

# 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](https://openstax.org))

## SUMMARY

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*Physics - φυσική - "phusiké": knowledge of nature*  
from φύσις - "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.



WAT.



## ESTIMATION/APPROXIMATION

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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

## ESTIMATION/APPROXIMATION

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

- A:  $550 \text{ kg/m}^3$
- B:  $920 \text{ kg/m}^3$
- C:  $1050 \text{ kg/m}^3$
- D:  $1200 \text{ kg/m}^3$

**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  $10 \text{ cm}^3$ . It is inflated such that the radius doubles. What is the new volume?

- A:  $20 \text{ cm}^3$
- B:  $40 \text{ cm}^3$
- C:  $60 \text{ cm}^3$
- D:  $80 \text{ cm}^3$

**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:  $10 \text{ m/s}^2$
- B:  $30 \text{ kg m/s}$
- C:  $7 \text{ m/s}$
- D: 40 miles per hour

*What physical quantities do each of the units represent?*

**Unit analysis:** What is  $9 \times 10^{-3} \text{ kg m/s}$  in  $\text{g cm/s}$ ?

- A:  $9 \text{ g cm/s}$
- B:  $90 \text{ g cm/s}$
- C:  $900 \text{ g cm/s}$
- D:  $9000 \text{ g cm/s}$

## VECTORS

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

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](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:  $4x\hat{i}$

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

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*?

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

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

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

$$\vec{\nabla} \cdot \vec{f} = y - x \quad (3)$$

*Notice that the result is a scalar function.*<sup>1</sup> It turns out that **charge** is proportional to the **divergence** of an electric field.

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<sup>1</sup>We call this operation the divergence of  $\vec{f}$ .

The *gradient* of a scalar function is

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

It turns out that the gradient of a scalar 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

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*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.

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*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 selection 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:  $2.0 \text{ m/s}^2$
- B:  $1.0 \text{ m/s}^2$
- C:  $-1.0 \text{ m/s}^2$
- D:  $-2.0 \text{ m/s}^2$

**Kinematics:** If the acceleration is  $1.0 \text{ m/s}^2$ , and the crate begins with a velocity of  $1 \text{ m/s}$ , what is the velocity after 5 seconds?

- A:  $4 \text{ m/s}$
- B:  $5 \text{ m/s}$
- C:  $6 \text{ m/s}$
- D:  $7 \text{ m/s}$

**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

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### 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  $\text{N m} = \text{kg m/s}^2$ , or *Joules*.

Let  $\theta$  be the angle between the force and the displacement.  
Then this equation

$$W = \vec{F} \cdot \vec{x} \quad (5)$$

becomes

$$W = Fx \cos \theta \quad (6)$$

**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:

$$W = \int_{AB} \vec{F} \cdot d\vec{r} \quad (7)$$

**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).

In the first semester we encountered *irreversible* processes: energy lost to *friction*, and energy lost to *drag*. The irreversible 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

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## DEFINITION OF MOMENTUM

Let the momentum of a system be

$$\vec{p} = m\vec{v} \quad (8)$$

Newton's second law is then

$$\vec{F}_{Net} = \frac{d\vec{p}}{dt} \quad (9)$$

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.

## DEFINITION OF MOMENTUM

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 → motions of molecules in gases → temperature and heat
- Work and energy → work done by thermal systems → energy conservation with heat
- Irreversible processes → energy dissipation → entropy

## CONCLUSION

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*Physics* - φυσική - "phusiké": *knowledge of nature*  
from φύσις - "phúsis": *nature* **Reading: Chapters 1 and 2 (for Unit 1)**

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- Unit analysis

### 2. Review of concepts from Newtonian mechanics

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- Work-energy theorem, energy conservation
- Momentum, conservation of momentum

## ANSWERS

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## ANSWERS

- 1 kg
- 30 tonnes
- $920 \text{ kg/m}^3$
- 2000
- 1 m/s
- 0.7 AU
- $80 \text{ cm}^3$
- 4
- $900 \text{ g cm/s}$
- $0\hat{i} + 4\hat{j}$
- 0
- $8x\hat{i}$
- $-2y^3$
- $4\hat{i} + 2\hat{j}$
- $2y - 1$
- -60.0 N
- 0.0 N
- $1.0 \text{ m/s}^2$
- 6 m/s
- -100 N
- 16 J
- $\sqrt{20} \text{ m/s}$

- 32 J
- The one with the small mass
- ...