine.

54. (3 pts - Processes & Engines)

In one or two sentences, explain why a machine that produces more energy than it consumes, with no other energy input, is impossible according to the laws of thermodynamics.

55. (4 pts - Processes & Engines)

Refer to Figure 7. Based on the chart, which real-world engine type shown has an efficiency CLOSEST to the ideal (Carnot) limit?

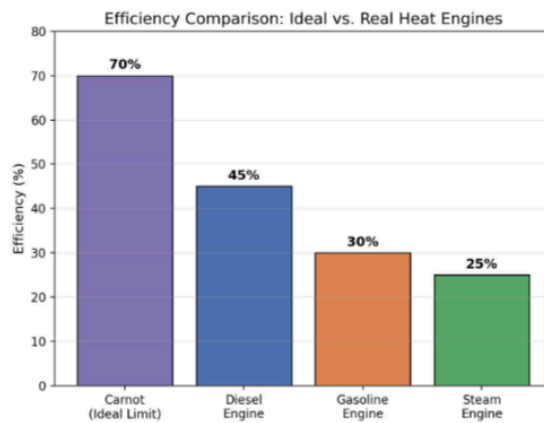


Figure 7: Efficiency Comparison: Ideal vs. Real Heat Engines

- A. Diesel Engine
- B. Gasoline Engine
- C. Steam Engine
- D. None of these are close

56. (2 pts - Processes & Engines)

A refrigerator does work to move heat from a colder space (its interior) to a warmer space (the surrounding room). This process directly demonstrates which law?

- A. The Zeroth Law
- B. The First Law
- C. The Second Law
- D. The Third Law

57. (2 pts - Processes & Engines)

Which of the following processes involves no change in a system's volume?

- A. Isobaric
- B. Isothermal
- C. Isochoric
- D. Adiabatic

58. (2 pts - Processes & Engines)

A gas expands against a constant external pressure, doing work on its surroundings. Which simple formula can be used to calculate this work?

- A. $W = P\Delta V$
- B. $W = mc\Delta T$
- C. $W = mL$
- D. $W = \sigma T^4$

59. (6 pts - Processes & Engines)

In three to four sentences, explain what the First and Second Laws of Thermodynamics each state, and describe how they work together to limit the efficiency of any real heat engine.

60. (2 pts - History)

The Kelvin temperature scale is named after William Thomson, who held which title?

- A. Lord Kelvin
- B. Sir Isaac Newton
- C. Count Rumford
- D. Baron Fourier

61. (2 pts - History)

Joseph Black is credited with the discovery of which thermodynamic concept?

- A. The Second Law of Thermodynamics
- B. Latent heat and specific heat
- C. The Ideal Gas Law
- D. The Stefan-Boltzmann Law

62. (2 pts - History)

James Joule's experiments are best known for establishing:

- A. The Ideal Gas Law
- B. The mechanical equivalent of heat (the numerical relationship between work and heat)
- C. The Second Law of Thermodynamics
- D. The concept of absolute zero

63. (2 pts - History)

Sadi Carnot is best known for describing:

- A. The first working steam engine
- B. An idealized, maximally efficient heat engine cycle
- C. The kinetic theory of gases
- D. The law of conservation of mass

64. (2 pts - History)

Which scientist's work connected the concept of entropy to the statistical behavior of large numbers of particles?

- A. James Clerk Maxwell
- B. Rudolf Clausius
- C. Ludwig Boltzmann
- D. Joseph Black

65. (3 pts - History)

In one or two sentences, describe Sadi Carnot's major contribution to the field of thermodynamics.

66. (2 pts - History)

James Clerk Maxwell's contribution to thermodynamics primarily relates to:

- A. The mechanical equivalent of heat
- B. The statistical distribution of molecular speeds in a gas
- C. The concept of latent heat
- D. The construction of the first steam engine

67. (2 pts - History)

Which scientist's early work on the emission spectrum of hot objects (blackbody radiation) led to the development of quantum theory?

- A. Rudolf Clausius
- B. Max Planck
- C. Joseph Black
- D. James Joule

68. (2 pts - History)

Rudolf Clausius is historically associated with which concept?

- A. The mechanical equivalent of heat
- B. A mathematical statement of the Second Law of Thermodynamics
- C. The Ideal Gas Law
- D. The construction of the first refrigerator

69. (2 pts - History)

Placed in roughly chronological order, whose foundational thermodynamics work came FIRST?

- A. Joseph Black (mid-1700s)
- B. Ludwig Boltzmann (late 1800s)
- C. Max Planck (early 1900s)
- D. Rudolf Clausius (mid-1800s)

70. (2 pts - Radiation & Third Law)

A "blackbody" in physics is best described as an idealized object that:

- A. Reflects all radiation that strikes it
- B. Absorbs and emits all wavelengths of electromagnetic radiation perfectly (with no reflection)
- C. Is always black in visible color, regardless of temperature
- D. Emits radiation only in the visible light spectrum

71. (3 pts - Radiation & Third Law)

Refer to Figure 8, which shows the emission spectrum (relative intensity vs. wavelength) of three blackbodies at different temperatures. Which curve represents the object with the HIGHEST temperature?

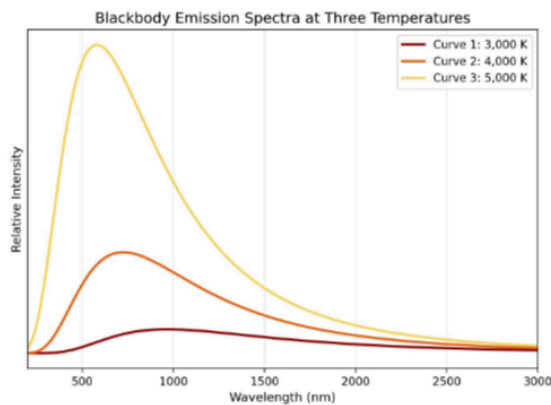


Figure 8: Blackbody Emission Spectra at Three Temperatures

- A. Curve 1
- B. Curve 2
- C. Curve 3
- D. All three curves represent the same temperature

72. (4 pts - Radiation & Third Law)

Refer to Figure 9. According to the Stefan-Boltzmann Law, the radiant exitance of a blackbody is proportional to the fourth power of its absolute temperature (T^4). Using the values marked on the graph, approximately how many times greater is the radiant exitance at 400 K compared to at 200 K?

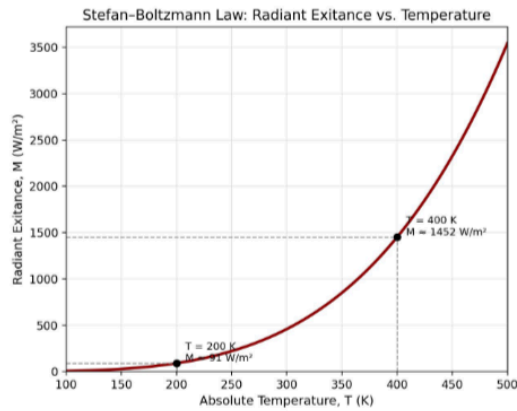


Figure 9: Stefan-Boltzmann Law — Radiant Exitance vs. Temperature

- A. 2 times
- B. 4 times
- C. 8 times
- D. 16 times

73. (3 pts - Radiation & Third Law)

Select ALL of the following statements that are TRUE about blackbody radiation and the Stefan-Boltzmann Law.

(Select ALL that apply)

- A. Hotter objects emit more total radiant energy than cooler objects
- B. Radiant exitance is directly (linearly) proportional to Kelvin temperature
- C. All real objects are perfect blackbodies
- D. The Stefan-Boltzmann Law relates radiated power to the fourth power of absolute temperature
- E. Blackbody radiation can travel through the vacuum of space

74. (4 pts - Radiation & Third Law)

Refer to Figure 10, which shows how the entropy of a perfect crystal changes as its temperature approaches absolute zero (0 K). In one or two sentences, describe the trend shown in the graph and state how it relates to the Third Law of Thermodynamics.

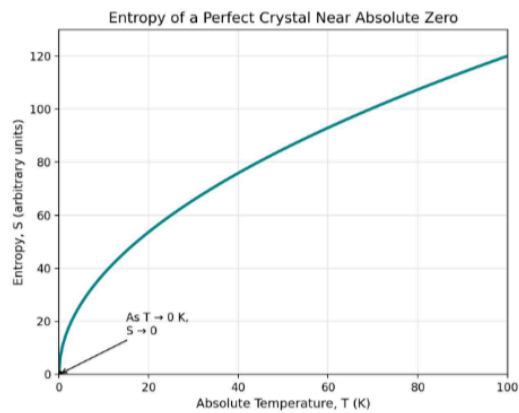


Figure 10: Entropy of a Perfect Crystal Near Absolute Zero

75. (2 pts - Radiation & Third Law)

Which of the following is the best statement of the Third Law of Thermodynamics?

- A. Energy cannot be created or destroyed, only transformed
- B. Heat naturally flows from hot objects to cold objects
- C. As the temperature of a perfect crystal approaches absolute zero, its entropy approaches a minimum (zero) value, and absolute zero itself cannot actually be reached
- D. Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other

76. (3 pts - Radiation & Third Law)

In one or two sentences, briefly describe Max Planck's key contribution to the study of blackbody radiation.

77. (3 pts - Radiation & Third Law)

According to the Stefan-Boltzmann Law, if the absolute temperature of an object is tripled, by approximately how many times does its radiant exitance increase?

- A. 3 times
- B. 9 times
- C. 27 times
- D. 81 times

78. (2 pts - Radiation & Third Law)

A blackbody at a higher temperature, compared to the same blackbody at a lower temperature, will emit its peak radiation at a wavelength that is:

- A. Longer (redder)
- B. Shorter (bluer)
- C. Unchanged
- D. Zero

79. (6 pts - Radiation & Third Law)

In three to four sentences, explain what a blackbody is, and describe how the Stefan-Boltzmann Law and the general shape of a blackbody's emission spectrum both relate to its temperature.

80. (6 pts - Radiation & Third Law)

In three to four sentences, state the Third Law of Thermodynamics and explain its significance, including why absolute zero can never actually be reached.

THERMODYNAMICS B — NATIONAL EXAM

ANSWER KEY

Division B (Middle School)

1. (2 pts - Multiple Choice)

According to the Zeroth Law of Thermodynamics, if Object A is in thermal equilibrium with Object B, and Object B is in thermal equilibrium with Object C, what can be concluded about Object A and Object C?

- A. Object A and Object C will always have different temperatures
- B. Object A and Object C are in thermal equilibrium with each other ✓ CORRECT**
- C. Object A and Object C cannot be measured with the same thermometer
- D. Object A and Object C must be made of the same material

Explanation: The Zeroth Law states that if two systems are each in thermal equilibrium with a third system, they are in thermal equilibrium with each other.

2. (2 pts - Multiple Choice)

The formula for converting Celsius to Fahrenheit is $^{\circ}\text{F} = (9/5)(^{\circ}\text{C}) + 32$. What is the Fahrenheit temperature equivalent to 20°C ?

- A. 52°F
- B. 68°F ✓ CORRECT**
- C. 36°F
- D. 72°F

Explanation: $(9/5)(20) + 32 = 36 + 32 = 68^{\circ}\text{F}$.

3. (2 pts - Multiple Choice)

Which property of a system is classified as an intensive property (does NOT depend on the amount of matter present)?

- A. Mass
- B. Volume
- C. Density ✓ CORRECT**
- D. Total thermal energy

Explanation: Density does not change with the amount of substance present, so it is intensive.

4. (2 pts - Multiple Choice)

Which unit is defined as the amount of heat required to raise the temperature of 1 gram of water by 1°C ?

- A. Joule
- B. Watt
- C. Calorie ✓ CORRECT**

D. Kelvin

Explanation: This is the definition of a calorie.

5. (3 pts - Multiple Choice)

Refer to Figure 1. Point X marks a temperature that is 65% of the way up the Celsius column, measured from water's freezing point to water's boiling point. What is the approximate Celsius temperature at Point X?

- A. 35°C
- B. 50°C
- C. 65°C ✓ CORRECT
- D. 80°C

Explanation: The freezing and boiling points of water are 0°C and 100°C, a 100-degree span. 65% of 100°C = 65°C.

6. (2 pts - Multiple Choice)

Approximately how many joules are equivalent to 5 calories? (1 calorie ≈ 4.18 J)

- A. 4.18 J
- B. 9.0 J
- C. 20.9 J ✓ CORRECT
- D. 41.8 J

Explanation: $5 \times 4.18 \text{ J} = 20.9 \text{ J}$.

7. (3 pts - Multi-Select)

Select ALL of the following that are examples of INTENSIVE properties of a system.

- A. Temperature ✓ CORRECT
- B. Mass
- C. Density ✓ CORRECT
- D. Volume
- E. Boiling point ✓ CORRECT
- F. Total heat content

Explanation: Temperature, density, and boiling point do not depend on the amount of substance present.

8. (3 pts - Short Answer)

In one or two sentences, explain the difference between heat and temperature.

Sample Full-Credit Answer: Heat is the transfer of thermal energy between objects or systems because of a temperature difference, while temperature is a measure of the average kinetic energy of the particles within a substance. Heat is energy in transit (measured in joules), whereas temperature is a state property (measured in degrees or kelvin).

9. (2 pts - Multiple Choice)

What is the Kelvin equivalent of 25°C? ($K = ^\circ C + 273$)

- A. 248 K
- B. 298 K ✓ CORRECT**
- C. 300 K
- D. 325 K

Explanation: $25 + 273 = 298\text{ K}$.

10. (2 pts - Multiple Choice)

Two objects that are in thermal equilibrium with each other must have the same:

- A. Mass
- B. Volume
- C. Temperature ✓ CORRECT**
- D. Density

Explanation: Thermal equilibrium means the two objects have reached the same temperature and no net heat flows between them.

11. (2 pts - Multiple Choice)

Which of the following is an example of an EXTENSIVE property (a property that DOES depend on the amount of matter present)?

- A. Temperature
- B. Density
- C. Mass ✓ CORRECT**
- D. Boiling point

Explanation: Mass scales directly with the amount of matter present, unlike temperature, density, or boiling point.

12. (2 pts - Multiple Choice)

The definition of a British Thermal Unit (BTU) relates to:

- A. The amount of heat needed to raise the temperature of 1 pound of water by 1°F ✓ CORRECT**
- B. The amount of work needed to lift 1 kg by 1 meter
- C. The speed of sound in air
- D. The pressure exerted by 1 atmosphere

Explanation: A BTU is defined as the heat required to raise 1 pound of water by 1°F.

