CALCULUS-BASED PHYSICS-2: ELECTRICITY, MAGNETISM, AND THERMODYNAMICS (PHYS180-02): UNIT 0

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3. Syllabus: Moodle (will examine shortly)
4. Office hours: Tuesdays, 12:00-17:00
5. PHYS150 or PHYS135A and MATH-141B or MATH-142 (concurrent)
6. Text: University Physics Volume 2 (openstax.org)

SUMMARY

Physics - $\phi\upsilon\sigma\iota\kappa\acute{\eta}$ - ”phusiké”: *knowledge of nature*

from $\phi\acute{\upsilon}\sigma\iota\varsigma$ - ”phúsis”: *nature*

Reading: Chapters 1 and 2 (for Unit 1)

1. Estimation/Approximation
   - Estimating the correct order of magnitude
   - Building complex quantities
   - Unit analysis
2. Review of concepts from Newtonian mechanics
   - Kinematics and Newton’s Laws
   - Work-energy theorem, energy conservation
   - Momentum, conservation of momentum

Bonus Essay assignment: If you submit a 10-page paper on the history of physics, including references from both online and library sources by the end of the semester, I will replace your lowest midterm score with the grade of the paper. Example topics:

- A paper on the Advanced LIGO experiment, and gravitational radiation (Nobel Prize 2017)
- Development of the idea of energy conservation versus caloric theory by James Joule and others
- Discovery of the charge to mass ratio of the electron by J.J. Thompson
- First description of the *photoelectric effect* by Albert Einstein

Before beginning the essay, please make an appointment with me in office hours so that we may agree upon a topic.

Estimation/Approximation

In science and engineering, estimation is to obtain a quantity in the absence of precision, informed by rational constraints.

1. Define relevant scales: mg, g, kg
2. Obtain complex quantities from simple ones
    - Obtain *areas* and *volumes* from *lengths*
    - Obtain *rates* from *numerators* and *denominators*
3. Constrain the unknown with upper and lower limits
4. Scaling problems: how does a complex quantity depend on other quantities?

Choose a reasonable scale: Estimate the mass of termites in a termite colony. Assume that the colony is a species known to have 10^6 individuals (roughly) per colony.

- A: 0.01 kg
- B: 0.1 kg
- C: 1 kg
- D: 10 kg

Volume/density from other quantities: An adult humpback whale is about 15 meters long. What is the mass of a humpback whale? (1 tonne = 1000 kg).

- A: 200 tonnes
- B: 30 tonnes
- C: 3 tonnes
- D: 1 tonnes

Upper and lower bound: The density of water is 1000 kg/m^3. What is the density of ice, approximately? (Don't think too hard!)

- A: 550 kg/m^3
- B: 920 kg/m^3
- C: 1050 kg/m^3
- D: 1200 kg/m^3

Volumes from other quantities: A jar at the coffee shop is filled with coffee beans, and a we can win a prize for guessing the number of beans. If the radius of the jar is about 4 cm, and the height is about 10 cm, how many beans are in the jar?

- A: 200
- B: 2,000
- C: 10,000
- D: Um, like, a million...

Rates from other quantities: A student travels from uptown Whittier to SLC in roughly 10 minutes. What is her average speed?

- A: 0.1 m/s
- B: 1 m/s
- C: 5 m/s
- D: 10 m/s

Scale: The distance between the Earth and the sun is 1 AU. What is the distance between the Sun and Venus?

- A: 10 million km
- B: 100 million km
- C: 0.2 AU
- D: 0.7 AU

Scaling problem: A balloon has an initial volume of 10 cm^3. It is inflated such that the radius doubles. What is the new volume?

- A: 20 cm^3
- B: 40 cm^3
- C: 60 cm^3
- D: 80 cm^3

Scaling problem: If the distance between two massive objects decreases by a factor of 2, by how much does the force of gravity between them change?

- A: 4
- B: 8
- C: 2
- D: 1

Unit analysis: Which of the following are top speeds of a runner at the end of a sprint?

- A: 10 m/s^2
- B: 30 kg m/s
- C: 7 m/s
- D: 40 miles per hour

What physical quantities do each of the units represent?

Unit analysis: What is 9×10^{-3} kg m/s in g cm/s?

- A: 9 g cm/s
- B: 90 g cm/s
- C: 900 g cm/s
- D: 9000 g cm/s

VECTORS

$\vec{p} = 4\hat{i} + 2\hat{j}$. $\vec{q} = -4\hat{i} + 2\hat{j}$.
Compute $\vec{p} + \vec{q}$.

- A: $4\hat{i} + 4\hat{j}$
- B: $0\hat{i} + 4\hat{j}$
- C: $4\hat{i} + 0\hat{j}$
- D: 0

$\vec{p} = -1\hat{i} + 6\hat{j}$. $\vec{q} = 3\hat{i} + 0.5\hat{j}$.
Compute $\vec{p} \cdot \vec{q}$.

