

# CALCULUS-BASED PHYSICS-1: MECHANICS (PHYS150-01): WEEK 6

---

Jordan Hanson

October 9th - October 13th, 2017

Whittier College Department of Physics and Astronomy

## WEEK 5 REVIEW

---

## 1. Friction

- Normal force and friction
- Static, kinetic

## 2. Drag

- Terminal velocity

## 3. Restoring Forces

- Hooke's Law
- Young's modulus
- Shear modulus
- Bulk modulus

## WEEK 5 REVIEW PROBLEM

---

## WEEK 5 REVIEW PROBLEM

A car rests on four shock absorbers, and each is like a spring with a spring constant  $k = 1000\text{N/cm}$ . The car weighs 10000 N. By what distance is each spring compressed?

- A: 2.5 cm
- B: 10 cm
- C: 1 meter
- D: 0 cm

## WEEK 6 SUMMARY

---

1. **Work** has a scientifically precise definition
  - Units
  - As a product of force and displacement vectors
2. Kinetic Energy and the **Work-Energy Theorem**
3. Gravitational potential energy
  - Potential energy
  - *Simplifying otherwise complex calculations*
  - Potential energy near Earth's surface
  - ...in space
4. Definition of a **conservative force**
  - Relationship between conservative forces and potential energy
  - Conservation of energy for conservative forces

## DEFINITIONS OF WORK

---



### 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*.

*Extra credit opportunity:* **Do you like beer?** Write a 10-page paper on the on the scientific challenge faced by James Prescott Joule, who began to formulate the modern view of energy in the 19th century, contrary to *caloric theory*. **Upon completion of this assignment I will change two homework scores to perfect scores.**

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

$$W = \vec{F} \cdot \vec{x} \quad (1)$$

becomes

$$W = Fx \cos \theta \quad (2)$$

## DEFINITIONS OF WORK

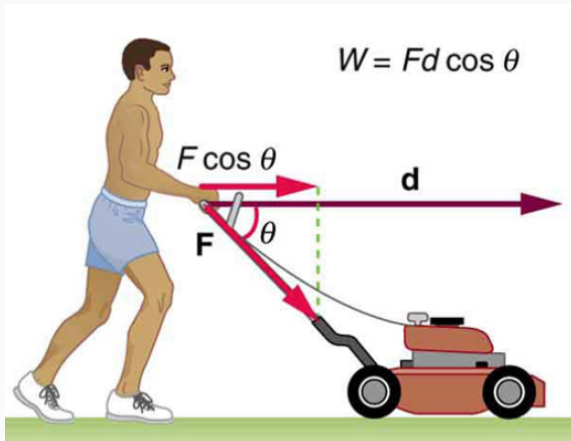
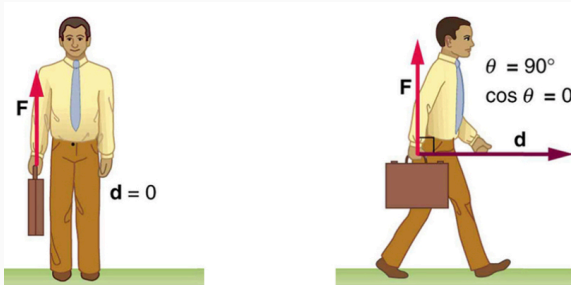


Figure 1: A case where  $\theta \neq 0$ .

## DEFINITIONS OF WORK



**Figure 2:** (Left): A case where  $x = 0$ , so  $W = 0$ . (Right): A case where  $\theta = 90^\circ$ , so  $W = 0$ .

Just because an action requires *energy* doesn't mean we are performing *work*. It requires muscular energy to hold up a heavy briefcase but this is not what we mean by work. Work is about moving objects.

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  $-F_{AB}$  on system A.

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

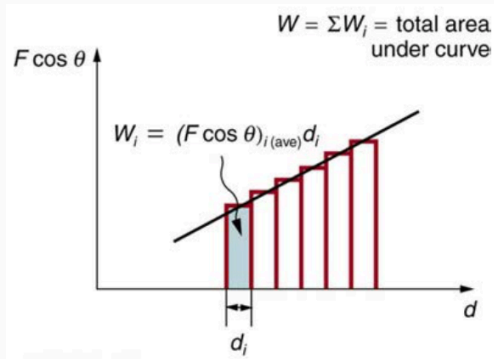
In Fig. 1, the work done by the man on the mower is positive, but the work done by the mower on the man is negative.