13. (2 pts - Multiple Choice)

If Object A has a higher temperature than Object B, and the two are placed in contact, heat will flow:

- A. From B to A
- B. From A to B ✓ CORRECT**
- C. Equally in both directions

D. Not at all

Explanation: Heat spontaneously flows from the higher-temperature object to the lower-temperature object.

14. (2 pts - Multiple Choice)

Which of the following correctly lists the three common phases of matter in order of INCREASING average particle spacing?

A. Gas, Liquid, Solid

B. Solid, Gas, Liquid

C. Solid, Liquid, Gas ✓ CORRECT

D. Liquid, Solid, Gas

Explanation: Particles are closest together in a solid, farther apart in a liquid, and farthest apart in a gas.

15. (2 pts - Multiple Choice)

A sample of ice at 0°C is heated until it becomes liquid water still at 0°C, with no change in temperature during the process. What type of heat was added to the ice?

A. Sensible heat

B. Latent heat ✓ CORRECT

C. Specific heat

D. Radiant heat

Explanation: Latent heat is absorbed or released during a phase change, without a change in temperature.

16. (3 pts - Multiple Choice)

Using the ideal gas law ($PV = nRT$), if the pressure of a fixed amount of gas is doubled while the temperature is held constant, what happens to the volume?

A. It doubles

B. It is cut in half ✓ CORRECT

C. It stays the same

D. It quadruples

Explanation: At constant n and T , pressure and volume are inversely proportional.

17. (3 pts - Multiple Choice)

Refer to Figure 2. Based on the location of Point X (60°C, 1 atm) on the diagram, what phase is the water in at that point?

A. Solid

B. Liquid ✓ CORRECT

C. Gas

D. At the triple point

Explanation: Point X (60°C, 1 atm) falls within the region of the diagram labeled LIQUID.

18. (4 pts - Short Answer)

Refer to Figure 3. Segment D on the graph is a flat plateau at 100°C. In one or two sentences, explain what is physically happening to the water molecules during segment D, and why the temperature does not increase even though heat is still being added.

Sample Full-Credit Answer: During segment D, the water is boiling — changing from the liquid phase to the gas phase. The heat energy added is being used to overcome the attractive forces between water molecules rather than increasing their average kinetic energy, so the temperature stays constant until the phase change is complete.

19. (2 pts - Multiple Choice)

The specific latent heat of fusion for a substance describes:

- A. The amount of heat needed to raise 1 gram of the substance by 1°C
- B. The amount of heat needed to melt 1 gram of the substance at its melting point ✓ CORRECT**
- C. The rate at which a substance conducts heat
- D. The pressure at which a substance boils

Explanation: Specific latent heat of fusion is the energy required to melt one gram of a substance at constant temperature.

20. (2 pts - Multiple Choice)

At the triple point of a substance on a phase diagram, what is true?

- A. Only the solid and liquid phases exist
- B. All three phases (solid, liquid, and gas) coexist in equilibrium ✓ CORRECT**
- C. The substance is at its critical temperature
- D. The substance cannot be a solid

Explanation: The triple point is the unique combination of temperature and pressure at which all three phases coexist in equilibrium.

21. (3 pts - Multi-Select)

Select ALL of the following statements that are TRUE about phase transitions.

- A. Melting is the transition from solid to liquid ✓ CORRECT**
- B. Sublimation is the transition from solid directly to gas ✓ CORRECT**
- C. Condensation releases energy to the surroundings ✓ CORRECT**
- D. Boiling occurs at a single fixed temperature regardless of pressure
- E. Freezing is an endothermic process

Explanation: Boiling point depends on pressure, and freezing is exothermic (not endothermic).

22. (2 pts - Multiple Choice)

Dry ice (solid carbon dioxide) turning directly into carbon dioxide gas without becoming a liquid is an example of:

- A. Melting
- B. Sublimation ✓ CORRECT**
- C. Condensation
- D. Deposition

Explanation: Sublimation is the direct transition from solid to gas.

23. (3 pts - Short Answer)

The latent heat of fusion of water is 334 J/g. Calculate the amount of heat, in joules, needed to melt 50 grams of ice at 0°C. Show your work.

Sample Full-Credit Answer: $q = mL = (50 \text{ g})(334 \text{ J/g}) = 16,700 \text{ J}$.

24. (2 pts - Multiple Choice)

In the ideal gas law $PV = nRT$, if volume and the number of moles are held constant, pressure is directly proportional to:

- A. Volume
- B. Kelvin temperature ✓ CORRECT**
- C. Mass
- D. Density

Explanation: At constant V and n , P and T are directly proportional.

25. (2 pts - Multiple Choice)

The process of a gas turning directly into a solid without becoming a liquid is called:

- A. Sublimation
- B. Deposition ✓ CORRECT**
- C. Condensation
- D. Fusion

Explanation: Deposition is the direct transition from gas to solid.

26. (2 pts - Multiple Choice)

The latent heat of vaporization of a substance is always ____ its latent heat of fusion.

- A. greater than ✓ CORRECT**
- B. less than
- C. equal to
- D. unrelated to

Explanation: Vaporization requires overcoming essentially all intermolecular attractions, which takes substantially more energy than the partial rearrangement involved in melting.

27. (2 pts - Multiple Choice)

On a phase diagram, the line separating the liquid and gas regions represents:

- A. Melting points

B. Boiling/condensation points ✓ CORRECT

C. Sublimation points

D. Triple points

Explanation: The liquid-gas boundary line shows the temperature and pressure combinations at which boiling and condensation occur.

28. (3 pts - Multiple Choice)

A fixed amount of gas at 2.0 atm and 4.0 L is compressed to 2.0 L at constant temperature. Using Boyle's Law ($P_1V_1 = P_2V_2$), what is the new pressure?

A. 1.0 atm

B. 2.0 atm

C. 4.0 atm ✓ CORRECT

D. 8.0 atm

Explanation: $P_2 = P_1V_1/V_2 = (2.0 \text{ atm})(4.0 \text{ L})/(2.0 \text{ L}) = 4.0 \text{ atm}$.

29. (6 pts - Long Answer)

In three to four sentences, describe the difference between latent heat and sensible heat, and explain how each relates to a substance's heating curve. Include an example of each in your answer.

Sample Full-Credit Answer: Sensible heat is heat that changes a substance's temperature without changing its phase — on a heating curve, this corresponds to the sloped segments (such as ice warming from -20°C to 0°C). Latent heat is heat that changes a substance's phase without changing its temperature — on a heating curve, this corresponds to the flat plateau segments (such as ice melting at 0°C , where all the added heat goes into breaking intermolecular bonds rather than raising kinetic energy). An example of sensible heat is warming liquid water from 20°C to 80°C ; an example of latent heat is boiling that same water into steam at 100°C .

30. (2 pts - Multiple Choice)

A metal spoon left resting in a hot bowl of soup becomes warm at the handle, even though only the tip of the spoon is touching the soup. This is an example of which type of heat transfer?

A. Convection

B. Radiation

C. Conduction ✓ CORRECT

D. Evaporation

Explanation: Conduction is heat transfer through direct contact between particles of a material.

31. (2 pts - Multiple Choice)

A material with a HIGH thermal conductivity will:

A. Transfer heat slowly through itself

B. Transfer heat quickly through itself ✓ CORRECT

C. Not transfer any heat

D. Only transfer heat by radiation

Explanation: A high thermal conductivity value means heat is conducted quickly through the material.

32. (2 pts - Multiple Choice)

Heat capacity is best defined as:

A. The amount of heat required to raise the temperature of an entire object by 1 °C
✓ CORRECT

B. The amount of heat required to raise the temperature of 1 gram of a substance by 1 °C

C. The maximum temperature an object can reach

D. The rate of heat transfer through a material

Explanation: Heat capacity applies to a specific object and depends on its total mass.

33. (3 pts - Multiple Choice)

Refer to Figure 4. Based on the chart, which material would make the BEST insulator (the poorest conductor of heat)?

A. Copper

B. Steel

C. Glass

D. Air ✓ CORRECT

Explanation: Air has by far the lowest thermal conductivity shown, making it the best insulator.

34. (2 pts - Multiple Choice)

A pot of water boiling on a stove transfers heat throughout the water mainly as warmer, less dense water rises and cooler, denser water sinks. This is an example of:

A. Conduction

B. Convection ✓ CORRECT

C. Radiation

D. Sublimation

Explanation: Convection is heat transfer through the bulk movement of a fluid, driven by density differences.

35. (2 pts - Multiple Choice)

You feel the warmth of a campfire on your skin from several feet away, even though the air between you and the fire is not especially hot. This warming occurs mainly through:

A. Conduction

B. Convection

C. Radiation ✓ CORRECT

D. Evaporation

Explanation: Radiation transfers energy as electromagnetic waves and does not require a medium.

36. (3 pts - Multi-Select)

Select ALL of the following materials that are generally considered GOOD conductors of heat.

- A. Copper ✓ CORRECT
- B. Wood
- C. Aluminum ✓ CORRECT
- D. Styrofoam
- E. Steel ✓ CORRECT
- F. Air

Explanation: Copper, aluminum, and steel are metals with relatively high thermal conductivity.

37. (4 pts - Short Answer)

The specific heat of water is $4.18 \text{ J}/(\text{g} \cdot ^\circ\text{C})$. Using $q = mc\Delta T$, calculate the amount of heat (in joules) required to raise the temperature of 50 grams of water from 20°C to 45°C . Show your work.

Sample Full-Credit Answer: $\Delta T = 45 - 20 = 25^\circ\text{C}$. $q = mc\Delta T = (50 \text{ g})(4.18 \text{ J}/(\text{g} \cdot ^\circ\text{C}))(25^\circ\text{C}) = 5,225 \text{ J}$.

38. (2 pts - Multiple Choice)

Heat naturally flows in which direction, without any additional energy input?

- A. From cold objects to hot objects
- B. From hot objects to cold objects ✓ CORRECT
- C. Heat does not flow without work being done
- D. Heat flows equally in both directions

Explanation: Heat spontaneously flows from higher-temperature objects to lower-temperature objects.

39. (3 pts - Short Answer)

In one or two sentences, explain the difference between heat capacity and specific heat.

Sample Full-Credit Answer: Heat capacity is the amount of heat needed to raise the temperature of an entire object by 1°C , while specific heat is the amount of heat needed to raise the temperature of exactly 1 gram of a particular substance by 1°C .

40. (4 pts - Multiple Choice)

Refer to Figure 5. Based on the chart, which mechanism accounts for the GREATEST fraction of a typical house's winter heat loss?

- A. Conduction
- B. Convection
- C. Radiation ✓ CORRECT
- D. All three are equal

Explanation: According to the chart, radiation (mainly through windows) accounts for 40% of heat loss, the largest of the three mechanisms shown.

41. (2 pts - Multiple Choice)

Styrofoam is commonly used as home insulation because it:

- A. Has high thermal conductivity
- B. Has low thermal conductivity due to trapped air pockets ✓ CORRECT**
- C. Conducts electricity poorly
- D. Has a high specific heat

Explanation: Styrofoam traps many small pockets of air, which is a poor conductor, giving the material a very low overall thermal conductivity.

42. (2 pts - Multiple Choice)

A thermos bottle keeps liquids hot primarily by reducing heat loss through:

- A. Conduction and convection (using a vacuum layer) ✓ CORRECT**
- B. Radiation only
- C. Sublimation
- D. Latent heat

Explanation: The vacuum layer between a thermos's inner and outer walls greatly reduces heat loss by conduction and convection, since there is little to no matter present to carry heat.

43. (2 pts - Multiple Choice)

Which everyday object is specifically designed to have LOW thermal conductivity?

- A. Copper wire
- B. Cast iron skillet
- C. Oven mitt ✓ CORRECT**
- D. Aluminum foil

Explanation: An oven mitt is made of insulating material specifically to prevent heat from quickly conducting to your hand.

44. (2 pts - Multiple Choice)

The specific heat of a substance describes how much heat is needed to change the temperature of:

- A. The entire object, regardless of its mass
- B. Exactly 1 gram of the substance by 1 °C ✓ CORRECT**
- C. 1 liter of any liquid
- D. The surrounding air

Explanation: Specific heat is defined per gram (or per kilogram) of a particular substance.

45. (6 pts - Long Answer)

In three to four sentences, explain how conduction, convection, and radiation differ from one another, and give a real-world example of each.

Sample Full-Credit Answer: Conduction is the transfer of heat through direct contact between particles within a material or between two touching objects, such as heat traveling along a metal spoon left in a hot pot. Convection is the transfer of heat through the bulk movement of a fluid, driven by density differences, such as warm air rising from a radiator to circulate heat through a room. Radiation is the transfer of heat through electromagnetic waves and does not require a medium, such as the warmth felt from sunlight or a campfire. All three mechanisms can occur simultaneously, but their relative importance depends on the materials and setting involved.

46. (2 pts - Multiple Choice)

A thermodynamic process in which a system's volume remains constant while its pressure and temperature may change is called:

- A. Isobaric
- B. Isothermal
- C. Isochoric ✓ CORRECT**
- D. Adiabatic

Explanation: Isochoric means constant volume.

47. (2 pts - Multiple Choice)

The First Law of Thermodynamics is most closely related to which principle?

- A. Heat always flows from cold objects to hot objects
- B. Energy cannot be created or destroyed, only transferred or transformed ✓ CORRECT**
- C. Entropy of an isolated system always increases
- D. All matter has the same temperature at absolute zero

Explanation: The First Law is a statement of conservation of energy.

48. (2 pts - Multiple Choice)

Which statement best describes the Second Law of Thermodynamics?

- A. Heat naturally flows from a colder object to a hotter object
- B. The total energy of an isolated system is always exactly conserved
- C. In any energy transfer, some usable energy becomes unusable heat, and no engine can be perfectly efficient ✓ CORRECT**
- D. Pressure and volume of a gas are always inversely proportional

Explanation: The Second Law implies that some energy is always lost as unusable heat, meaning no real process can be perfectly efficient.

49. (3 pts - Multiple Choice)

A heat engine takes in 600 J of heat energy and performs 150 J of useful work. What is the efficiency of the engine, expressed as a percentage? (Efficiency = $\text{Work Output} \div \text{Heat Input} \times 100\%$)

- A. 15%
- B. 25% ✓ CORRECT**
- C. 40%
- D. 60%

Explanation: $\text{Efficiency} = 150 \text{ J} \div 600 \text{ J} \times 100\% = 25\%$.

