Applied Thermodynamics Workbook

Supplementary Exercises for In-Class Learning

Serhat Beyenir

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Preface

This workbook is a collection of lecture notes on Applied Thermodynamics. It aims to provide concise yet essential insights into the topics covered in class. Each chapter includes a problem set designed to help you understand the material better.

Chapter 1: Mastering and practicing SI units may seem like a small step, but it's a powerful one! Building a strong foundation in SI units will not only support you in this course but will also give you a solid footing in future studies and practical applications. This skill is essential in so many courses, and your efforts now are setting you up for success.

Chapter 2: We commonly think of temperature as an indication of the degree of hotness or coldness in a body. A more accurate definition would be "a measure of the level, or intensity of internal energy."

Chapter 3: Linear expansion refers to a change in one direction (or dimension) only. Generally, it occurs in a long, relatively thin object where the predominant dimension under consideration is length.

Chapter 4: Explain the methods of heat transfer: conduction, convection, and radiation.

Chapter 5: A perfect gas may be defined as a gas that remains in its gaseous state during changes in condition. Another way to state this is that the gas will not condense (even partially) if any of its conditions (temperature, volume or pressure) are changed.

Chapter 6: To expand a gas, the gas is allowed to increase in volume and reduce in pressure. In this case, the gas itself is capable of performing work as it expands. For example, in an internal combustion engine, fuel is burned with air in a cylinder, producing high pressure and temperature.

Chapter 7: When the fuel burns inside the engine's cylinder, it gives out heat which is absorbed by the air previously taken into the cylinder, the temperature of the air is therefore increased with a consequent increase in pressure and/or change in volume and the piston moves due to the heat energy imparted to it. The reciprocating motion of the piston is converted into a rotary motion in the crankshaft by the connecting rod and crank or piston rod, cross-head and crank in the case of the large two- stroke marine engines.

Chapter 1

International System of Units

1.1 Objectives

- Recall the base and derived units.
- Practice the application of unity fraction.

1.2 Concepts

The International System of Units (SI) is the globally accepted standard for measurement. Established to provide a consistent framework for scientific and technical measurements, SI units facilitate clear communication and data comparison across various fields and countries. The system is based on seven fundamental units: the meter for length, the kilogram for mass, the second for time, the ampere for electric current, the kelvin for temperature, the mole for substance, and the candela for luminous intensity.

Table 1.1: Base SI units.

Physical Quantity	SI Base Unit	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric Current	Ampere	A
Temperature	Kelvin	K
Amount of Substance	Mole	mol
Luminous Intensity	Candela	cd

Table 1.2: Derived SI units.

Physical Quantity	Derived SI Unit	Symbol
Area	Square meter	m^2
Volume	Cubic meter	m^3
Speed	Meter per second	m/s
Acceleration	Meter per second squared	m/s^2
Force	Newton	N
Pressure	Pascal	Pa
Energy	Joule	J
Power	Watt	W
Electric Charge	Coulomb	C
Electric Potential	Volt	V
Resistance	Ohm	Ω
Capacitance	Farad	F
Frequency	Hertz	Hz
Luminous Flux	Lumen	lm
Illuminance	Lux	lx
Specific Energy	Joule per kilogram	J/kg
Specific Heat Capacity	Joule per kilogram Kelvin	$J/(kg \cdot K)$

Table 1.3: Common multiples and submultiples for SI units.

Factor	Prefix	Symbol
10^9	giga	G
10^6	mega	M
10^3	kilo	k
10^2	hecto	h
10^1	deca	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	µ

1.2.1 Unity Fraction

The **unity fraction** method, or **unit conversion using unity fractions**, is a systematic way to convert one unit of measurement into another. This method relies on multiplying by fractions that are equal to one, where the numerator and the denominator represent the same quantity in different units. Since any number multiplied by one remains the same, unity fractions allow for seamless conversion without changing the value.

The principle of unity fractions is based on:

1. **Setting up equal values**: Write a fraction where the numerator and denominator are equivalent values in different units, so the fraction equals one. For example, $\frac{1km}{1000m}$ is a unity fraction because 1 km equals 1000 m.
2. **Multiplying by unity fractions**: Multiply the initial quantity by the unity fraction(s) so that the undesired units cancel out, leaving only the desired units.

