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

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1. Professor Jordan Hanson
2. Contact: jhanson2@whittier.edu, SLC 212
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 is the force of friction?

- A: 60.0 N
- B: 30.0 N
- C: -30.0 N
- D: -60.0 N

Newton's First Law: A man walks past a palette crate at rest in his shop. *From his perspective*, the crate moves at 2 m/s. What is the net force on the palette crate?

- A: 30.0 N
- B: -30.0 N
- C: 0.0 N
- D: 60.0 N

Newton's Second Law: The crate has a mass of 50 kg, and the force of friction is -10.0 N. If the pushing force is still 60 N, what is the acceleration?

- A: 2.0 m/s^2
- B: 1.0 m/s^2
- C: -1.0 m/s^2
- D: -2.0 m/s^2

Kinematics: If the acceleration is 1.0 m/s^2, 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 crate is now touching a wall, and it is on wheels (so there is no friction). If a 70 kg man pushes the crate with 100 N, what is the net force on the man by the crate?

- A: 100 N
- B: -100 N
- C: 0 N
- D: 700 N

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

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

Definitions of Work: Suppose an object is located at $(4, 0)$ in a 2D coordinate system. The object is in a force field $\vec{f} = -4\hat{i}$. If the object is moved to the origin by the force, what is the work done?

- A: 4 J
- B: -4 J
- C: 16 J
- D: -16 J

Work-Energy theorem: If the work done is 16 J, what is the final velocity of the object, if the mass is 1.6 kg?

- A: $\sqrt{20}$ m/s
- B: $\sqrt{10}$ m/s
- C: 20 m/s
- D: -10 m/s

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

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

Definitions of Work: Suppose an object is located at $(4, 0)$ in a 2D coordinate system. The object is in a force field $\vec{f} = -4x\hat{i}$. If the object is moved to the origin by the force, what is the work done?

- A: 16 J
- B: -16 J
- C: 32 J
- D: 4 J

(Professor: more examples on the board).

WORK AND REVERSIBLE PROCESSES: THE EXAMPLE OF FRICTION

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. 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*)?

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?

MOMENTUM

Let the momentum of a system be

$$\vec{p} = m\vec{v} \tag{8}$$

Newton's second law is then

$$\vec{F}_{Net} = \frac{d\vec{p}}{dt} \tag{9}$$

Momentum is a conserved quantity, and in interactions where the kinetic energy is also conserved, we denote them *elastic interactions.* Otherwise, we denote them *inelastic.* Totally inelastic collisions correspond to maximum kinetic energy lost.

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

Hint: plug in your own numbers to test your answer.

Group board problem: Two charged particles, each having opposite sign charge, will always repel each other. Particle 1 has mass $3m$, and particle 2 has just m. Each approaches the other with speed v (particle 2 is going to the left, particle 1 to the right). Particle 1 is observed after the collision with speed $-\frac{1}{6}v$. What is the speed of particle 2?

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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    - Momentum, conservation of momentum

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
- $8x\hat{i}$
- $-2y^3$
- $4\hat{i} + 2\hat{j}$
- $2y - 1$
- -60.0 N
- 0.0 N
- 1.0 m/s^2
- 6 m/s
- -100 N
- 16 J
- $\sqrt{20}$ m/s

ANSWERS, CONTINUED

- 32 J
- The one with the small mass

- ...