50. (3 pts - Multiple Choice)

Refer to Figure 6. During which labeled process does the gas do positive work on its surroundings by expanding at constant pressure?

- A. 1→2 ✓ CORRECT**
- B. 2→3
- C. 3→4
- D. 4→1

Explanation: During 1→2, the volume increases at constant pressure (isobaric expansion), so the gas does positive work on its surroundings.

51. (2 pts - Multiple Choice)

At the end of one complete thermodynamic cycle, a heat engine's working substance:

- A. Has more internal energy than at the start
- B. Has less internal energy than at the start
- C. Returns to its original state (same pressure, volume, and temperature) ✓ CORRECT**
- D. Is completely converted into work

Explanation: A complete cycle returns the working substance to its original state, even though net work has been done.

52. (3 pts - Multi-Select)

Select ALL of the following statements that are TRUE about heat engines.

- A. No heat engine can be 100% efficient ✓ CORRECT**
- B. All the heat absorbed by an engine is converted into useful work
- C. A heat engine requires a temperature difference between a hot and a cold reservoir to do net work ✓ CORRECT**
- D. Increasing an engine's efficiency means less waste heat is produced per unit of work ✓ CORRECT**
- E. Engines violate the First Law of Thermodynamics

Explanation: Statements 1, 3, and 4 are true. Statement 2 is false, and statement 5 is false.

53. (4 pts - Short Answer)

In one or two sentences, describe what happens to the working substance (such as a gas) over the course of one complete thermodynamic cycle in a heat engine.

Sample Full-Credit Answer: Over one complete cycle, the working substance undergoes a series of processes and returns to its original pressure, volume, and temperature by the end of the cycle. In doing so, the engine converts some of the absorbed heat into net useful work, while exhausting the remaining heat to the surroundings.

54. (3 pts - Short Answer)

In one or two sentences, explain why a machine that produces more energy than it consumes, with no other energy input, is impossible according to the laws of thermodynamics.

Sample Full-Credit Answer: Such a machine would violate the First Law of Thermodynamics, since it cannot produce more energy output than the energy put into it. The Second Law also guarantees that some energy is always lost as unusable heat, making a perfectly efficient (let alone energy-creating) machine impossible.

55. (4 pts - Multiple Choice)

Refer to Figure 7. Based on the chart, which real-world engine type shown has an efficiency CLOSEST to the ideal (Carnot) limit?

- A. Diesel Engine ✓ CORRECT
- B. Gasoline Engine
- C. Steam Engine
- D. None of these are close

Explanation: The Diesel engine's 45% efficiency is closest to the 70% Carnot ideal limit shown, compared to the gasoline engine (30%) and steam engine (25%).

56. (2 pts - Multiple Choice)

A refrigerator does work to move heat from a colder space (its interior) to a warmer space (the surrounding room). This process directly demonstrates which law?

- A. The Zeroth Law
- B. The First Law
- C. The Second Law ✓ CORRECT
- D. The Third Law

Explanation: Heat does not flow from cold to hot on its own — the Second Law requires that work be done (by the refrigerator's compressor) to force this direction of heat flow.

57. (2 pts - Multiple Choice)

Which of the following processes involves no change in a system's volume?

- A. Isobaric
- B. Isothermal
- C. Isochoric ✓ CORRECT
- D. Adiabatic

Explanation: Isochoric processes occur at constant volume.

58. (2 pts - Multiple Choice)

A gas expands against a constant external pressure, doing work on its surroundings. Which simple formula can be used to calculate this work?

- A. $W = P\Delta V$ ✓ CORRECT
- B. $W = mc\Delta T$
- C. $W = mL$
- D. $W = \sigma T^4$

Explanation: Work done during expansion or compression at constant pressure is calculated as $W = P\Delta V$.

59. (6 pts - Long Answer)

In three to four sentences, explain what the First and Second Laws of Thermodynamics each state, and describe how they work together to limit the efficiency of any real heat engine.

Sample Full-Credit Answer: The First Law states that energy cannot be created or destroyed, only converted from one form to another – meaning a heat engine cannot produce more work than the heat energy it takes in. The Second Law states that in any energy transfer, some energy is always lost as unusable heat, and that heat naturally flows from hot to cold. Together, these laws mean that no heat engine can convert 100% of its input heat into useful work: the First Law caps the total energy available, while the Second Law guarantees that some of that energy will always be wasted as heat exhaust, limiting real-world efficiency below the theoretical Carnot maximum.

60. (2 pts - Multiple Choice)

The Kelvin temperature scale is named after William Thomson, who held which title?

- A. Lord Kelvin ✓ CORRECT
- B. Sir Isaac Newton
- C. Count Rumford
- D. Baron Fourier

Explanation: William Thomson was granted the title Lord Kelvin.

61. (2 pts - Multiple Choice)

Joseph Black is credited with the discovery of which thermodynamic concept?

- A. The Second Law of Thermodynamics
- B. Latent heat and specific heat ✓ CORRECT
- C. The Ideal Gas Law
- D. The Stefan-Boltzmann Law

Explanation: Joseph Black's experiments led to his identification of latent heat and specific heat capacity.

62. (2 pts - Multiple Choice)

James Joule's experiments are best known for establishing:

- A. The Ideal Gas Law

B. The mechanical equivalent of heat (the numerical relationship between work and heat) ✓ CORRECT

C. The Second Law of Thermodynamics

D. The concept of absolute zero

Explanation: Joule's experiments quantified the relationship between mechanical work and the heat it produces.

63. (2 pts - Multiple Choice)

Sadi Carnot is best known for describing:

A. The first working steam engine

B. An idealized, maximally efficient heat engine cycle ✓ CORRECT

C. The kinetic theory of gases

D. The law of conservation of mass

Explanation: Carnot developed the concept of an idealized, reversible heat engine cycle that sets the theoretical maximum efficiency limit.

64. (2 pts - Multiple Choice)

Which scientist's work connected the concept of entropy to the statistical behavior of large numbers of particles?

A. James Clerk Maxwell

B. Rudolf Clausius

C. Ludwig Boltzmann ✓ CORRECT

D. Joseph Black

Explanation: Ludwig Boltzmann developed the statistical interpretation connecting entropy to the number of possible microscopic arrangements of particles.

65. (3 pts - Short Answer)

In one or two sentences, describe Sadi Carnot's major contribution to the field of thermodynamics.

Sample Full-Credit Answer: Sadi Carnot developed the concept of an idealized heat engine cycle (the Carnot cycle) and showed that there is a maximum possible efficiency for any heat engine operating between two temperatures. His work laid an important foundation for what became the Second Law of Thermodynamics.

66. (2 pts - Multiple Choice)

James Clerk Maxwell's contribution to thermodynamics primarily relates to:

A. The mechanical equivalent of heat

B. The statistical distribution of molecular speeds in a gas ✓ CORRECT

C. The concept of latent heat

D. The construction of the first steam engine

Explanation: Maxwell developed the statistical distribution describing the range of molecular speeds in a gas at a given temperature.

67. (2 pts - Multiple Choice)

Which scientist's early work on the emission spectrum of hot objects (blackbody radiation) led to the development of quantum theory?

- A. Rudolf Clausius
- B. Max Planck ✓ CORRECT**
- C. Joseph Black
- D. James Joule

Explanation: Planck's work on blackbody radiation, involving the idea of energy quanta, marked the beginning of quantum theory.

68. (2 pts - Multiple Choice)

Rudolf Clausius is historically associated with which concept?

- A. The mechanical equivalent of heat
- B. A mathematical statement of the Second Law of Thermodynamics ✓ CORRECT**
- C. The Ideal Gas Law
- D. The construction of the first refrigerator

Explanation: Clausius formalized the Second Law and is credited with introducing the concept of entropy.

69. (2 pts - Multiple Choice)

Placed in roughly chronological order, whose foundational thermodynamics work came FIRST?

- A. Joseph Black (mid-1700s) ✓ CORRECT**
- B. Ludwig Boltzmann (late 1800s)
- C. Max Planck (early 1900s)
- D. Rudolf Clausius (mid-1800s)

Explanation: Joseph Black's experiments on latent and specific heat in the 1750s-60s predate the work of Clausius, Boltzmann, and Planck.

70. (2 pts - Multiple Choice)

A "blackbody" in physics is best described as an idealized object that:

- A. Reflects all radiation that strikes it
- B. Absorbs and emits all wavelengths of electromagnetic radiation perfectly (with no reflection) ✓ CORRECT**
- C. Is always black in visible color, regardless of temperature
- D. Emits radiation only in the visible light spectrum

Explanation: A blackbody is a theoretical perfect absorber and emitter of radiation at all wavelengths.

71. (3 pts - Multiple Choice)

Refer to Figure 8, which shows the emission spectrum (relative intensity vs. wavelength) of three blackbodies at different temperatures. Which curve represents the object with the HIGHEST temperature?

- A. Curve 1
- B. Curve 2
- C. Curve 3 ✓ CORRECT**
- D. All three curves represent the same temperature

Explanation: Curve 3 has both the greatest overall intensity and a peak shifted to the shortest wavelength, both of which indicate it belongs to the hottest object.

72. (4 pts - Multiple Choice)

Refer to Figure 9. According to the Stefan-Boltzmann Law, the radiant exitance of a blackbody is proportional to the fourth power of its absolute temperature (T^4). Using the values marked on the graph, approximately how many times greater is the radiant exitance at 400 K compared to at 200 K?

- A. 2 times
- B. 4 times
- C. 8 times
- D. 16 times ✓ CORRECT**

Explanation: Since $M \propto T^4$, doubling the temperature increases the radiant exitance by a factor of $2^4 = 16$, matching the graph.

73. (3 pts - Multi-Select)

Select ALL of the following statements that are TRUE about blackbody radiation and the Stefan-Boltzmann Law.

- A. Hotter objects emit more total radiant energy than cooler objects ✓ CORRECT**
- B. Radiant exitance is directly (linearly) proportional to Kelvin temperature
- C. All real objects are perfect blackbodies
- D. The Stefan-Boltzmann Law relates radiated power to the fourth power of absolute temperature ✓ CORRECT**
- E. Blackbody radiation can travel through the vacuum of space ✓ CORRECT**

Explanation: Statements 1, 4, and 5 are correct. Statement 2 is false (proportional to T^4 , not T), and statement 3 is false (real objects only approximate blackbody behavior).

74. (4 pts - Short Answer)

Refer to Figure 10, which shows how the entropy of a perfect crystal changes as its temperature approaches absolute zero (0 K). In one or two sentences, describe the trend shown in the graph and state how it relates to the Third Law of Thermodynamics.

Sample Full-Credit Answer: The graph shows that as the temperature of a perfect crystal approaches absolute zero, its entropy also approaches zero. This illustrates the Third Law of Thermodynamics, which states that the entropy of a perfect crystal at a temperature of absolute zero is exactly zero, and that absolute zero itself can never actually be reached.

75. (2 pts - Multiple Choice)

Which of the following is the best statement of the Third Law of Thermodynamics?

- A. Energy cannot be created or destroyed, only transformed
- B. Heat naturally flows from hot objects to cold objects
- C. As the temperature of a perfect crystal approaches absolute zero, its entropy approaches a minimum (zero) value, and absolute zero itself cannot actually be reached ✓ CORRECT
- D. Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other

Explanation: Option C correctly states the Third Law; the other options restate the First, Second, and Zeroth Laws, respectively.

76. (3 pts - Short Answer)

In one or two sentences, briefly describe Max Planck's key contribution to the study of blackbody radiation.

Sample Full-Credit Answer: Max Planck proposed that energy is emitted and absorbed by matter in discrete packets called quanta, rather than continuously, which allowed him to correctly derive the mathematical relationship describing the spectrum of blackbody radiation. This idea marked the beginning of quantum theory in physics.

77. (3 pts - Multiple Choice)

According to the Stefan-Boltzmann Law, if the absolute temperature of an object is tripled, by approximately how many times does its radiant exitance increase?

- A. 3 times
- B. 9 times
- C. 27 times
- D. 81 times ✓ CORRECT

Explanation: Since $M \propto T^4$, tripling the temperature increases radiant exitance by a factor of $3^4 = 81$.

78. (2 pts - Multiple Choice)

A blackbody at a higher temperature, compared to the same blackbody at a lower temperature, will emit its peak radiation at a wavelength that is:

- A. Longer (redder)
- B. Shorter (bluer) ✓ CORRECT
- C. Unchanged
- D. Zero

Explanation: As an object's temperature increases, its blackbody emission spectrum peaks at progressively shorter (bluer) wavelengths.

79. (6 pts - Long Answer)

In three to four sentences, explain what a blackbody is, and describe how the Stefan-Boltzmann Law and the general shape of a blackbody's emission spectrum both relate to its temperature.

Sample Full-Credit Answer: A blackbody is an idealized object that perfectly absorbs and re-emits all wavelengths of electromagnetic radiation, without reflecting any incoming radiation. The Stefan-Boltzmann Law states that the total radiant exitance of a blackbody is proportional to the fourth power of its absolute temperature ($M = \sigma T^4$), so even a modest increase in temperature causes a very large increase in the total energy emitted. Additionally, hotter blackbodies emit their peak radiation at shorter wavelengths and with greater overall intensity than cooler blackbodies, which is why very hot objects (like stars) glow with different colors depending on their surface temperature.

80. (6 pts - Long Answer)

In three to four sentences, state the Third Law of Thermodynamics and explain its significance, including why absolute zero can never actually be reached.

Sample Full-Credit Answer: The Third Law of Thermodynamics states that as the temperature of a perfect crystal approaches absolute zero (0 K), its entropy approaches a minimum, constant value (often taken to be zero). This means that at absolute zero, a perfect crystal would have essentially no disorder in the arrangement of its particles. The law also implies that absolute zero can never actually be reached in a finite number of physical processes, because each successive cooling step removes progressively less entropy, requiring an infinite number of steps to reach exactly 0 K. This makes absolute zero a theoretical limiting value rather than an attainable temperature.