1.3 Classwork

Example 1.1. Suppose we want to convert 5 kilometers to meters.

1. Start with 5 kilometers:
$$5\,\mathrm{km}$$
2. Multiply by a unity fraction that cancels kilometers and introduces meters. We use $(\frac{1000\,\mathrm{m}}{1\,\mathrm{km}}), since\, 1\,\mathrm{km} = 1000\,\mathrm{m}$:
$$5\,\mathrm{km} \times \frac{1000\,\mathrm{m}}{1\,\mathrm{km}} = 5000\,\mathrm{m}$$
3. The kilometers km cancel out, leaving us with meters m:

$$5\,\mathrm{km} = 5000\,\mathrm{m}$$

This step-by-step approach illustrates how the unity fraction cancels the undesired units and achieves the correct result in meters.

Unity fractions can be extended by using multiple conversion steps. For example, converting hours to seconds would require two unity fractions: one to convert hours to minutes and another to convert minutes to seconds. This approach ensures accuracy and is widely used in science, engineering, and other fields that require precise unit conversions.

Example 1.2. Convert $15\,\mathrm{m/s}$ to km/h.

1. Start with $15\,\mathrm{m/s}$.
2. To convert meters to kilometers, multiply by $\frac{1\,\mathrm{km}}{1000\,\mathrm{m}}$.
3. To convert seconds to hours, multiply by $\frac{3600\,\mathrm{s}}{1\,\mathrm{h}}$.

$$15\,\mathrm{m/s} \times \frac{1\,\mathrm{km}}{1000\,\mathrm{m}} \times \frac{3600\,\mathrm{s}}{1\,\mathrm{h}} = 54\,\mathrm{km/h}$$

The meters and seconds cancel out, leaving kilometers per hour: $54\,\mathrm{km/h}$.

1.4 Problem Set

Instructions:

1. Use unity fraction to convert between derived SI units.
2. Show each step of your work to ensure accuracy.
3. Simplify your answers and include correct units.

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1. **Speed**
   Convert $72\,\mathrm{km/h}$ to m/s.
2. **Force**
   Convert $980\,\mathrm{N}$ (newtons) to $\mathrm{kg}\cdot\mathrm{m/s}^2$.
3. **Energy**
   Convert $2500\,\mathrm{J}$ (joules) to kJ.
4. **Power**
   Convert $1500\,\mathrm{W}$ (watts) to kW.
5. **Pressure**
   Convert $101325\,\mathrm{Pa}$ (pascals) to kPa.
6. **Volume Flow Rate**
   Convert $3\,\mathrm{m}^3/\mathrm{min}$ to L/s.

7. **Density**
   Convert $1000\,\mathrm{kg/m^3}$ to $\mathrm{g/cm^3}$.
8. **Acceleration**
   Convert $9.8\,\mathrm{m/s^2}$ to $\mathrm{cm/s^2}$.
9. **Torque**
   Convert $50\,\mathrm{N\cdot m}$ to $\mathrm{kN\cdot cm}$.
10. **Frequency**
    Convert $500\,\mathrm{Hz}$ (hertz) to kHz.
11. **Work to Energy Conversion**
    A force of $20\,\mathrm{N}$ moves an object $500\,\mathrm{cm}$. Convert the work done to joules.
12. **Kinetic Energy Conversion**
    Calculate the kinetic energy in kilojoules of a $1500\,\mathrm{kg}$ car moving at $72\,\mathrm{km/h}$.
13. **Power to Energy Conversion**
    A machine operates at $2\,\mathrm{kW}$ for 3 hours. Convert the energy used to megajoules.
14. **Pressure to Force Conversion**
    Convert a pressure of $200\,\mathrm{kPa}$ applied to an area of $0.5\,\mathrm{m}^2$ to force in newtons.
15. **Density to Mass Conversion**
    Convert $0.8\,\mathrm{g/cm^3}$ for an object with a volume of $250\,\mathrm{cm}^3$ to mass in grams.