- A: -1
- B: 1
- C: 0
- D: 3

Vector *fields*:
`http://user.mendelu.cz/marik/EquationExplorer/vectorfield.html`

$\vec{f}(x,y) = 4x\hat{i} + 2y\hat{j}$.
$\vec{g}(x,y) = 4x\hat{i} - 2y\hat{j}$.
Compute $\vec{f} + \vec{g}$.

- A: $4x\hat{i} + 4y\hat{j}$
- B: $8x\hat{j}$
- C: $8x\hat{i}$
- D: $4x\hat{i}$

$\vec{f}(x,y) = x^2\hat{i} + y^2\hat{j}$. $\vec{g}(x,y) = -2y\hat{j}$.
Compute $\vec{f} \cdot \vec{g}$.

- A: y^3
- B: $-2y^2$
- C: $-2y^3$
- D: -2

What about a dot-product with an *operator*?

$$\vec{\nabla} = \left(\frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right) \tag{1}$$

Equation 1 is called the *gradient operator*. We use it like this:

$$\vec{f}(x, y) = xy\hat{i} - xy\hat{j} \tag{2}$$

$$\vec{\nabla} \cdot \vec{f} = y - x \tag{3}$$

Notice that the result is a scalar function.[1] It turns out that **charge** is proportional to the **divergence** of an electric field.

[1] We call this operation the divergence of $\vec{f}$.

The *gradient* of a scalar function is

$$\nabla f(x,y) = \frac{\partial f}{\partial x}\hat{i} + \frac{\partial f}{\partial y}\hat{j} \tag{4}$$

It turns out that the gradient of a scalara function called **voltage** is proportional to the **electric field**. The gradient of **gravitational potential energy** is proportional to the **gravitational field.**

(Professor: pause here for some examples).

$f(x, y) = 4x + 2y$. What is $\nabla f(x, y)$?

- A: $4\hat{i} + 2\hat{j}$
- B: 6
- C: $4x\hat{i} + 2y\hat{j}$
- D: $-4\hat{i} - 2\hat{j}$

$\vec{f}(x, y) = -x\hat{i} + y^2\hat{j}$. What is $\nabla \cdot \vec{f}(x, y)$?

- A: $-x\hat{i} + y^2\hat{j}$
- B: $x - y^2$
- C: $-x + y^2$
- D: $2y - 1$

Kinematics and Newton's Laws

Kinematics - A description of the motion of particles and systems
Dynamics - An explanation of the motion of particles and systems

What causes an object to move? **Forces**. Forces exist as a result of the **interactions** of objects or systems.

Evolution - A description of the change of biological species
Natural Selection - An explanation of change in biological species

What causes species to evolve? **Natural selection**. Natural selection exists because of election pressures, numerous offspring, and variation among offspring.

Newton's First Law: A man slides a palette crate across a concrete floor of his shop. He exerts a force of 60.0 N, and the box has a constant velocity of 0.5 m/s. What force cancels his pushing force, and what is the value in Newtons?

- A: wind, 60.0 N
- B: friction: 60.0 N
- C: friction: -60.0 N
- D: weight: -60.0 N

Newton's Second Law: The crate has a mass of 50 kg, and encounters an area where there is no longer friction. If the pushing force is still 60 N, what is the acceleration?

- A: 1.0 m/s/s
- B: 0.8 m/s
- C: 1.2 m/s
- D: 1.2 m/s/s

Kinematics: If the acceleration is 1.2 m/s/s, and the crate begins with a velocity of 1 m/s, what is the velocity after 5 seconds?

- A: 4 m/s
- B: 5 m/s
- C: 6 m/s
- D: 7 m/s

Newton's Third Law: Suppose the frictionless area continues indefinitely, and the velocity reaches 7 m/s. What will be the velocity if the pushing force decreases to 0 N, when the crate has traveled 10 m?

- A: 7 m/s
- B: 8 m/s
- C: 9 m/s
- D: 10 m/s

WORK-ENERGY THEOREM AND CONSERVATION OF ENERGY

Physical Definition of Work

Let $\vec{F}$ be a force exerted on a system, which is displaced by a displacement $\vec{x}$. The **work** done on the system is $W = \vec{F} \cdot \vec{x}$

The units of work are N m = kg m/s^2, or *Joules*.

Let θ be the angle between the force and the displacement. Then this equation

$$W = \vec{F} \cdot \vec{x} \tag{5}$$

becomes

$$W = Fx \cos \theta \tag{6}$$

What about Newton's 3rd Law? If one system A exerts a force F_{AB} on a system B, then Newton's 3rd law states that system B exerts a force $-F_{\mathrm{AB}}$ on system A.

If the work done by A on B is $W = (F_{\mathrm{AB}})x \cos\theta$, then the work done by B on A is $W = -(F_{\mathrm{AB}})x \cos\theta$.

What if the force varies over the trajectory of the system? We simply have to add up each contribution along the trajectory:

$$W = \int_{AB} \vec{F} \cdot d\vec{r} \tag{7}$$

In the first semester we encountered *irreversable* processes: energy lost to *friction*, and energy lost to *drag*. The irreversable process is a deeper notion in thermal physics, because it leads to the Second Law of Thermodynamics.