THERMODYNAMICS C — NATIONAL EXAM

Science Olympiad — Division C (High School)

2027

Team Name / Number: _____

Team Members: _____

Score: _____ / 233 points

TEST DIRECTIONS

- This exam contains 80 questions: 60 multiple choice, 5 multi-select, 10 short answer, and 5 long answer, worth a total of 233 points.
- For multiple choice questions, select the ONE best answer. For multi-select questions, select ALL choices that apply — there may be more than one correct answer.
- For short answer questions, write a brief response (one or two sentences, plus any calculation work) in the space provided. For long answer questions, write a more complete response (three to four sentences) that fully addresses every part of the prompt.
- 10 questions (#5, #16, #19, #29, #35, #45, #49, #63, #64, #74) ask you to analyze an accompanying figure. Figures appear directly below their associated question.
- This exam includes content on radiant exitance, blackbody radiation, the Stefan-Boltzmann Law, and the Third Law of Thermodynamics (Questions 62-71), as well as entropy and enthalpy (Questions 72-80), which are assessed only at the State and National level.
- Unless otherwise noted, answers should use metric units and appropriate significant figures.
- Calculators (Class III) and team notes may be used per Event Parameters. Show your work for full credit on calculation-based questions.

1. (2 pts - Systems & Temperature)

Three objects, P, Q, and R, are brought into contact with each other. After reaching equilibrium, object P is measured to be at the same temperature as object Q, and object Q is at the same temperature as object R. Which law of thermodynamics guarantees that P and R must also be in thermal equilibrium, and why is this law considered fundamental to the concept of temperature?

- A. The First Law; it shows that energy is conserved between P, Q, and R
- B. The Zeroth Law; it establishes that thermal equilibrium is a transitive relationship, which is what allows temperature to be defined and measured with a thermometer
- C. The Second Law; it shows that entropy is equal among all three objects
- D. The Third Law; it proves that P, Q, and R can never reach absolute zero

2. (3 pts - Systems & Temperature)

A liquid has a temperature of 68°F. What is this temperature in Kelvin? First convert to Celsius using $^{\circ}\text{C} = (5/9)(^{\circ}\text{F} - 32)$, then convert to Kelvin using $\text{K} = ^{\circ}\text{C} + 273.15$.

- A. 293.15 K
- B. 253.15 K
- C. 310.15 K
- D. 200.15 K

3. (2 pts - Systems & Temperature)

Which of the following is an example of an EXTENSIVE property of a system?

- A. Temperature
- B. Specific heat
- C. Total internal energy
- D. Pressure

4. (2 pts - Systems & Temperature)

Which of the following could correctly be used as a unit to express an amount of heat energy?

- A. Joule
- B. Watt
- C. Pascal
- D. Newton

5. (3 pts - Systems & Temperature)

Refer to Figure 1. Point X marks a temperature that is 30% of the way up the Kelvin column, measured from water's freezing point (273 K) to water's boiling point (373 K). What is the equivalent Fahrenheit temperature at Point X?

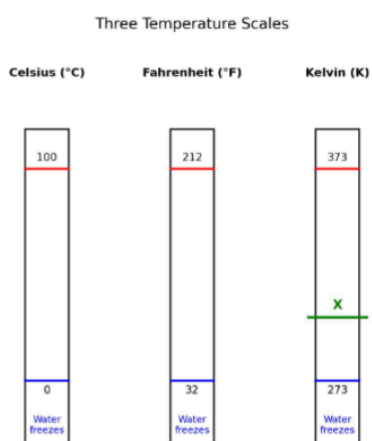


Figure 1: Three Temperature Scales

- A. 76° F
- B. 86° F
- C. 96° F
- D. 106° F

6. (3 pts - Systems & Temperature)

Select ALL of the following that are units used to express thermal energy or heat.

(Select ALL that apply)

- A. Joule
- B. Watt
- C. Calorie
- D. British Thermal Unit (BTU)
- E. Kelvin
- F. Pascal

7. (3 pts - Systems & Temperature)

In one or two sentences, explain why the Zeroth Law of Thermodynamics is necessary for the concept of temperature to be scientifically meaningful and measurable.

8. (2 pts - Systems & Temperature)

A liquid has a temperature of 212 °F. What is this temperature in Celsius?

- A. 100 °C
- B. 90 °C
- C. 110 °C
- D. 212 °C

9. (2 pts - Systems & Temperature)

Which of the following is the correct SI base-compatible unit for expressing an amount of thermal energy?

- A. Joule
- B. Calorie
- C. BTU
- D. Watt

10. (2 pts - Systems & Temperature)

The Kelvin temperature scale has no negative values under normal thermodynamic conditions because:

- A. It was defined arbitrarily with 0 K at the freezing point of water
- B. 0 K represents absolute zero, the theoretical lowest possible temperature
- C. Kelvin uses a logarithmic scale
- D. Negative temperatures are not allowed by convention, though they physically exist

11. (2 pts - Systems & Temperature)

A thermometer measures temperature by relying on which general principle?

- A. The Second Law of Thermodynamics
- B. A physical property of a material (such as volume or electrical resistance) that changes predictably with temperature
- C. The conservation of momentum
- D. The ideal gas law exclusively

12. (2 pts - Phases & Gas Law)

Which of the following best explains why particles in the gas phase are, on average, much farther apart than particles in the liquid phase of the same substance?

- A. Gas particles have lost their electrons
- B. Gas particles have enough kinetic energy to overcome intermolecular attractive forces almost entirely
- C. Gas particles are chemically different from liquid particles
- D. Gas particles have no mass

13. (3 pts - Phases & Gas Law)

A 150 g sample of water at 100°C absorbs 169,500 J of heat while remaining at 100°C throughout the process (the latent heat of vaporization of water is 2,260 J/g). What fraction of the sample vaporizes?

- A. 25%
- B. 50%
- C. 75%
- D. 100%

14. (3 pts - Phases & Gas Law)

A fixed mass of ideal gas occupies 4.0 L at 2.0 atm and 250 K. If the gas expands to 10.0 L and the temperature rises to 500 K, what is the new pressure? (Use the combined gas law: $P_1V_1/T_1 = P_2V_2/T_2$)

- A. 0.8 atm
- B. 1.0 atm
- C. 1.6 atm
- D. 3.2 atm

15. (3 pts - Phases & Gas Law)

Select ALL of the following statements that are TRUE regarding the ideal gas law, $PV = nRT$.

(Select ALL that apply)

- A. At constant temperature and moles, pressure and volume are inversely proportional
- B. At constant volume and moles, pressure is directly proportional to Kelvin temperature
- C. The ideal gas law can be used with Celsius temperatures without conversion
- D. Increasing the number of moles of gas at constant P and T increases the volume
- E. The ideal gas law assumes gas particles have significant volume and strong intermolecular forces

16. (3 pts - Phases & Gas Law)

Refer to Figure 2. The solid-liquid boundary line for water slopes up and to the left (a negative slope), which is unusual compared to most other substances. Based on this feature of the diagram – and the path shown rising from Point Y at constant temperature – what happens to water's melting point as pressure increases?

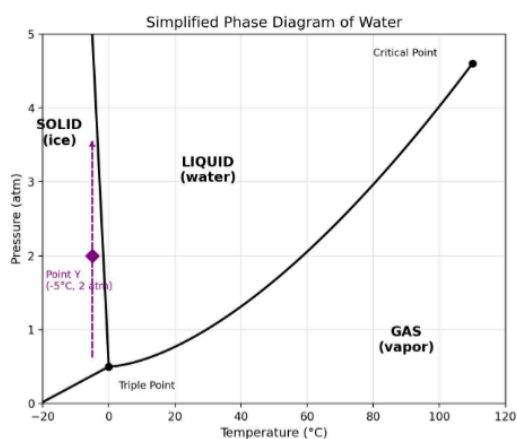


Figure 2: Simplified Phase Diagram of Water, with Point Y and a constant-temperature pressure increase shown

- A. The melting point increases significantly
- B. The melting point decreases slightly
- C. The melting point is completely unaffected by pressure
- D. Water cannot exist as a solid above 1 atm

17. (2 pts - Phases & Gas Law)

Which of the following phase changes is EXOTHERMIC (releases energy to the surroundings)?

- A. Melting
- B. Vaporization
- C. Sublimation
- D. Condensation

18. (2 pts - Phases & Gas Law)

On a pressure-temperature phase plot, three coexistence curves intersect at one coordinate. What thermodynamic condition is represented there?

- A. Only the solid and liquid phases exist
- B. All three phases (solid, liquid, and gas) coexist in equilibrium
- C. The substance is at its critical temperature
- D. The substance cannot be a solid

19. (5 pts - Phases & Gas Law)

Refer to Figure 3, which shows the heating curve for a 100 g sample of water, along with reference data for specific heats and latent heats. Calculate the total heat (in joules) required to take the sample from the start of segment C (0°C , all liquid) through the end of segment D (100°C , all vaporized). Show your work for each segment separately, then find the total.

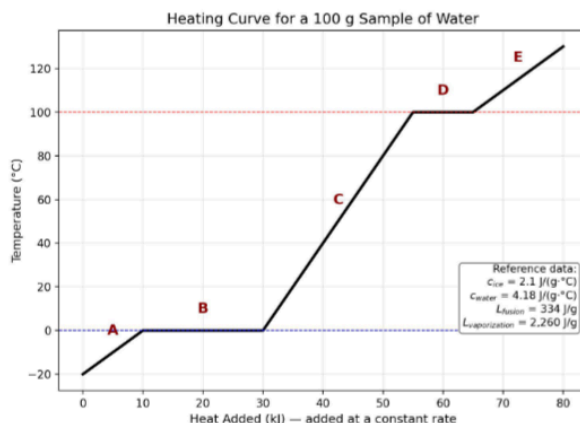


Figure 3: Heating Curve for a 100 g Sample of Water (with reference data)

20. (5 pts - Phases & Gas Law)

A 75 g sample of ice starts at -15°C . Using the specific heat of ice ($2.1 \text{ J}/(\text{g}\cdot^{\circ}\text{C})$) and the latent heat of fusion of water (334 J/g), calculate the total heat required to convert the ice completely into liquid water at 0°C . Show your work for each step.

21. (3 pts - Phases & Gas Law)

A fixed mass of ideal gas occupies 2.0 L at 3.0 atm and 300 K. If the gas expands to 6.0 L and the temperature rises to 600 K, what is the new pressure? (Use the combined gas law:

$$P_1V_1/T_1 = P_2V_2/T_2)$$

- A. 1.0 atm
- B. 1.5 atm
- C. 2.0 atm
- D. 3.0 atm

22. (2 pts - Phases & Gas Law)

Which of the following phase changes ABSORBS energy from the surroundings (is endothermic)?

- A. Freezing
- B. Condensation
- C. Deposition
- D. Sublimation

23. (2 pts - Phases & Gas Law)

According to the kinetic molecular theory of gases, an increase in the temperature of a gas corresponds directly to an increase in:

- A. The size of the gas particles
- B. The average kinetic energy of the gas particles
- C. The mass of the gas particles
- D. The chemical identity of the gas particles

24. (2 pts - Phases & Gas Law)

Which of the following describes the difference between sublimation and deposition?

- A. Sublimation is solid to gas; deposition is gas to solid
- B. Sublimation is gas to solid; deposition is solid to gas
- C. Both describe solid to liquid transitions
- D. Both describe liquid to gas transitions

25. (6 pts - Phases & Gas Law)

In three to four sentences, explain how the ideal gas law ($PV = nRT$) relates the pressure, volume, temperature, and number of moles of a gas, and describe one real-world limitation of the ideal gas model.

26. (2 pts - Heat Transfer)

A temperature difference drives energy through the body of a metal cooking utensil from the immersed end toward the handle. Which transfer mode governs this motion?

- A. Convection
- B. Radiation
- C. Conduction
- D. Evaporation

27. (3 pts - Heat Transfer)

Fourier's law of heat conduction states that the rate of heat transfer through a material, Q/t , is given by $Q/t = kA\Delta T/d$, where k is thermal conductivity, A is cross-sectional area, ΔT is the temperature difference, and d is thickness. Doubling the thickness of a wall, while holding k , A , and ΔT constant, will:

- A. Double the rate of heat loss
- B. Cut the rate of heat loss in half
- C. Have no effect on the rate of heat loss
- D. Quadruple the rate of heat loss

28. (2 pts - Heat Transfer)

The heat capacity of an object depends on:

- A. Only the material it is made of
- B. Only its temperature
- C. Both the material and the total mass of the object
- D. Only its shape

29. (4 pts - Heat Transfer)

Refer to Figure 4. A copper plate has a thickness of 0.20 cm and a cross-sectional area of 500 cm². If the temperature difference across the plate is 8 °C, use Fourier's Law ($Q/t = kA\Delta T/d$) and the k value for copper from the chart to find the rate of heat transfer through the plate, in watts. (Convert units to meters first: 0.20 cm = 0.0020 m; 500 cm² = 0.050 m².)

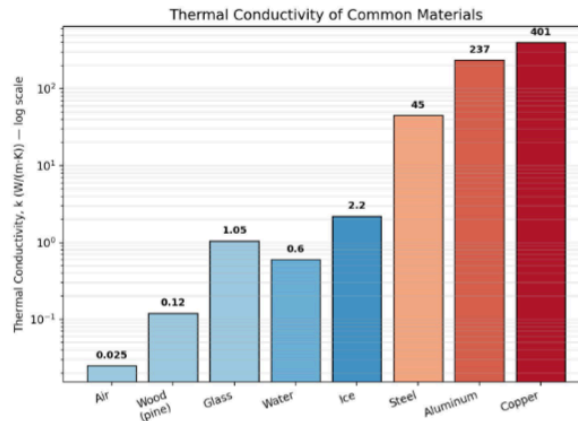


Figure 4: Thermal Conductivity of Common Materials (with k values labeled)

- A. 8,020 W
- B. 40,100 W
- C. 80,200 W
- D. 160,400 W

30. (2 pts - Heat Transfer)

In an isolated pair of bodies with unequal temperatures, which direction of net heat transfer can occur spontaneously?

- A. From cold objects to hot objects
- B. From hot objects to cold objects
- C. Heat does not flow without work being done
- D. Heat flows equally in both directions

31. (2 pts - Heat Transfer)

A thermal detector faces glowing coals across a gap and warms even when air circulation is blocked. Which mechanism carried the energy across the gap?

- A. Conduction
- B. Convection
- C. Radiation
- D. Evaporation

32. (3 pts - Heat Transfer)

Select ALL of the following statements that are TRUE about thermal conductivity and heat capacity.

(Select ALL that apply)

- A. A material's thermal conductivity is an intensive property
- B. A larger object always has a higher thermal conductivity than a smaller object made of the same material
- C. Metals generally have higher thermal conductivity than gases
- D. Heat capacity increases as the mass of an object increases, for a given material
- E. Thermal conductivity has SI units of $\text{W}/(\text{m}\cdot\text{K})$

33. (5 pts - Heat Transfer)

A 0.50 kg block of aluminum (specific heat = $0.90 \text{ J}/(\text{g}\cdot^\circ\text{C})$) is heated from 20°C to 150°C . Using $q = mc\Delta T$, calculate the heat absorbed by the block, in joules. Be careful with your units, and show your work.