1.4.1 Answer Key

1. $72\,\mathrm{km/h} = 20\,\mathrm{m/s}$
2. $980\,\mathrm{N} = 980\,\mathrm{kg\cdot m/s^2}$
3. $2500\,\mathrm{J} = 2.5\,\mathrm{kJ}$
4. $1500\,\mathrm{W} = 1.5\,\mathrm{kW}$
5. $101325\,\mathrm{Pa} = 101.325\,\mathrm{kPa}$
6. $3\,\mathrm{m}^3/\mathrm{min} = 50\,\mathrm{L/s}$
7. $1000\,\mathrm{kg/m^3} = 1\,\mathrm{g/cm^3}$
8. $9.8\,\mathrm{m/s^2} = 980\,\mathrm{cm/s^2}$
9. $50\,\mathrm{N\cdot m} = 0.5\,\mathrm{kN\cdot cm}$
10. $500\,\mathrm{Hz} = 0.5\,\mathrm{kHz}$
11. $20\,\mathrm{N} \times 5\,\mathrm{m} = 100\,\mathrm{J}$
12. Kinetic energy $= 1500\,\mathrm{kg} \times (20\,\mathrm{m/s})^2/2 = 300\,\mathrm{kJ}$
13. $2\,\mathrm{kW} \times 3\,\mathrm{hours} = 21.6\,\mathrm{MJ}$
14. $200\,\mathrm{kPa} \times 0.5\,\mathrm{m}^2 = 100,000\,\mathrm{N}$

15. $0.8\,\mathrm{g/cm^3} \times 250\,\mathrm{cm^3} = 200\,\mathrm{g}$

1.5 Further Reading

Read Chapter 1in Russell, Embleton, and Jackson (2022) and complete the end of chapter problems.

Chapter 2

Heat

2.1 Objectives

- Define heat, specific heat, temperature, and explain temperature measurement scales.
- Explain state changes, latent heat, including fusion and evaporation, and their role in energy transfer.
- Calculate the heat required to change the state of water and other substances.
- Describe a simple calorimeter and use the calorimeter equation to calculate specific heat and final temperature.
- Calculate water equivalents and perform calorimeter and heat calculations.

2.2 Concepts

2.2.1 Temperature

Temperature quantifies hotness or coldness and is measured with a thermometer. It reflects the average kinetic energy of vibrating and colliding atoms.

Thermometers are calibrated in various temperature scales, including Celsius (°C), Fahrenheit (°F), and Kelvin (K). Kelvin is the primary scientific scale and one of the seven base units in the International System of Units (SI).

2.2.1.1 Temperature Scales

Figure 2.1 shows the relationship between temperature scales and the key temperatures of consideration for each. Refer to Figure 2.1 during the descriptions of each scale.

Note that there are three temperatures that are used as the key reference points for these scales. These are:

- Absolute zero
- Freezing point (temperature) of water at atmospheric pressure
- Boiling point (temperature) of water at atmospheric pressure

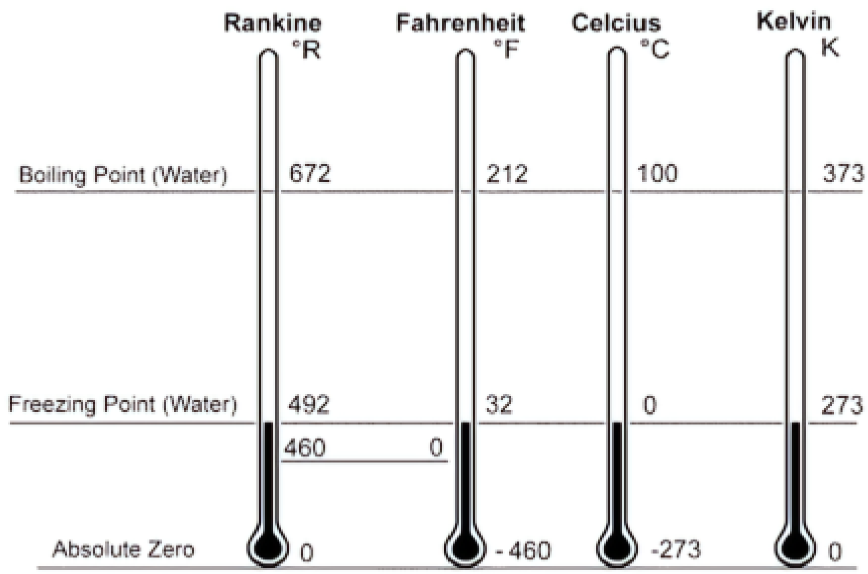

Figure 2.1: Temperature Scales

2.3 Classwork

2.4 Problem Set

2.5 Further Reading

Read Chapter 2 in Russell, Embleton, and Jackson (2022), for additional information.