## DEFINITIONS OF WORK

More units of energy:

Unit Name	Definition	Value
electron-volt (eV)	energy of 1 e <sup>-</sup> through 1 V	$1.60 \times 10^{-19} \text{ J}$
1 Rydberg (Rd)	ionize 1 hydrogen atom	$21.8 \times 10^{-19} \text{ J}$
<b>Joule</b>	<b>1 N·m</b>	<b>1.0 J</b>
foot-pound	1 ft·lb	1.36 J
calorie	Raise 1 gram of water 1° C	4.184 J
British Thermal Unit	Raise 1 lb of ice to boil (°F)	1054.3 J
food calorie (kcal)	1000 calories	4184 J
kilowatt hours	1 kilowatt system for 1 hr	$3.6 \times 10^6 \text{ J}$
gasoline gallon equiv.	burning a gallon of gas	$\approx 120 \times 10^6 \text{ J}$
$E = mc^2$ , 1 mole of H <sup>+</sup>	Rest mass (fusion/fission)	$9 \times 10^{13} \text{ J}$

## DEFINITIONS OF WORK



**Figure 3:** Breaking the displacement  $\vec{x}$  into pieces, and summing them.

This interpretation naturally leads to the subject of *integration* in calculus.

## DEFINITIONS OF WORK

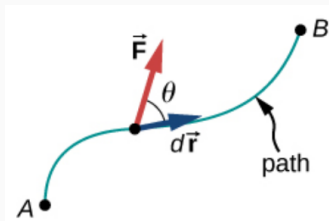


Figure 4: Summary of the concept of the work integral.

$$W = \int_{AB} \vec{F} \cdot d\vec{r} \quad (3)$$



## SURVEY - THE INSIGHTS AND DATA (UNDER ANALYSIS)

- **Group problem solving is a boost**
  1. Must mix participation, someone knows how to start
  2. Prof. Hanson make rounds
  3. Show each and every step for iClicker and examples
- **Exams**
  1. Review day
  2. Practice problems and study guides are a boost
  3. Similarity to homework, lecture?
- **Lab activities** and **Final Group Project**
  1. Some want to drop them
  2. Scientific process is important (don't just *assume*)
  3. *The goal is to blend them*
- **Office hours are crucial**

- "You're not a bad person, you just suck at explaining things."
- "The tests are not fair."
- **NO PARTIAL CREDIT??**
- "Everything should change except lab activities, and it's good that those are not graded."

My response: There is something called **The 80/20 Rule**... Bottom line: we are here to develop and grow into professionals.

Consider the case where the force doing the work on the system of mass  $m$  is friction:

$$W = \int_{AB} \vec{F} \cdot d\vec{r} = - \int_{AB} \mu_k N dx = -\mu_k mg \int_{AB} dx \quad (4)$$

- Friction acts in opposite direction, so the dot product gives a minus sign
- Friction acts along path  $AB$  (whatever direction of motion is)

The driver of a 900 kg car slams on the breaks, and the tires slide on the pavement with  $\mu_k = 0.2$ . The initial speed is 25 m/s. Assuming  $g = 10 \text{ m/s}^2$ , how far does the car travel before coming to a stop?

- A: 312.5 m
- B: 625 m
- C: 31.25 m
- D: 62.5 m

What is the work done on the car?

- A: 280 J
- B: -280 J
- C: 280 kJ
- D: -280 kJ

Take your *algebraic* answer for the breaking distance (displacement from two slides ago), and substitute it into the expression for the work done on the car (force of friction times displacement). What do you get? (*Check your units*).

- A:  $mv_i^2$
- B:  $mg\frac{1}{2}mv_i^2$
- C:  $-\frac{1}{2}mv_i^2$
- D:  $\mu_k mv_i^2$

*Keep this result in mind...*

Suppose we raise the 900 kg car by a displacement of 10 meters. What is the work done on the car?

- A: 9 J
- B: 90 J
- C: 900 kJ
- D: 90 kJ

What if we drop the car from a height of 10 m? What is the final velocity of the car?

- A:  $10\sqrt{2}$  m/s
- B: 20 m/s
- C: 10 m/s
- D:  $10\sqrt{10}$  m/s



Stand up, and show in your groups that the work done on the falling car is equal to  $\frac{1}{2}mv_f^2$ , both numerically and algebraically.