34. (4 pts - Heat Transfer)

Using the concepts of particle spacing and free (delocalized) electrons, explain why metals such as copper are typically much better conductors of heat than gases such as air.

35. (4 pts - Heat Transfer)

Analyze Figure 5's distribution of residential winter losses. Which pathway occupies the largest share of the total?

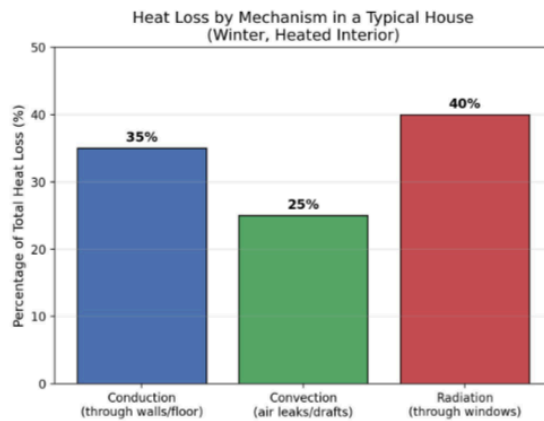


Figure 5: Heat Loss by Mechanism in a Typical House

- A. Conduction
- B. Convection
- C. Radiation
- D. All three are equal

36. (2 pts - Heat Transfer)

Two rods of equal length and cross-sectional area, made of different materials, conduct heat at different rates when placed between the same two temperatures. This difference is due to their different:

- A. Specific heats
- B. Thermal conductivities
- C. Densities
- D. Melting points

37. (2 pts - Heat Transfer)

A cup of hot coffee cools faster in a room with moving air (a fan blowing across it) than in still air. This is because the fan increases heat loss by:

- A. Conduction
- B. Convection
- C. Radiation
- D. Sublimation

38. (3 pts - Heat Transfer)

Which of the following would most effectively reduce heat loss through RADIATION specifically?

- A. Adding a layer of foam insulation
- B. Wrapping an object in a reflective (low-emissivity) material
- C. Sealing air gaps to prevent drafts
- D. Painting an object a darker color

39. (2 pts - Heat Transfer)

A cooking pot with a thick copper bottom heats food more evenly than one with a thin steel bottom, primarily because copper has a:

- A. Higher specific heat
- B. Higher thermal conductivity
- C. Lower density
- D. Higher melting point

40. (6 pts - Heat Transfer)

In three to four sentences, explain why materials like copper and aluminum are used in cookware, while materials like wood and plastic are used for handles, referencing thermal conductivity.

41. (2 pts - Processes & Engines)

In an adiabatic process, which of the following is true?

- A. No work is done on or by the system
- B. No heat is exchanged between the system and its surroundings
- C. The temperature of the system remains constant
- D. The pressure of the system remains constant

42. (3 pts - Processes & Engines)

A gas system absorbs 750 J of heat and does 300 J of work on its surroundings. According to the First Law of Thermodynamics ($\Delta U = Q - W$), what is the change in the internal energy of the system?

- A. 450 J
- B. 1,050 J
- C. -450 J
- D. 300 J

43. (2 pts - Processes & Engines)

Which of the following is a direct real-world consequence of the Second Law of Thermodynamics?

- A. A perpetual motion machine that runs forever with no energy input is possible
- B. Heat spontaneously flows from a cold object to a hot object
- C. No heat engine can convert 100% of the heat it absorbs into useful work
- D. Energy can be created from nothing

44. (2 pts - Processes & Engines)

In a reversible Carnot cycle, which two processes make up the cycle in addition to the two isothermal processes?

- A. Two isobaric processes
- B. Two adiabatic processes
- C. Two isochoric processes
- D. Two isenthalpic processes

45. (4 pts - Processes & Engines)

Refer to Figure 6, which shows an idealized Carnot engine operating between a hot reservoir at $T_h = 800\text{ K}$ and a cold reservoir at $T_c = 200\text{ K}$. Using the Carnot efficiency formula, $\eta = 1 - (T_c / T_h)$, what is the maximum possible efficiency of this engine?

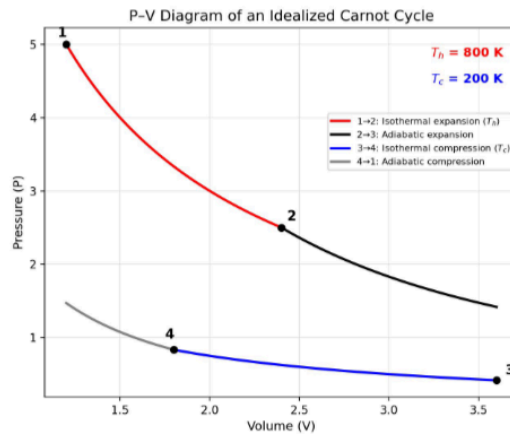


Figure 6: P-V Diagram of an Idealized Carnot Cycle

- A. 25%
- B. 50%
- C. 75%
- D. 90%

46. (2 pts - Processes & Engines)

A cyclic device returns its working fluid to the same pressure, volume, and temperature after one loop. Which conclusion about the fluid follows?

- A. Has more internal energy than at the start
- B. Has less internal energy than at the start
- C. Returns to its original state (same pressure, volume, and temperature)
- D. Is completely converted into work

47. (3 pts - Processes & Engines)

Evaluate the statements about cyclic engines, reservoir exchanges, work production, and maximum efficiency. Select every correct statement.

(Select ALL that apply)

- A. No heat engine can be 100% efficient
- B. All the heat absorbed by an engine is converted into useful work
- C. A heat engine requires a temperature difference between a hot and a cold reservoir to do net work
- D. Increasing an engine's efficiency means less waste heat is produced per unit of work
- E. Engines violate the First Law of Thermodynamics

48. (5 pts - Processes & Engines)

Two heat engines operate between the same two temperature reservoirs. Engine 1 is a real engine with friction and other losses. Engine 2 is an idealized, reversible Carnot engine. In two or three sentences, explain which engine will have the higher efficiency, and why, referencing the Second Law of Thermodynamics.

49. (4 pts - Processes & Engines)

Compare each engine bar in Figure 7 with the Carnot-reference bar. Which real device has the smallest efficiency gap?

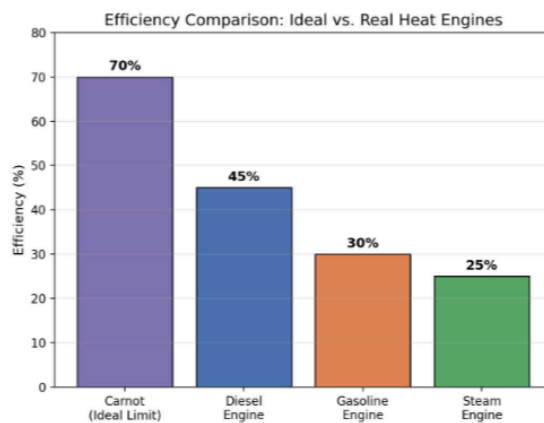


Figure 7: Efficiency Comparison: Ideal vs. Real Heat Engines

- A. Diesel Engine
- B. Gasoline Engine
- C. Steam Engine
- D. None of these are close

50. (2 pts - Processes & Engines)

A gas undergoes an isothermal expansion. Which of the following must be true?

- A. Its temperature increases
- B. Its temperature decreases
- C. Its temperature remains constant
- D. Its pressure remains constant

51. (3 pts - Processes & Engines)

For an ideal gas undergoing an adiabatic expansion ($Q = 0$), what happens to the gas's temperature?

- A. It increases
- B. It decreases
- C. It remains constant
- D. It depends only on the initial pressure

52. (2 pts - Processes & Engines)

On a Pressure-Volume (P-V) diagram, the area enclosed by a complete thermodynamic cycle represents:

- A. The total heat absorbed by the gas
- B. The net work done by the gas over one cycle
- C. The change in internal energy of the gas
- D. The entropy change of the gas

53. (6 pts - Processes & Engines)

In three to four sentences, explain what is meant by an "idealized, reversible" process in thermodynamics, and describe why real engines can never actually achieve this ideal.

54. (2 pts - History)

Rudolf Clausius is best known for which contribution to thermodynamics?

- A. Discovering latent heat
- B. Formulating a mathematical statement of the Second Law of Thermodynamics and introducing the concept of entropy
- C. Establishing the mechanical equivalent of heat
- D. Developing the kinetic theory of gases

55. (2 pts - History)

James Clerk Maxwell's major contribution to the study of thermodynamics was:

- A. The invention of the steam engine
- B. Describing the statistical distribution of molecular speeds in a gas (part of the kinetic theory of gases)
- C. The discovery of the Zeroth Law
- D. The construction of the first working refrigerator

56. (2 pts - History)

Who developed the statistical interpretation that relates entropy to the multiplicity of microscopic states?

- A. James Clerk Maxwell
- B. Rudolf Clausius
- C. Ludwig Boltzmann
- D. Joseph Black

57. (2 pts - History)

Max Planck's introduction of the concept of energy "quanta" was originally developed to correctly explain:

- A. The photoelectric effect
- B. The spectrum of blackbody radiation
- C. The structure of the atom
- D. The theory of relativity

58. (3 pts - History)

Explain how Carnot's analysis of a reversible engine established a temperature-based upper bound for the efficiency of every heat engine.

59. (2 pts - History)

Joseph Black's experimental work most directly contributed to the later development of:

- A. The kinetic theory of gases
- B. The concept of latent heat and specific heat
- C. The Second Law of Thermodynamics
- D. Quantum theory

60. (2 pts - History)

Which of the following scientists is credited with establishing the mechanical equivalent of heat?

- A. Rudolf Clausius
- B. James Joule
- C. Ludwig Boltzmann
- D. Max Planck

61. (2 pts - History)

William Thomson (Lord Kelvin) is best known for:

- A. Proposing an absolute temperature scale
- B. Discovering latent heat
- C. Formulating the kinetic theory of gases
- D. Inventing the steam engine

62. (2 pts - Radiation & Third Law)

Which model describes a perfect absorber whose equilibrium emission depends only on absolute temperature?

- A. Reflects all radiation that strikes it
- B. Absorbs and emits all wavelengths of electromagnetic radiation perfectly (with no reflection)
- C. Is always black in visible color, regardless of temperature
- D. Emits radiation only in the visible light spectrum

63. (3 pts - Radiation & Third Law)

In Figure 8, which spectral curve combines the shortest peak wavelength with the greatest emitted intensity?

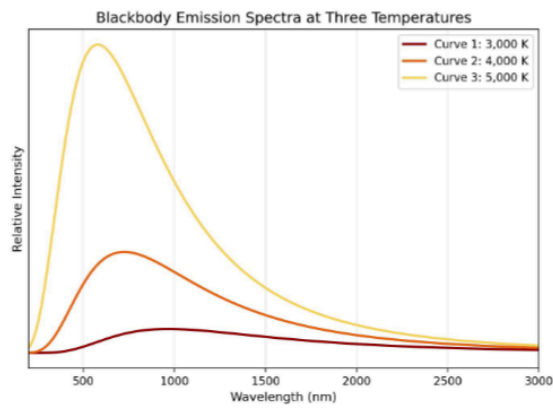


Figure 8: Blackbody Emission Spectra at Three Temperatures

- A. Curve 1
- B. Curve 2
- C. Curve 3
- D. All three curves represent the same temperature

64. (5 pts - Radiation & Third Law)

The Stefan-Boltzmann Law states that the radiant exitance of a blackbody is $M = \sigma T^4$, where $\sigma = 5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$. Refer to Figure 9 for context, then calculate the radiant exitance, in W/m^2 , of a blackbody at a temperature of 300 K. Show your work.

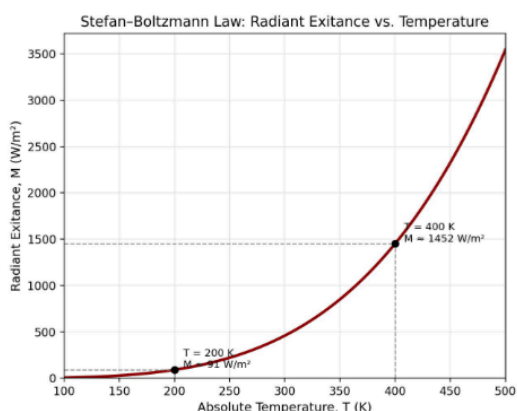


Figure 9: Stefan-Boltzmann Law – Radiant Exitance vs. Temperature

- A. 46 W/m^2
- B. 459 W/m^2
- C. 4,590 W/m^2
- D. 45,900 W/m^2

65. (3 pts - Radiation & Third Law)

Select every statement consistent with thermal spectra and the fourth-power dependence of total blackbody emission on absolute temperature.

(Select ALL that apply)

- A. Hotter objects emit more total radiant energy than cooler objects
- B. Radiant exitance is directly (linearly) proportional to Kelvin temperature
- C. All real objects are perfect blackbodies
- D. The Stefan-Boltzmann Law relates radiated power to the fourth power of absolute temperature
- E. Blackbody radiation can travel through the vacuum of space

66. (2 pts - Radiation & Third Law)

As a defect-free crystal is cooled toward zero kelvin, which limiting statement about its entropy is predicted?

- A. Energy cannot be created or destroyed, only transformed
- B. Heat naturally flows from hot objects to cold objects
- C. As the temperature of a perfect crystal approaches absolute zero, its entropy approaches a minimum (zero) value, and absolute zero itself cannot actually be reached
- D. Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other

67. (3 pts - Radiation & Third Law)

In one or two sentences, explain what it means for absolute zero to be "unattainable," as implied by the Third Law of Thermodynamics.

68. (3 pts - Radiation & Third Law)

For the same emitting surface, temperature changes from T to $3T$. By what factor does σT^4 change?

- A. 3 times
- B. 9 times
- C. 27 times
- D. 81 times

69. (2 pts - Radiation & Third Law)

When an ideal emitter is made hotter, in which direction does the wavelength of maximum emission shift?

- A. Longer (redder)
- B. Shorter (bluer)
- C. Unchanged
- D. Zero

70. (3 pts - Radiation & Third Law)

Which of the following best explains why the Third Law of Thermodynamics implies that absolute zero can never be reached in practice?