Chapter 3

Thermal Expansion

3.1 Objectives

- Explain thermal conditions causing solid and liquid expansion and their linear, superficial (area), and volumetric relationships.
- Calculate linear, superficial, and volumetric expansion, solids or liquids.
- Calculate stress in a pipe or supports due to thermal expansion.

3.2 Concepts

Thermal expansion is the tendency of materials to change their shape, area, and volume in response to a change in temperature. When most substances are heated, their particles move more vigorously and tend to occupy more space, leading to an increase in dimensions. Conversely, when substances are cooled, they generally contract. This phenomenon occurs in solids, liquids, and gases, although the degree and nature of expansion vary depending on the material's state and properties.

3.2.1 Linear Expansion

This occurs along a specific dimension or direction, primarily in long, narrow objects (like rods or beams). When the temperature of a solid object increases, its length expands by an amount proportional to its original length and the temperature change. The equation for linear expansion is:

$$\Delta L = \alpha L_0 \Delta T \tag{3.1}$$

where:

- ΔL is the change in length,
- α is the coefficient of linear expansion (unique to each material),
- L_0 is the original length, and
- ΔT is the temperature change.

3.2.2 Superficial Expansion

Applicable to two-dimensional surfaces, such as sheets or plates. Here, both length and width expand, leading to an increase in surface area. The formula for area expansion is:

$$\Delta A = 2\alpha A_0 \Delta T \tag{3.2}$$

where:

- ΔA is the change in area,
- A_0 is the initial area, and
- ΔT is the temperature change.

3.2.3 Volumetric Expansion

Relevant for three-dimensional objects (like solids, liquids, and gases). The volume of an object expands with temperature, especially in fluids where this effect is more pronounced. The formula is:

$$\Delta V = \beta V_0 \Delta T \tag{3.3}$$

where:

- ΔV is the change in volume,
- β is the coefficient of volumetric expansion, which is approximately three times the linear expansion coefficient for isotropic solids,
- V_0 is the initial volume, and
- ΔT is the temperature change.

3.3 Classwork

3.4 Problem Set

3.5 Further Reading

Read Chapter 3 in Russell, Embleton, and Jackson (2022), for additional information.

Chapter 4

Heat Transfer

4.1 Objectives

- Explain the methods of heat transfer: conduction, convection, and radiation.
- Define thermal conductivity and calculate the quantity of heat conducted, the temperature difference, or the material thickness when heat is transferred through flat walls and plates.

4.2 Concepts

4.3 Conduction

This method involves the flow of heat from molecule to molecule within a single solid object or from the molecules of one object to those of another object when the two are in direct contact. Molecules at a high temperature are in rapid vibration and this vibration is transferred, through molecular collision, to adjacent molecules within the same body. This causes the adjacent molecules to vibrate faster, thus increasing the temperature.

This vibration transfer, and subsequent heat transfer, will also occur between the molecules of two different objects (or substances). If one object is at a higher temperature its molecules will be vibrating faster than those of the second object. Upon contact, the vibration energy will be passed to the second object, resulting in a transfer of heat and a temperature increase in the second object.

An example of conduction is an iron bar having one end in contact with a flame. The other end will soon become hot due to the conduction of heat from molecule to molecule through the iron.

$$Q = \frac{kAt\Delta T}{s} \tag{4.1}$$

4.3.1 Convection

Heat transfer by convection involves the movement of a fluid (ie. a liquid or a gas). When a fluid is in contact with a hotter surface, the fluid near that surface will be heated, causing the fluid to expand and its density to decrease. Cooler, denser fluid will displace the heated fluid and will, in turn, become heated. This continuing process of heat transfer establishes a circulation of fluid (called a convection current), which then carries heat throughout the fluid.

One example involves water in a boiler, which is heated by means of convection currents. The part of the water in contact with the hot tube walls or shell will be heated and will be displaced by cooler water, which in turn is heated and displaced.