## APPLICATIONS OF THE CONCEPT OF WORK

---

**Work done on an oscillator.** Let  $\vec{x}$  be the displacement of a mass  $m$  attached to an oscillator (a spring), with spring constant  $k$ . The spring applies a force  $\vec{F}$  to the mass:

$$F = -kx \quad (5)$$

$$W = \int \vec{F} \cdot d\vec{x} \quad (6)$$

$$W = -k \int_{AB} x dx = -\frac{1}{2} kx^2 \quad (7)$$

Equation 7 the work done *on the mass by the spring*. The work performed *by the system applying the force* is:

$$W_{\text{spring}} = \frac{1}{2} kx^2 \quad (8)$$

Work done on an oscillator:

$$W_{\text{spring}} = \frac{1}{2}kx^2 \quad (9)$$

*For two points A and B that are neither at equilibrium point of oscillator:*

$$W_{\text{spring,AB}} = \frac{1}{2}kx_B^2 - \frac{1}{2}kx_A^2 = \frac{1}{2}k(x_B^2 - x_A^2) \quad (10)$$

What about gravity as the force?

$$W_g = \int_A^B -mg\hat{j} \cdot dy\hat{j} = -mg(y_B - y_A) = -mg\Delta y \quad (11)$$

*Why the minus sign?* Gravity does negative work if we raise an object  $\Delta y$ . We contribute  $W_g = mg\Delta y$  (J) of energy to raise an object  $\Delta y$  against gravity.

## List of work applications:

- Mass  $m$  through distance  $l$  against friction:  $W_f = \mu_k mgl$
- Displacing an oscillator (spring) from  $x_A$  to  $x_B$ :  
 $W_s = \frac{1}{2}k(x_B^2 - x_A^2)$
- Displacing an object  $\Delta y$  with mass  $m$ :  $W_g = mg\Delta y$

## Cases corresponding to $W = 0$ :

- The normal force ( $\vec{F} \cdot d\vec{x} = 0$ )
- Centripetal force ( $\vec{F} \cdot d\vec{x} = 0$ )
- *Static friction* ( $d\vec{x} = 0$ )

# KINETIC ENERGY AND THE WORK-ENERGY THEOREM

---

The formal proof involves combining **Newton's Second Law**, and the **Definition of Work**:

$$W = \int_{AB} \vec{F} \cdot d\vec{x} \quad (12)$$

$$W = \int_{AB} (m\vec{a}) \cdot d\vec{x} \quad (13)$$

$$W = m \int_{AB} \left( \frac{d\vec{v}}{dt} \right) \cdot d\vec{x} \quad (14)$$

$$W = m \int_{AB} \vec{v} \cdot d\vec{v} \quad (15)$$

$$W = \frac{1}{2}mv_B^2 - \frac{1}{2}mv_A^2 = \Delta KE \quad (16)$$

$$W = \Delta KE \quad (17)$$



## The Work-Energy Theorem

If  $W$  is the work done on a system, and  $KE$  is the kinetic energy of the system, then  $W = \Delta KE$ .

**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?

- A: 31.6 m/s, 50 m
- B: 22.4 m/s, 5 m
- C: 31.6 m/s, 20 m
- D: 22.4 m/s, 50 m

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

- A:  $1 \text{ J}$
- B:  $5 \text{ J}$
- C:  $10 \text{ J}$
- D:  $50 \text{ J}$

**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?

- A: 1 m/s
- B:  $\sqrt{20}$  m/s
- C: 100 m/s
- D:  $\sqrt{30}$  m/s

**iClicker:** If the projectile begins 1.5 m above the ground and is launched horizontally, where does it land?

- A:  $\sqrt{2}$  m horizontally
- B:  $\sqrt{3}$  m horizontally
- C:  $\sqrt{6}$  m horizontally
- D: 8 m horizontally

**iClicker:** Recall the problem from the midterm about measuring coefficient of *kinetic* friction. Suppose we compress a spring, and use the spring to slide a 1 kg steel block across a wet surface with unknown kinetic friction coefficient  $\mu_k$ . If the spring has  $k = 1000$  N/m, we compress it by 10 cm, and the plate slides 10 m, what is  $\mu_k$ ?

- A: 0.001
- B: 1
- C: 0.05
- D: 0.2

*Interactive simulation:*

<https://openstaxcollege.org/l/21PhETSimRamp>

- Push an object up the ramp (which includes friction)
- Copy the energy plot to your lab notebook, and explain each feature of it.
  1. Where is the energy constant?
  2. Where is the energy changing?

## GRAVITATIONAL POTENTIAL ENERGY

---



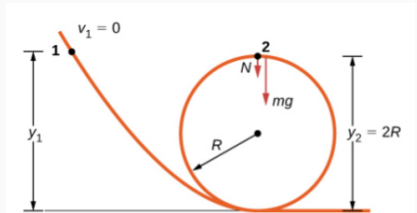
Suppose we raise an object against gravity, and then, it remains motionless. *Does it have energy?* Well, it **cannot have any kinetic energy**, because it has no velocity. Work has been performed on it, however, so we say that it has **potential energy**.