- A. Because temperature has no theoretical lower limit
- B. Because each successive step of cooling removes progressively less entropy, requiring infinitely many steps to reach exactly 0 K
- C. Because entropy increases without bound as temperature decreases
- D. Because heat always flows into a system regardless of its temperature

71. (6 pts - Radiation & Third Law)

Define an ideal blackbody, then relate increasing temperature separately to its total radiant output and to the position and shape of its emission spectrum.

72. (2 pts - Entropy & Enthalpy)

In thermodynamics, entropy is best described as:

- A. A measure of the total energy of a system
- B. A measure of the disorder, or the number of possible microscopic arrangements, of a system
- C. The heat content of a system at constant pressure
- D. The rate of heat transfer through a material

73. (2 pts - Entropy & Enthalpy)

Enthalpy is best described as:

- A. A measure of disorder in a system
- B. The total kinetic energy of a system's particles
- C. A thermodynamic quantity equal to a system's internal energy plus the product of its pressure and volume, often used to describe heat content at constant pressure
- D. The temperature at which a system's entropy is zero

74. (4 pts - Entropy & Enthalpy)

Refer to Figure 10, which shows the entropy of a 100 g water sample as its temperature rises, including vertical jumps at the melting and boiling points. Which segment of the graph corresponds to the LARGEST increase in entropy?

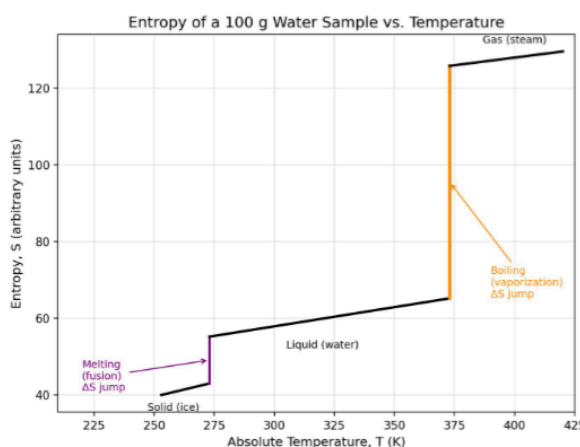


Figure 10: Entropy of a 100 g Water Sample vs. Temperature

- A. The gradual rise while heating solid ice
- B. The vertical jump at the melting point
- C. The gradual rise while heating liquid water
- D. The vertical jump at the boiling point

75. (2 pts - Entropy & Enthalpy)

According to the Second Law of Thermodynamics, what is true about the change in entropy (ΔS) of an isolated system undergoing a spontaneous process?

- A. ΔS is always negative
- B. ΔS is always exactly zero
- C. ΔS is always positive or zero
- D. ΔS depends only on the system's temperature

76. (5 pts - Entropy & Enthalpy)

Calculate the entropy change, ΔS , when 20 g of ice melts completely at 0°C (273 K). The latent heat of fusion of ice is 334 J/g, and for a reversible process at constant temperature, $\Delta S = Q/T$. Show your work.

77. (4 pts - Entropy & Enthalpy)

In one or two sentences, explain the relationship between a system's change in enthalpy and the heat it absorbs or releases at constant pressure, and explain why enthalpy is a useful quantity in thermodynamics.

78. (2 pts - Entropy & Enthalpy)

Which of the following processes results in a DECREASE in the entropy of the system itself (though not necessarily the entropy of the universe)?

- A. Melting
- B. Vaporization
- C. Freezing
- D. Sublimation

79. (2 pts - Entropy & Enthalpy)

The enthalpy change for an exothermic process, ΔH , is:

- A. Always positive
- B. Always negative
- C. Always zero
- D. Dependent only on the process's entropy change

80. (6 pts - Entropy & Enthalpy)

In three to four sentences, explain the relationship between entropy, enthalpy, and spontaneity in a thermodynamic process, referencing the Second Law of Thermodynamics.

THERMODYNAMICS C — NATIONAL EXAM

ANSWER KEY

Division C (High School) — Honors Level — 2027 Draft Rules, Section 3

1. (2 pts - Multiple Choice)

Three objects, P, Q, and R, are brought into contact with each other. After reaching equilibrium, object P is measured to be at the same temperature as object Q, and object Q is at the same temperature as object R. Which law of thermodynamics guarantees that P and R must also be in thermal equilibrium, and why is this law considered fundamental to the concept of temperature?

A. The First Law; it shows that energy is conserved between P, Q, and R

B. The Zeroth Law; it establishes that thermal equilibrium is a transitive relationship, which is what allows temperature to be defined and measured with a thermometer ✓ CORRECT

C. The Second Law; it shows that entropy is equal among all three objects

D. The Third Law; it proves that P, Q, and R can never reach absolute zero

Explanation: The Zeroth Law establishes the transitive property of thermal equilibrium, which is the logical basis for using a thermometer to compare and define temperature.

2. (3 pts - Multiple Choice)

A liquid has a temperature of 68°F. What is this temperature in Kelvin? First convert to Celsius using $^{\circ}\text{C} = (5/9)(^{\circ}\text{F} - 32)$, then convert to Kelvin using $\text{K} = ^{\circ}\text{C} + 273.15$.

A. 293.15 K ✓ CORRECT

B. 253.15 K

C. 310.15 K

D. 200.15 K

Explanation: $(5/9)(68 - 32) = (5/9)(36) = 20.0^{\circ}\text{C}$. Then $20.0 + 273.15 = 293.15 \text{ K}$.

3. (2 pts - Multiple Choice)

Which of the following is an example of an EXTENSIVE property of a system?

A. Temperature

B. Specific heat

C. Total internal energy ✓ CORRECT

D. Pressure

Explanation: Total internal energy scales with the amount of matter in a system, so it is extensive.

4. (2 pts - Multiple Choice)

Which of the following could correctly be used as a unit to express an amount of heat energy?

A. Joule ✓ CORRECT

B. Watt

C. Pascal

D. Newton

Explanation: The joule is the SI unit of energy, including heat.

5. (3 pts - Multiple Choice)

Refer to Figure 1. Point X marks a temperature that is 30% of the way up the Kelvin column, measured from water's freezing point (273 K) to water's boiling point (373 K). What is the equivalent Fahrenheit temperature at Point X?

A. 76° F

B. 86° F ✓ CORRECT

C. 96° F

D. 106° F

Explanation: 30% of the 100 K span above 273 K gives $X = 303$ K, i.e. 30°C. Converting: $^{\circ}\text{F} = (9/5)(30) + 32 = 86^{\circ}\text{F}$.

6. (3 pts - Multi-Select)

Select ALL of the following that are units used to express thermal energy or heat.

A. Joule ✓ CORRECT

B. Watt

C. Calorie ✓ CORRECT

D. British Thermal Unit (BTU) ✓ CORRECT

E. Kelvin

F. Pascal

Explanation: Joule, calorie, and BTU are all units of energy/heat. Watt is power, Kelvin is temperature, and Pascal is pressure.

7. (3 pts - Short Answer)

In one or two sentences, explain why the Zeroth Law of Thermodynamics is necessary for the concept of temperature to be scientifically meaningful and measurable.

Sample Full-Credit Answer: Without the Zeroth Law, there would be no logical basis for comparing the temperatures of two objects that are not in direct contact with each other. The law establishes that thermal equilibrium is transitive, which is what allows a thermometer to be used to indirectly compare and assign temperature values to other objects.

8. (2 pts - Multiple Choice)

A liquid has a temperature of 212° F. What is this temperature in Celsius?

A. 100° C ✓ CORRECT

B. 90° C

C. 110° C

D. 212° C

Explanation: $(5/9)(212 - 32) = (5/9)(180) = 100^{\circ}\text{C}$.

9. (2 pts - Multiple Choice)

Which of the following is the correct SI base-compatible unit for expressing an amount of thermal energy?

- A. Joule ✓ CORRECT
- B. Calorie
- C. BTU
- D. Watt

Explanation: The joule is the SI unit of energy. Calorie and BTU are non-SI energy units, and the watt is a unit of power, not energy.

10. (2 pts - Multiple Choice)

The Kelvin temperature scale has no negative values under normal thermodynamic conditions because:

- A. It was defined arbitrarily with 0 K at the freezing point of water
- B. 0 K represents absolute zero, the theoretical lowest possible temperature ✓ CORRECT
- C. Kelvin uses a logarithmic scale
- D. Negative temperatures are not allowed by convention, though they physically exist

Explanation: The Kelvin scale is an absolute temperature scale, with 0 K defined as absolute zero – the theoretical lower limit of temperature.

11. (2 pts - Multiple Choice)

A thermometer measures temperature by relying on which general principle?

- A. The Second Law of Thermodynamics
- B. A physical property of a material (such as volume or electrical resistance) that changes predictably with temperature ✓ CORRECT
- C. The conservation of momentum
- D. The ideal gas law exclusively

Explanation: Thermometers work by measuring a temperature-dependent physical property (like the thermal expansion of mercury or the resistance of a metal) that changes in a known, predictable way.

12. (2 pts - Multiple Choice)

Which of the following best explains why particles in the gas phase are, on average, much farther apart than particles in the liquid phase of the same substance?

- A. Gas particles have lost their electrons
- B. Gas particles have enough kinetic energy to overcome intermolecular attractive forces almost entirely ✓ CORRECT
- C. Gas particles are chemically different from liquid particles
- D. Gas particles have no mass

Explanation: In the gas phase, particles possess enough kinetic energy to largely overcome the attractive intermolecular forces that hold particles close together in a liquid.

13. (3 pts - Multiple Choice)

A 150 g sample of water at 100°C absorbs 169,500 J of heat while remaining at 100°C throughout the process (the latent heat of vaporization of water is 2,260 J/g). What fraction of the sample vaporizes?

- A. 25%
- B. 50% ✓ CORRECT**
- C. 75%
- D. 100%

Explanation: Mass vaporized = $169,500 \text{ J} \div 2,260 \text{ J/g} = 75 \text{ g}$. Fraction = $75 \text{ g} \div 150 \text{ g} = 0.50$, or 50%.

14. (3 pts - Multiple Choice)

A fixed mass of ideal gas occupies 4.0 L at 2.0 atm and 250 K. If the gas expands to 10.0 L and the temperature rises to 500 K, what is the new pressure? (Use the combined gas law: $P_1V_1/T_1 = P_2V_2/T_2$)

- A. 0.8 atm
- B. 1.0 atm
- C. 1.6 atm ✓ CORRECT**
- D. 3.2 atm

Explanation: $P_2 = P_1V_1T_2 / (T_1V_2) = (2.0)(4.0)(500) / [(250)(10.0)] = 4,000/2,500 = 1.6 \text{ atm}$.

15. (3 pts - Multi-Select)

Select ALL of the following statements that are TRUE regarding the ideal gas law, $PV = nRT$.

- A. At constant temperature and moles, pressure and volume are inversely proportional ✓ CORRECT**
- B. At constant volume and moles, pressure is directly proportional to Kelvin temperature ✓ CORRECT**
- C. The ideal gas law can be used with Celsius temperatures without conversion
- D. Increasing the number of moles of gas at constant P and T increases the volume ✓ CORRECT**
- E. The ideal gas law assumes gas particles have significant volume and strong intermolecular forces

Explanation: Statements 1, 2, and 4 are correct. Temperature must always be converted to Kelvin (statement 3 is false), and the ideal gas model assumes negligible particle volume and no intermolecular forces (statement 5 is false).

16. (3 pts - Multiple Choice)

Refer to Figure 2. The solid-liquid boundary line for water slopes up and to the left (a negative slope), which is unusual compared to most other substances. Based on this feature

of the diagram — and the path shown rising from Point Y at constant temperature — what happens to water's melting point as pressure increases?

- A. The melting point increases significantly
- B. The melting point decreases slightly ✓ CORRECT**
- C. The melting point is completely unaffected by pressure
- D. Water cannot exist as a solid above 1 atm

Explanation: Because the solid-liquid line has a negative slope, increasing pressure at a constant sub-zero temperature can cross from the solid region into the liquid region — meaning water's melting point decreases slightly as pressure increases.

17. (2 pts - Multiple Choice)

Which of the following phase changes is EXOTHERMIC (releases energy to the surroundings)?

- A. Melting
- B. Vaporization
- C. Sublimation
- D. Condensation ✓ CORRECT**

Explanation: Condensation (gas → liquid) releases energy as intermolecular bonds form.

18. (2 pts - Multiple Choice)

On a pressure-temperature phase plot, three coexistence curves intersect at one coordinate. What thermodynamic condition is represented there?

- A. Only the solid and liquid phases exist
- B. All three phases (solid, liquid, and gas) coexist in equilibrium ✓ CORRECT**
- C. The substance is at its critical temperature
- D. The substance cannot be a solid

Explanation: The triple point is the unique combination of temperature and pressure at which all three phases coexist in equilibrium.

19. (5 pts - Short Answer)

Refer to Figure 3, which shows the heating curve for a 100 g sample of water, along with reference data for specific heats and latent heats. Calculate the total heat (in joules) required to take the sample from the start of segment C (0°C, all liquid) through the end of segment D (100°C, all vaporized). Show your work for each segment separately, then find the total.

Sample Full-Credit Answer: Segment C (warming liquid water from 0°C to 100°C): $q_1 = mc\Delta T = (100\text{ g})(4.18\text{ J/(g}\cdot^\circ\text{C)})(100^\circ\text{C}) = 41,800\text{ J}$. Segment D (vaporizing at 100°C): $q_2 = m L_{\text{vaporization}} = (100\text{ g})(2,260\text{ J/g}) = 226,000\text{ J}$. Total heat = 41,800 J + 226,000 J = 267,800 J (267.8 kJ).

20. (5 pts - Short Answer)

A 75 g sample of ice starts at -15°C. Using the specific heat of ice (2.1 J/(g·°C)) and the latent heat of fusion of water (334 J/g), calculate the total heat required to convert the ice completely into liquid water at 0°C. Show your work for each step.

Sample Full-Credit Answer: Step 1 (warming ice from -15°C to 0°C): $q_1 = mc\Delta T = (75\text{ g})(2.1\text{ J/(g}\cdot^{\circ}\text{C)})(15^{\circ}\text{C}) = 2,362.5\text{ J}$. Step 2 (melting at 0°C): $q_2 = mL_{\text{fusion}} = (75\text{ g})(334\text{ J/g}) = 25,050\text{ J}$. Total heat = $2,362.5\text{ J} + 25,050\text{ J} \approx 27,413\text{ J}$.