Likewise, hot gases rising in a boiler stack, air rising from a room radiator, water heated in a heat exchanger and rising into a storage tank are all examples of convection. These are examples of natural convection, in which the fluid motion is created without the use of mechanical devices.

If fluid movement is created by a pump or a fan, heat is being transferred by forced convection. Examples are a pump circulating hot water through a building heating system, a fan forcing air through an automobile radiator, or a forced draft fan pushing hot gases through a boiler.

4.3.2 Radiation

Heat transfer by radiation involves the transmission of electromagnetic waves. All bodies emit these waves and the higher the body's temperature the greater will be the emission. These waves are similar to light waves in they travel in straight lines and are able to pass through a vacuum. When they strike another body they are absorbed, reflected, or transmitted through, depending upon the material of the body. If the waves are absorbed by a body, the waves will increase the molecular activity of the body, thus creating an increase in temperature.

The condition of a body's surface will determine the amount that is absorbed or reflected. A black, rough surface will readily absorb the radiant energy. A smooth, highly polished surface will reflect most of the radiant energy. Some substances, such as air, will absorb a small portion of the radiant energy, but will permit the majority of the energy to pass through.

A typical example of radiation is heat reaching the earth from the sun. The energy waves first pass through the vacuum above the earth's atmosphere and then through the atmosphere itself where a portion is absorbed. Upon striking the earth's surface the remaining energy is absorbed and converted to heat.

In a steam boiler, radiation occurs in the furnace. Any heating surfaces that are directly exposed to the furnace will receive heat directly by radiation from the flame. These include the waterwalls and some generating tubes of a watertube boiler, radiant superheater tubes (located at the outlet of the furnace), and the furnace walls of a firetube boiler.

4.4 Classwork

4.5 Problem Set

4.6 Further Reading

Read Chapter 4 in Russell, Embleton, and Jackson (2022), for additional information.

Chapter 5

Gas Laws

5.1 Objectives

- Explain Boyle's Law, Charles' Law, and the General Gas Law and use these to calculate pressure, temperature and/or volume changes for perfect gases.
- Explain the Characteristic Gas Constant and use the Characteristic Gas Equation to determine the mass, the conditions, and the constant for a gas.
- Explain isothermal, adiabatic, and polytropic processes (expansion and compression) for a gas, state the formula for each process, and compare the processes on a pressure/volume diagram

5.2 Concepts

A perfect gas may be defined as a gas that remains in its gaseous state during changes in condition. Another way to state this is that the gas will not condense (even partially) if any of its conditions (temperature, volume or pressure) are changed.

Gases such as nitrogen, oxygen, and dry air can usually be treated as perfect gases. However, saturated steam is not considered a perfect gas, since it may condense under normal operating conditions. Although it is not technically a perfect gas, superheated steam, provided it never drops to the saturation temperature, does approximately act as a perfect gas.

For a perfect gas in a closed environment, there are specific relationships that exist between the temperature, pressure and volume of the gas. Furthermore, when any of these three conditions changes, the relationships between them can be used to predict and calculate the changes in the other conditions. For example, if the pressure and temperature change, it is possible to calculate what the change in pressure will be, and so on.

The relationships between pressure, temperature and volume have been proven by experimentation and have been described in three basic laws, called Laws of Perfect Gases. These laws are Boyle's Law, Charles' Laws, and the General Gas Law.

5.2.1 Boyle's Law

A physicist, Robert Boyle (1627-1691), investigated the behavior of a perfect gas at a constant temperature. By removing or adding heat during a controlled change in the volume and pressure of a confined gas, he was able to hold the temperature constant. He discovered that, under this condition, the absolute pressure of a gas varies inversely with the volume. That is, if the volume increases, then the pressure decreases and, conversely, if the volume decreases, then the pressure increases. This can be stated as:\index{Boyle's Law}

$$P \propto \frac{1}{V} \tag{5.1}$$

5.3 Classwork

5.4 Problem Set

5.5 Further Reading

Read Chapter 5 in Russell, Embleton, and Jackson (2022), for additional information.

Chapter 6

Expansion and Compression of Gases

6.1 Objectives

- Explain and calculate the work done in a cylinder during an isothermal expansion or compression.
- Explain and calculate the work done in a cylinder during an adiabatic expansion or compression.
- Explain and calculate the work done in a cylinder during a polytropic expansion or compression.