Potential energy  $\leftrightarrow$  Kinetic energy

## GRAVITATIONAL POTENTIAL ENERGY

**The famous roller coaster problem:** Suppose a roller coaster has a circular loop with radius  $R$ , and the cars begin on a hill of height  $y_1$ . Since work has been performed on the cars to get them that high, they have energy  $W = mgy_1$  (they have mass  $m$ ). If the cars are released, the kinetic energy propels them through the loop. What is the ratio of  $y_1$  to  $R$ ?

- A:  $y_1 = \frac{1}{2}R$
- B:  $y_1 = R$
- C:  $y_1 = \frac{3}{2}R$
- D:  $y_1 = \frac{5}{2}R$



## LAB ACTIVITY FOR GRAVITATIONAL POTENTIAL ENERGY

### Materials:

- Pipe liner
- A marble
- Scissors
- Tape

### Build the system:

- Cut pipe liner in half, lengthwise
- Shape the pipe liner into the shape on prior slide
- Use tape to fix in place

### Measure:

- Measure the initial height required to traverse loop
- Compare to loop radius

**Bonus:** *Two loops?*

POWER

---

**Power** is the derivative of **work**:

$$P = \frac{dW}{dt} \quad (18)$$

$$W = \int P dt \quad (19)$$

The unit of power is the Watt, or  $1 \text{ J/s} = 1 \text{ N m/s}$ .

A common scale for home power usage is the kW hr, or kilowatt hours, which is a unit of energy. If a home consumes 1000 kW hr in one month, what is the average power consumed at a given time in this home? (Convert 1000 kW hr to kJ, then divide by the time of one month).

- A: 0.1 kW
- B: 1.4 kW
- C: 10 kW
- D: 1.2 MW

*According to Google, central AC uses about 3500 W for a home. Think about this the next time you get your electric bill...*

Since  $P = \frac{dW}{dt}$  we may show that  $P = \vec{F} \cdot \vec{v}$ . Suppose a 1000 kg car is driving up an incline of 30 degrees at 90 km/hr, meaning no change in kinetic energy. Technically, the net work is therefore zero Joules. However, we know that it takes gas to go up a hill. Therefore,  $\vec{F} \cdot \vec{v}$  must be the power required to raise the car against the force of gravity,  $\vec{F} = -mg\hat{j}$ . Use  $\vec{F} = mg\hat{j}$  and  $\vec{v}$  to compute the power output of the car against gravity as it moves.

- A: 12.5 kW
- B: 125 kW
- C: 1250 kW
- D: 1 MW

## DEFINITION OF CONSERVATIVE FORCE

---



## DEFINITION OF CONSERVATIVE FORCE

### Definition of Conservative Force

Let  $\vec{F}(x, y)$  describe some *force field*. The field is **conservative** if the line integral around a closed path is zero:

$$\oint_p \vec{F} \cdot d\vec{r} = 0 \quad (20)$$

Returning the system to the same point implies no net work.

### Corollary 1

$$\frac{dF_y}{dx} = \frac{dF_x}{dy} \quad (21)$$

## DEFINITION OF CONSERVATIVE FORCE

Consider the case of gravity:  $\vec{F}(x, y) = 0\hat{i} - mg\hat{j}$ . So it depends neither on  $x$  nor  $y$ . Let's check that it is conservative:

$$\frac{dF_y}{dx} = 0 \quad (22)$$

$$\frac{dF_x}{dy} = 0 \quad (23)$$

$$\frac{dF_y}{dx} = \frac{dF_x}{dy} \quad (24)$$

Which force is conservative?

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

*Hint: when you picture a conservative force, picture symmetry.*

## CONCLUSION

---

1. **Work** has a scientifically precise definition
  - Units
  - As a product of force and displacement vectors
2. Kinetic Energy and the **Work-Energy Theorem**
3. Gravitational potential energy
  - Potential energy
  - *Simplifying otherwise complex calculations*
  - Potential energy near Earth's surface
  - ...in space
4. Definition of a **conservative force**
  - Relationship between conservative forces and potential energy
  - Conservation of energy for conservative forces

## ANSWERS

---

- 2.5 cm
- 312.5 m
- -280 kJ
- $-\frac{1}{2}mv_i^2$
- 90 kJ
- $10\sqrt{2}$  m/s
- 31.6 m/s, 50 m
- 10 J
- $\sqrt{20}$  m/s
- $\sqrt{6}$  m horizontally
- 0.05
- $h = \frac{5}{2}r$
- 1.4 kW
- 125 kW