21. (3 pts - Multiple Choice)

A fixed mass of ideal gas occupies 2.0 L at 3.0 atm and 300 K. If the gas expands to 6.0 L and the temperature rises to 600 K, what is the new pressure? (Use the combined gas law:

$$P_1V_1/T_1 = P_2V_2/T_2)$$

- A. 1.0 atm
- B. 1.5 atm
- C. 2.0 atm ✓ CORRECT**
- D. 3.0 atm

Explanation: $P_2 = P_1V_1T_2 / (T_1V_2) = (3.0)(2.0)(600) / [(300)(6.0)] = 3,600/1,800 = 2.0\text{ atm}$.

22. (2 pts - Multiple Choice)

Which of the following phase changes ABSORBS energy from the surroundings (is endothermic)?

- A. Freezing
- B. Condensation
- C. Deposition
- D. Sublimation ✓ CORRECT**

Explanation: Sublimation (solid $\rightarrow$ gas) requires an input of energy to overcome intermolecular forces, making it endothermic. Freezing, condensation, and deposition are all exothermic.

23. (2 pts - Multiple Choice)

According to the kinetic molecular theory of gases, an increase in the temperature of a gas corresponds directly to an increase in:

- A. The size of the gas particles
- B. The average kinetic energy of the gas particles ✓ CORRECT**
- C. The mass of the gas particles
- D. The chemical identity of the gas particles

Explanation: Temperature is a direct measure of the average kinetic energy of a substance's particles.

24. (2 pts - Multiple Choice)

Which of the following describes the difference between sublimation and deposition?

- A. Sublimation is solid to gas; deposition is gas to solid ✓ CORRECT**
- B. Sublimation is gas to solid; deposition is solid to gas
- C. Both describe solid to liquid transitions
- D. Both describe liquid to gas transitions

Explanation: Sublimation is the direct solid-to-gas transition, while deposition is the reverse: the direct gas-to-solid transition.

25. (6 pts - Long Answer)

In three to four sentences, explain how the ideal gas law ($PV = nRT$) relates the pressure, volume, temperature, and number of moles of a gas, and describe one real-world limitation of the ideal gas model.

Sample Full-Credit Answer: The ideal gas law states that the pressure, volume, and temperature of a gas are related through $PV = nRT$, where n is the number of moles and R is the gas constant — meaning that if the amount of gas is fixed, increasing the temperature will increase the pressure and/or volume, and vice versa. This relationship allows scientists to predict how a gas will behave under changing conditions using simple algebra. However, the ideal gas model assumes gas particles have no volume and experience no intermolecular forces, which breaks down at very high pressures or very low temperatures, where real gases can deviate significantly from ideal behavior — such as when a gas approaches the conditions needed to condense into a liquid.

26. (2 pts - Multiple Choice)

A temperature difference drives energy through the body of a metal cooking utensil from the immersed end toward the handle. Which transfer mode governs this motion?

- A. Convection
- B. Radiation
- C. Conduction ✓ CORRECT**
- D. Evaporation

Explanation: Conduction is the transfer of heat through direct contact between particles of a material.

27. (3 pts - Multiple Choice)

Fourier's law of heat conduction states that the rate of heat transfer through a material, Q/t , is given by $Q/t = kA\Delta T/d$, where k is thermal conductivity, A is cross-sectional area, ΔT is the temperature difference, and d is thickness. Doubling the thickness of a wall, while holding k , A , and ΔT constant, will:

- A. Double the rate of heat loss
- B. Cut the rate of heat loss in half ✓ CORRECT**
- C. Have no effect on the rate of heat loss
- D. Quadruple the rate of heat loss

Explanation: Since Q/t is inversely proportional to thickness d , doubling d cuts the rate of heat transfer in half.

28. (2 pts - Multiple Choice)

The heat capacity of an object depends on:

- A. Only the material it is made of
- B. Only its temperature
- C. Both the material and the total mass of the object ✓ CORRECT**
- D. Only its shape

Explanation: Heat capacity is an extensive property – it scales with both the specific heat of the material and the total mass of the object.

29. (4 pts - Multiple Choice)

Refer to Figure 4. A copper plate has a thickness of 0.20 cm and a cross-sectional area of 500 cm². If the temperature difference across the plate is 8°C, use Fourier's Law ($Q/t = kA\Delta T/d$) and the k value for copper from the chart to find the rate of heat transfer through the plate, in watts. (Convert units to meters first: 0.20 cm = 0.0020 m; 500 cm² = 0.050 m².)

- A. 8,020 W
- B. 40,100 W
- C. 80,200 W ✓ CORRECT**
- D. 160,400 W

Explanation: $Q/t = kA\Delta T/d = (401)(0.050)(8) / (0.0020) = 160.4 / 0.0020 = 80,200 \text{ W}$.

30. (2 pts - Multiple Choice)

In an isolated pair of bodies with unequal temperatures, which direction of net heat transfer can occur spontaneously?

- A. From cold objects to hot objects
- B. From hot objects to cold objects ✓ CORRECT**
- C. Heat does not flow without work being done
- D. Heat flows equally in both directions

Explanation: Heat spontaneously flows from higher-temperature objects to lower-temperature objects.

31. (2 pts - Multiple Choice)

A thermal detector faces glowing coals across a gap and warms even when air circulation is blocked. Which mechanism carried the energy across the gap?

- A. Conduction
- B. Convection
- C. Radiation ✓ CORRECT**
- D. Evaporation

Explanation: Radiation transfers energy as electromagnetic waves and does not require a medium.

32. (3 pts - Multi-Select)

Select ALL of the following statements that are TRUE about thermal conductivity and heat capacity.

- A. A material's thermal conductivity is an intensive property ✓ CORRECT**
- B. A larger object always has a higher thermal conductivity than a smaller object made of the same material
- C. Metals generally have higher thermal conductivity than gases ✓ CORRECT**
- D. Heat capacity increases as the mass of an object increases, for a given material ✓ CORRECT**

E. Thermal conductivity has SI units of $\text{W}/(\text{m}\cdot\text{K})$ ✓ CORRECT

Explanation: Thermal conductivity (k) is intensive — it does not depend on object size, so statement 2 is false. Statements 1, 3, 4, and 5 are all correct.

33. (5 pts - Short Answer)

A 0.50 kg block of aluminum (specific heat = $0.90 \text{ J}/(\text{g}\cdot^\circ\text{C})$) is heated from 20°C to 150°C . Using $q = mc\Delta T$, calculate the heat absorbed by the block, in joules. Be careful with your units, and show your work.

Sample Full-Credit Answer: First convert mass to grams: $0.50 \text{ kg} = 500 \text{ g}$. $\Delta T = 150^\circ\text{C} - 20^\circ\text{C} = 130^\circ\text{C}$. $q = mc\Delta T = (500 \text{ g})(0.90 \text{ J}/(\text{g}\cdot^\circ\text{C}))(130^\circ\text{C}) = 58,500 \text{ J}$ (58.5 kJ).

34. (4 pts - Short Answer)

Using the concepts of particle spacing and free (delocalized) electrons, explain why metals such as copper are typically much better conductors of heat than gases such as air.

Sample Full-Credit Answer: In metals, atoms are packed closely together, and free electrons can move readily throughout the material, rapidly transferring kinetic energy from hotter regions to cooler regions through both particle collisions and electron movement. In gases, particles are far apart and collide much less frequently, so kinetic energy is transferred far more slowly, making gases poor conductors compared to metals.

35. (4 pts - Multiple Choice)

Analyze Figure 5's distribution of residential winter losses. Which pathway occupies the largest share of the total?

- A. Conduction
- B. Convection
- C. Radiation ✓ CORRECT**
- D. All three are equal

Explanation: According to the chart, radiation (mainly through windows) accounts for 40% of heat loss, the largest of the three mechanisms shown.

36. (2 pts - Multiple Choice)

Two rods of equal length and cross-sectional area, made of different materials, conduct heat at different rates when placed between the same two temperatures. This difference is due to their different:

- A. Specific heats
- B. Thermal conductivities ✓ CORRECT**
- C. Densities
- D. Melting points

Explanation: Thermal conductivity (k) directly determines the rate of conductive heat transfer through a material, per Fourier's Law.

37. (2 pts - Multiple Choice)

A cup of hot coffee cools faster in a room with moving air (a fan blowing across it) than in still air. This is because the fan increases heat loss by:

- A. Conduction
- B. Convection ✓ CORRECT**
- C. Radiation
- D. Sublimation

Explanation: Moving air carries heat away from the coffee's surface more efficiently than still air, which is an example of forced convection.

38. (3 pts - Multiple Choice)

Which of the following would most effectively reduce heat loss through RADIATION specifically?

- A. Adding a layer of foam insulation
- B. Wrapping an object in a reflective (low-emissivity) material ✓ CORRECT**
- C. Sealing air gaps to prevent drafts
- D. Painting an object a darker color

Explanation: A reflective, low-emissivity surface specifically reduces radiative heat transfer, unlike foam insulation (which targets conduction) or sealing drafts (which targets convection).

39. (2 pts - Multiple Choice)

A cooking pot with a thick copper bottom heats food more evenly than one with a thin steel bottom, primarily because copper has a:

- A. Higher specific heat
- B. Higher thermal conductivity ✓ CORRECT**
- C. Lower density
- D. Higher melting point

Explanation: Copper's high thermal conductivity allows heat to spread quickly and evenly across the bottom of the pot.

40. (6 pts - Long Answer)

In three to four sentences, explain why materials like copper and aluminum are used in cookware, while materials like wood and plastic are used for handles, referencing thermal conductivity.

Sample Full-Credit Answer: Copper and aluminum are excellent conductors of heat, meaning they quickly and evenly transfer heat from a stove to the food inside a pot, which helps food cook efficiently and uniformly. Wood and plastic, on the other hand, have very low thermal conductivity, so they conduct heat away from a hot pot much more slowly, keeping the handle cool enough to touch safely. This combination allows cookware to be both efficient at transferring heat where it's needed (the cooking surface) and safe to handle (the grip), by pairing materials with very different thermal conductivities for different parts of the same object.

41. (2 pts - Multiple Choice)

In an adiabatic process, which of the following is true?

- A. No work is done on or by the system
- B. No heat is exchanged between the system and its surroundings ✓ CORRECT**
- C. The temperature of the system remains constant
- D. The pressure of the system remains constant

Explanation: Adiabatic means $Q = 0$ – no heat enters or leaves the system, though work and temperature can still change.

42. (3 pts - Multiple Choice)

A gas system absorbs 750 J of heat and does 300 J of work on its surroundings. According to the First Law of Thermodynamics ($\Delta U = Q - W$), what is the change in the internal energy of the system?

- A. 450 J ✓ CORRECT**
- B. 1,050 J
- C. -450 J
- D. 300 J

Explanation: $\Delta U = Q - W = 750 \text{ J} - 300 \text{ J} = 450 \text{ J}$.

43. (2 pts - Multiple Choice)

Which of the following is a direct real-world consequence of the Second Law of Thermodynamics?

- A. A perpetual motion machine that runs forever with no energy input is possible
- B. Heat spontaneously flows from a cold object to a hot object
- C. No heat engine can convert 100% of the heat it absorbs into useful work ✓ CORRECT**
- D. Energy can be created from nothing

Explanation: The Second Law implies that some energy is always lost as unusable heat, so no heat engine can be perfectly (100%) efficient.

44. (2 pts - Multiple Choice)

In a reversible Carnot cycle, which two processes make up the cycle in addition to the two isothermal processes?

- A. Two isobaric processes
- B. Two adiabatic processes ✓ CORRECT**
- C. Two isochoric processes
- D. Two isenthalpic processes

Explanation: The idealized Carnot cycle consists of two isothermal processes connected by two adiabatic processes.

45. (4 pts - Multiple Choice)

Refer to Figure 6, which shows an idealized Carnot engine operating between a hot reservoir at $T_h = 800 \text{ K}$ and a cold reservoir at $T_c = 200 \text{ K}$. Using the Carnot efficiency formula, $\eta = 1 - (T_c / T_h)$, what is the maximum possible efficiency of this engine?

- A. 25%
- B. 50%
- C. 75% ✓ CORRECT**
- D. 90%

Explanation: $\eta = 1 - (200/800) = 1 - 0.25 = 0.75$, or 75%.

46. (2 pts - Multiple Choice)

A cyclic device returns its working fluid to the same pressure, volume, and temperature after one loop. Which conclusion about the fluid follows?

- A. Has more internal energy than at the start
- B. Has less internal energy than at the start
- C. Returns to its original state (same pressure, volume, and temperature) ✓ CORRECT**
- D. Is completely converted into work

Explanation: A complete cycle returns the working substance to its original state, even though net work has been done.

47. (3 pts - Multi-Select)

Evaluate the statements about cyclic engines, reservoir exchanges, work production, and maximum efficiency. Select every correct statement.

- A. No heat engine can be 100% efficient ✓ CORRECT**
- B. All the heat absorbed by an engine is converted into useful work
- C. A heat engine requires a temperature difference between a hot and a cold reservoir to do net work ✓ CORRECT**
- D. Increasing an engine's efficiency means less waste heat is produced per unit of work ✓ CORRECT**
- E. Engines violate the First Law of Thermodynamics

Explanation: Statements 1, 3, and 4 are true. Statement 2 is false (some heat is always exhausted), and statement 5 is false (engines obey the First Law).

48. (5 pts - Short Answer)

Two heat engines operate between the same two temperature reservoirs. Engine 1 is a real engine with friction and other losses. Engine 2 is an idealized, reversible Carnot engine. In two or three sentences, explain which engine will have the higher efficiency, and why, referencing the Second Law of Thermodynamics.

Sample Full-Credit Answer: The idealized Carnot engine (Engine 2) will always have a higher (or, at best, equal) efficiency than the real engine, because the reversible Carnot cycle represents the theoretical maximum efficiency possible between two given temperature reservoirs. Real engines have irreversible losses, such as friction and unwanted heat transfer, which the Second Law of Thermodynamics guarantees will always keep their efficiency below the Carnot limit.

49. (4 pts - Multiple Choice)

Compare each engine bar in Figure 7 with the Carnot-reference bar. Which real device has the smallest efficiency gap?

- A. Diesel Engine ✓ CORRECT
- B. Gasoline Engine
- C. Steam Engine
- D. None of these are close

Explanation: The Diesel engine's 45% efficiency is closest to the 70% Carnot ideal limit shown.

50. (2 pts - Multiple Choice)

A gas undergoes an isothermal expansion. Which of the following must be true?

- A. Its temperature increases
- B. Its temperature decreases
- C. Its temperature remains constant ✓ CORRECT
- D. Its pressure remains constant

Explanation: Isothermal means the temperature is held constant throughout the process.