Group board exercise: Suppose a system moves at constant speed along a rough surface. Draw two closed, two-dimensional paths, each describing the trajectory of the system. A closed path means the system has a final displacement of zero. Recall that the frictional force is not conservative. Which path requires more work? **Key question**: If the speed is constant the entire time, and one path requires more work than the other, what happens to the excess energy (*they have the same final kinetic energy*)?

The formal proof involves combining **Newton's Second Law**, and the **Definition of Work**. Let the *kinetic energy* of a particle be defined by the mass and velocity of the particle, such that $KE = \frac{1}{2}mv^2$. Consider that

$$W = \int_{\mathrm{AB}} \vec{F} \cdot d\vec{x} \tag{8}$$

$$W = \int_{\mathrm{AB}} (m\vec{a}) \cdot d\vec{x} \tag{9}$$

$$W = m \int_{\mathrm{AB}} \left(\frac{d\vec{v}}{dt}\right) \cdot d\vec{x} \tag{10}$$

$$W = m \int_{\mathrm{AB}} \vec{v} \cdot d\vec{v} \tag{11}$$

$$W = \frac{1}{2}mv_{\mathrm{B}}^2 - \frac{1}{2}mv_{\mathrm{A}}^2 = \Delta KE \tag{12}$$

$$W = \Delta KE \tag{13}$$

Group board exercise: A firework of mass 1 kg is launched straight upwards. The gunpowder releases 500 J of energy. What is the velocity of the shell as it leaves the launcher? How high does it fly straight upwards?

Group board exercise: A slingshot is like a spring with a spring constant of 2000 N/m. If a projectile is placed in the slingshot pouch, how much work is required to draw it back 10 cm?

*Actually, we learned last semester from our group projects that rubber doesn't always provide a **linear** restoring force.*

Group board exercise: If the pouch is released, what is the final velocity of the projectile if all of the work is converted into kinetic energy?

Momentum is defined as follows:

Definition of Momentum

A particle of mass m and velocity $\vec{v}$ has the vector *momentum*:

$$\vec{p} = m\vec{v}$$

There is a corollary:

Newton's Second Law with momentum

If a particle has acceleration $\vec{a} = \frac{d\vec{v}}{dt}$, then

$\vec{F}_{\mathrm{Net}} = \frac{d\vec{p}}{dt}$

An object that has a small mass and an object that has a large mass have the same momentum. Which mass has the largest kinetic energy?

- A: The one with the small mass
- B: The one with the large mass
- C: If the momentum is the same the kinetic energy is the same
- D: Cannot determine the answer

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- D: Cannot determine the answer

Last semester we went into detail classifying collisions. For our purposes this semester, we just need to remember that collisions come in two basic forms:

- *Elastic type*: **Both** kinetic energy and momentum are conserved.
- *Inelastic type*: Momentum is conserved.

A puff of dust is composed of 10^6 dust particles, each with mass of 1μg (microgram), or 10^{-6} grams. The average velocity of each particle is 1 m/s. What is the total kinetic energy, adding up the contributions from all the particles?

- A: $\frac{1}{2}$ mJ, or a millijoule (0.001 Joules)
- B: $\frac{1}{2}$ μJ, or a microjoule (10^{-6} Joules)
- C: 1 millijoule
- D: 1 Joule

What is the mass of the puff of dust, if it has 10^6 particles each with a mass of 1 microgram?

- A: 1 kilogram
- B: 1 milligram
- C: 1 gram
- D: 1 μg

Which condition will cause this number to change?

- A: The temperature of the puff is increased.
- B: All of the collisions were somehow inelastic.
- C: All of the collisions were somehow elastic.
- D: Dust particles were removed from the puff.

Which condition will cause the *temperature* of the dust cloud to change? (Think conceptually, from your intuition).

- A: The average speed of the particles increases.
- B: The collisions are all inelastic; kinetic energy of the particles decreases on average.
- C: The collisions are all elastic; the kinetic energy of the particles stays constant.
- D: Dust particles were removed from the puff.

So which parts of Newtonian mechanics are we going to need to understand thermal physics? (Heat, temperature, energy transfer).

- Newton's laws, momentum and kinetics $\rightarrow$ motions of molecules in gases $\rightarrow$ temperature and heat
- Work and energy $\rightarrow$ work done by thermal systems $\rightarrow$ energy conservation with heat
- Irreversable processes $\rightarrow$ energy dissapation $\rightarrow$ entropy

CONCLUSION

Physics - $\phi\upsilon\sigma\iota\kappa\acute{\eta}$ - "phusiké": *knowledge of nature*
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ANSWERS

ANSWERS

- 1 kg
- 30 tonnes
- 920 kg/m^3
- 2000
- 1 m/s
- 0.7 AU
- 80 cm^3
- 4
- 900 g cm/s
- $0\hat{i} + 4\hat{j}$
- 0
- $8x\hat{i}$
- $-2y^3$
- $4\hat{i} + 2\hat{j}$
- $2y - 1$

ANSWERS, CONTINUED

- ...

- ...