6.2 Concepts

To expand a gas, the gas is allowed to increase in volume and reduce in pressure. In this case, the gas itself is capable of performing work as it expands. For example, in an internal combustion engine, fuel is burned with air in a cylinder, producing high pressure and temperature. This pressure exerts force upon a piston, causing the piston to move within the cylinder. As the piston moves, the volume of the gas increases and the pressure drops, until the gas is exhausted from the cylinder. During expansion, unless heat is added to the gas from an external source, the work performed by the gas results in a reduction in temperature.

To compress a gas, external work is applied to the gas to reduce the volume and increase the pressure of the gas. One familiar example is a reciprocating air compressor, in which air is trapped inside a closed cylinder and a moving piston, driven by an external motor or engine, compresses the air within the cylinder before it is released from the cylinder at higher pressure. This compression requires that work be performed on the air, causing the air temperature to increase as it is compressed. Unless heat is somehow removed, through cooling, the temperature of a gas will increase when it is compressed.

6.2.1 Isothermal Compression and Expansion

If compression or expansion occurs with no change in the temperature of the gas, then the process is called an isothermal process and Boyle's Law, as described previously, applies to the process. That is, the relationship between any two points in the process can be stated as:

6.2.2 Adiabatic Compression and Expansion

If compression or expansion of a gas occurs with no external transfer of heat to or from the gas, then the process is said to be adiabatic. Since no heat transfer can occur, the cylinder must be perfectly insulated.

During an adiabatic expansion, the temperature of the expanding gas decreases. During an adiabatic compression, the temperature of the gas rises.

For an adiabatic process, the relationship between pressure and volume is stated as:

In this relationship, γ (Greek letter gamma) is called the "index of compression or expansion". It is calculated as the ratio of the specific heat of the gas at constant pressure c_p to the specific heat of the gas at constant volume c_v.

6.2.3 Polytropic Compression and Expansion

The isothermal and adiabatic processes are both theoretical processes, which can only be approached, but never perfectly achieved. There can never be perfect cooling, nor perfect insulating of a cylinder. Consequently, there is always some heat loss, some heat gain, and/or some temperature change. This more practical process, in which there is a partial transfer of heat to/from the gas, is called polytropic and the relationship between pressure and volume is stated as:

6.3 Classwork

6.4 Problem Set

6.5 Further Reading

Read Chapter 6 in Russell, Embleton, and Jackson (2022), for additional information.

Chapter 7

Internal Combustion Engines

7.1 Objectives

- Explain.

7.2 Concepts

Internal combustion (IC) engines are given this name due to the combustion of the fuel taking place inside the engine. When the fuel burns inside the engine's cylinder, it gives out heat which is absorbed by the air previously taken into the cylinder, the temperature of the air is therefore increased with a consequent increase in pressure and/or change in volume and the piston moves due to the heat energy imparted to it. The reciprocating motion of the piston is converted into a rotary motion in the crankshaft by the connecting rod and crank or piston rod, cross-head and crank in the case of the large two- stroke marine engines.

With IC engines the method of igniting the fuel shows a fundamental difference between the diesel engine and the petrol engine. In diesel engines the air in the cylinder is compressed to a high pressure and therefore, following the gas laws, the air reaches a high temperature. When the fuel is injected into this high temperature it ignites after a short delay (see the section on combustion and heat release).

When the ignition of the fuel is only caused by the heat from the compression of the air, the engine is classed as a compression–ignition (CI) engine. In petrol engines the fuel is usually taken in with the charge of air. The charge is compressed and then ignited by an electrically induced spark. These engines are designated as spark ignition (SI) engines.

7.3 Classwork

7.4 Problem Set

7.5 Further Reading

Read Chapter 7 in Russell, Embleton, and Jackson (2022), for additional information.

Summary

You have solved a great many problems in your studies this term, reading various texts like Joel (1996), Russell, Embleton, and Jackson (2022), Fermi (1956) and Polya and Conway (2014). These sources have helped you understand complex concepts.

As you near the final exam, remember that your knowledge and skills will help you succeed in your future courses. Stay confident, trust your preparation, and be composed. You have put in a lot of effort; now's the time to show what you know.

We wish you the best on the exam.

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