51. (3 pts - Multiple Choice)

For an ideal gas undergoing an adiabatic expansion ($Q = 0$), what happens to the gas's temperature?

- A. It increases
- B. It decreases ✓ CORRECT
- C. It remains constant
- D. It depends only on the initial pressure

Explanation: Since no heat enters the system ($Q = 0$), the work done by the expanding gas comes entirely from its internal energy, so the gas's temperature decreases ($\Delta U = -W$).

52. (2 pts - Multiple Choice)

On a Pressure-Volume (P-V) diagram, the area enclosed by a complete thermodynamic cycle represents:

- A. The total heat absorbed by the gas
- B. The net work done by the gas over one cycle ✓ CORRECT
- C. The change in internal energy of the gas
- D. The entropy change of the gas

Explanation: The enclosed area on a P-V diagram equals the net work done by (or on) the gas over one complete cycle.

53. (6 pts - Long Answer)

In three to four sentences, explain what is meant by an "idealized, reversible" process in thermodynamics, and describe why real engines can never actually achieve this ideal.

Sample Full-Credit Answer: An idealized, reversible process is one that occurs infinitely slowly, remaining in equilibrium at every instant, so that it could in principle be run backward through the

exact same sequence of states with no net change to the universe. In such a process, no energy is lost to friction, turbulence, or other irreversible losses. Real engines, however, always operate at finite speeds and involve some friction, turbulence, and uncontrolled heat transfer, all of which generate entropy and waste useful energy. As a result, real engines can only approach – but never fully reach – the theoretical efficiency of an idealized reversible cycle, such as the Carnot cycle.

54. (2 pts - Multiple Choice)

Rudolf Clausius is best known for which contribution to thermodynamics?

- A. Discovering latent heat
- B. Formulating a mathematical statement of the Second Law of Thermodynamics and introducing the concept of entropy ✓ CORRECT**
- C. Establishing the mechanical equivalent of heat
- D. Developing the kinetic theory of gases

Explanation: Clausius formalized the Second Law and is credited with introducing the concept of entropy.

55. (2 pts - Multiple Choice)

James Clerk Maxwell's major contribution to the study of thermodynamics was:

- A. The invention of the steam engine
- B. Describing the statistical distribution of molecular speeds in a gas (part of the kinetic theory of gases) ✓ CORRECT**
- C. The discovery of the Zeroth Law
- D. The construction of the first working refrigerator

Explanation: Maxwell developed the statistical distribution describing the range of molecular speeds in a gas at a given temperature.

56. (2 pts - Multiple Choice)

Who developed the statistical interpretation that relates entropy to the multiplicity of microscopic states?

- A. James Clerk Maxwell
- B. Rudolf Clausius
- C. Ludwig Boltzmann ✓ CORRECT**
- D. Joseph Black

Explanation: Ludwig Boltzmann developed the statistical interpretation connecting entropy to the number of possible microscopic arrangements of particles.

57. (2 pts - Multiple Choice)

Max Planck's introduction of the concept of energy "quanta" was originally developed to correctly explain:

- A. The photoelectric effect
- B. The spectrum of blackbody radiation ✓ CORRECT**
- C. The structure of the atom

D. The theory of relativity

Explanation: Planck proposed that energy is emitted and absorbed in discrete quanta to correctly derive the observed spectrum of blackbody radiation.

58. (3 pts - Short Answer)

Explain how Carnot's analysis of a reversible engine established a temperature-based upper bound for the efficiency of every heat engine.

Sample Full-Credit Answer: Sadi Carnot developed the concept of an idealized heat engine cycle (the Carnot cycle) and showed that there is a maximum possible efficiency for any heat engine operating between two given temperatures. His work laid an important foundation for what became the Second Law of Thermodynamics.

59. (2 pts - Multiple Choice)

Joseph Black's experimental work most directly contributed to the later development of:

- A. The kinetic theory of gases
- B. The concept of latent heat and specific heat ✓ CORRECT
- C. The Second Law of Thermodynamics
- D. Quantum theory

Explanation: Joseph Black's 18th-century experiments led to his identification of latent heat and specific heat capacity.

60. (2 pts - Multiple Choice)

Which of the following scientists is credited with establishing the mechanical equivalent of heat?

- A. Rudolf Clausius
- B. James Joule ✓ CORRECT
- C. Ludwig Boltzmann
- D. Max Planck

Explanation: James Joule's experiments quantified the numerical relationship between mechanical work and the heat it produces.

61. (2 pts - Multiple Choice)

William Thomson (Lord Kelvin) is best known for:

- A. Proposing an absolute temperature scale ✓ CORRECT
- B. Discovering latent heat
- C. Formulating the kinetic theory of gases
- D. Inventing the steam engine

Explanation: Lord Kelvin proposed an absolute temperature scale, now known as the Kelvin scale, with a theoretical lowest possible value.

62. (2 pts - Multiple Choice)

Which model describes a perfect absorber whose equilibrium emission depends only on absolute temperature?

- A. Reflects all radiation that strikes it
- B. Absorbs and emits all wavelengths of electromagnetic radiation perfectly (with no reflection) ✓ CORRECT**
- C. Is always black in visible color, regardless of temperature
- D. Emits radiation only in the visible light spectrum

Explanation: A blackbody is a theoretical perfect absorber and emitter of radiation at all wavelengths.

63. (3 pts - Multiple Choice)

In Figure 8, which spectral curve combines the shortest peak wavelength with the greatest emitted intensity?

- A. Curve 1
- B. Curve 2
- C. Curve 3 ✓ CORRECT**
- D. All three curves represent the same temperature

Explanation: Curve 3 has both the greatest overall intensity and a peak shifted to the shortest wavelength, both of which indicate it belongs to the hottest object.

64. (5 pts - Multiple Choice)

The Stefan-Boltzmann Law states that the radiant exitance of a blackbody is $M = \sigma T^4$, where $\sigma = 5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$. Refer to Figure 9 for context, then calculate the radiant exitance, in W/m^2 , of a blackbody at a temperature of 300 K. Show your work.

- A. 46 W/m^2
- B. 459 W/m^2 ✓ CORRECT**
- C. 4,590 W/m^2
- D. 45,900 W/m^2

Explanation: $M = \sigma T^4 = (5.67 \times 10^{-8})(300)^4 \approx 459 \text{ W}/\text{m}^2$.

65. (3 pts - Multi-Select)

Select every statement consistent with thermal spectra and the fourth-power dependence of total blackbody emission on absolute temperature.

- A. Hotter objects emit more total radiant energy than cooler objects ✓ CORRECT**
- B. Radiant exitance is directly (linearly) proportional to Kelvin temperature
- C. All real objects are perfect blackbodies
- D. The Stefan-Boltzmann Law relates radiated power to the fourth power of absolute temperature ✓ CORRECT**
- E. Blackbody radiation can travel through the vacuum of space ✓ CORRECT**

Explanation: Statements 1, 4, and 5 are correct. Statement 2 is false (proportional to T^4 , not T), and statement 3 is false.

66. (2 pts - Multiple Choice)

As a defect-free crystal is cooled toward zero kelvin, which limiting statement about its entropy is predicted?

- A. Energy cannot be created or destroyed, only transformed
- B. Heat naturally flows from hot objects to cold objects
- C. As the temperature of a perfect crystal approaches absolute zero, its entropy approaches a minimum (zero) value, and absolute zero itself cannot actually be reached ✓ CORRECT
- D. Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other

Explanation: Option C correctly states the Third Law; the other options restate the First, Second, and Zeroth Laws.

67. (3 pts - Short Answer)

In one or two sentences, explain what it means for absolute zero to be "unattainable," as implied by the Third Law of Thermodynamics.

Sample Full-Credit Answer: The Third Law implies that while a system's entropy can get arbitrarily close to its minimum value as its temperature approaches absolute zero, it is impossible to actually cool any real system to exactly 0 K using a finite number of steps or processes. This makes absolute zero a theoretical limiting value rather than a temperature that can actually be reached.

68. (3 pts - Multiple Choice)

For the same emitting surface, temperature changes from T to $3T$. By what factor does σT^4 change?

- A. 3 times
- B. 9 times
- C. 27 times
- D. 81 times ✓ CORRECT

Explanation: Since $M \propto T^4$, tripling the temperature increases radiant exitance by a factor of $3^4 = 81$.

69. (2 pts - Multiple Choice)

When an ideal emitter is made hotter, in which direction does the wavelength of maximum emission shift?

- A. Longer (redder)
- B. Shorter (bluer) ✓ CORRECT
- C. Unchanged
- D. Zero

Explanation: As an object's temperature increases, its blackbody emission spectrum peaks at progressively shorter (bluer) wavelengths.

70. (3 pts - Multiple Choice)

Which of the following best explains why the Third Law of Thermodynamics implies that absolute zero can never be reached in practice?

- A. Because temperature has no theoretical lower limit
- B. Because each successive step of cooling removes progressively less entropy, requiring infinitely many steps to reach exactly 0 K ✓ CORRECT**
- C. Because entropy increases without bound as temperature decreases
- D. Because heat always flows into a system regardless of its temperature

Explanation: As a system approaches 0 K, further cooling removes ever-smaller amounts of entropy, meaning an infinite number of steps would be needed to fully reach absolute zero.

71. (6 pts - Long Answer)

Define an ideal blackbody, then relate increasing temperature separately to its total radiant output and to the position and shape of its emission spectrum.

Sample Full-Credit Answer: A blackbody is an idealized object that perfectly absorbs and re-emits all wavelengths of electromagnetic radiation, without reflecting any incoming radiation. The Stefan-Boltzmann Law states that the total radiant exitance of a blackbody is proportional to the fourth power of its absolute temperature ($M = \sigma T^4$), so even a modest increase in temperature causes a very large increase in the total energy emitted. Additionally, hotter blackbodies emit their peak radiation at shorter wavelengths and with greater overall intensity than cooler blackbodies, which is why very hot objects (like stars) glow with different colors depending on their surface temperature.

72. (2 pts - Multiple Choice)

In thermodynamics, entropy is best described as:

- A. A measure of the total energy of a system
- B. A measure of the disorder, or the number of possible microscopic arrangements, of a system ✓ CORRECT**
- C. The heat content of a system at constant pressure
- D. The rate of heat transfer through a material

Explanation: Entropy is a measure of a system's disorder or the number of ways its particles can be microscopically arranged.

73. (2 pts - Multiple Choice)

Enthalpy is best described as:

- A. A measure of disorder in a system
- B. The total kinetic energy of a system's particles
- C. A thermodynamic quantity equal to a system's internal energy plus the product of its pressure and volume, often used to describe heat content at constant pressure ✓ CORRECT**
- D. The temperature at which a system's entropy is zero

Explanation: Enthalpy ($H = U + PV$) is convenient because, at constant pressure, the change in enthalpy equals the heat absorbed or released by a system.

74. (4 pts - Multiple Choice)

Refer to Figure 10, which shows the entropy of a 100 g water sample as its temperature rises, including vertical jumps at the melting and boiling points. Which segment of the graph corresponds to the LARGEST increase in entropy?

- A. The gradual rise while heating solid ice
- B. The vertical jump at the melting point
- C. The gradual rise while heating liquid water
- D. The vertical jump at the boiling point ✓ CORRECT

Explanation: The vertical jump at the boiling point (vaporization) is the largest entropy increase, since $\Delta S = \Delta H/T$ and the latent heat of vaporization is much larger than the latent heat of fusion.

75. (2 pts - Multiple Choice)

According to the Second Law of Thermodynamics, what is true about the change in entropy (ΔS) of an isolated system undergoing a spontaneous process?

- A. ΔS is always negative
- B. ΔS is always exactly zero
- C. ΔS is always positive or zero ✓ CORRECT
- D. ΔS depends only on the system's temperature

Explanation: The Second Law states that the entropy of an isolated system undergoing a spontaneous process never decreases – $\Delta S \geq 0$.

76. (5 pts - Short Answer)

Calculate the entropy change, ΔS , when 20 g of ice melts completely at 0°C (273 K). The latent heat of fusion of ice is 334 J/g, and for a reversible process at constant temperature, $\Delta S = Q/T$. Show your work.

Sample Full-Credit Answer: $Q = mL = (20 \text{ g})(334 \text{ J/g}) = 6,680 \text{ J}$. $\Delta S = Q/T = 6,680 \text{ J} \div 273 \text{ K} \approx 24.5 \text{ J/K}$.

77. (4 pts - Short Answer)

In one or two sentences, explain the relationship between a system's change in enthalpy and the heat it absorbs or releases at constant pressure, and explain why enthalpy is a useful quantity in thermodynamics.

Sample Full-Credit Answer: At constant pressure, the change in a system's enthalpy (ΔH) is equal to the heat absorbed or released by the system ($q_p = \Delta H$). This makes enthalpy a convenient quantity for tracking heat flow in processes that occur at constant pressure – such as most everyday physical and chemical changes occurring in open containers – without needing to separately account for pressure-volume work.

78. (2 pts - Multiple Choice)

Which of the following processes results in a DECREASE in the entropy of the system itself (though not necessarily the entropy of the universe)?

- A. Melting
- B. Vaporization
- C. Freezing ✓ CORRECT

D. Sublimation

Explanation: Freezing converts a relatively disordered liquid into a more ordered solid, decreasing the system's entropy – even though the surroundings' entropy increases by a larger amount, keeping total entropy from decreasing.

79. (2 pts - Multiple Choice)

The enthalpy change for an exothermic process, ΔH , is:

- A. Always positive
- B. Always negative ✓ CORRECT
- C. Always zero
- D. Dependent only on the process's entropy change

Explanation: By convention, an exothermic process releases heat to the surroundings, corresponding to a negative ΔH .

80. (6 pts - Long Answer)

In three to four sentences, explain the relationship between entropy, enthalpy, and spontaneity in a thermodynamic process, referencing the Second Law of Thermodynamics.

Sample Full-Credit Answer: Entropy (S) is a measure of a system's disorder, while enthalpy (H) reflects the heat content of a system at constant pressure; changes in these two quantities together help determine whether a process will occur spontaneously. The Second Law of Thermodynamics states that the total entropy of an isolated system (including its surroundings) must increase or stay the same for any spontaneous process, even if the entropy of the system itself decreases (such as during freezing), as long as the surroundings' entropy increases by a greater amount. Processes that release heat (negative ΔH) and increase overall disorder (positive total ΔS) are generally favored to occur spontaneously, so the balance between enthalpy and entropy changes ultimately governs whether a given process happens on its own.