Lecture 6

Fundamentals of Physics

Phys 120, Fall 2014

Energy

A. J. Wagner
North Dakota State University, Fargo, ND 58102

Fargo, September 10, 2015

Overview

- Doing work
- Helmholtz “living force”
- Defining an energy for mechanical systems
- Work and Energy
- Gravitational energy
- Other forms of energy
- Power

Doing work

As the development of machines increased in the 17th century it became important to understand the power these machines had in practical terms? How much work could they perform. And how would you quantify work?

A practical and simple measure of work turned out to be the height to which a weight could be raised. It turns out that, as long as you use a slow an steady motion, you find that a machine can raise a weight to a certain height, wheras double the weight could only be raised only half the distance.

This corresponds to the force required to raise the weight times the distance it will be raised, i.e.

$$W = F \cdot d$$

Work

Physicists definition: work is done whenever an object is pushed or pulled through a distance.

More precisely: object A does **work** on object B is A exerts a force on B while B mores in the direction of that force*.

*We won't consider the situation where motion and force don't align here.

Concept check

I lie on the floor in a relaxed state. Do I perform any work?

I hold myself in a painful push-up position. Do I perform any work?

I push the table across the floor at a constant speed. Do I perform any work?

Work defined quantitatively

$$\text{work} = \text{force} \times \text{distance}$$

or

$$w = Fd$$

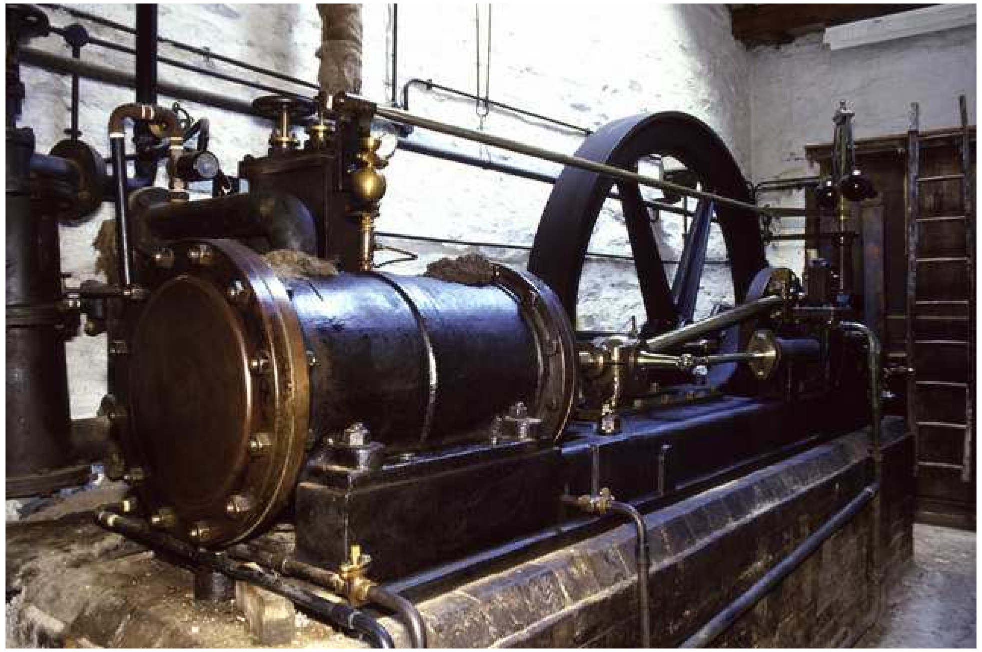
The units of work are $Nm = J$ also called a Joule.

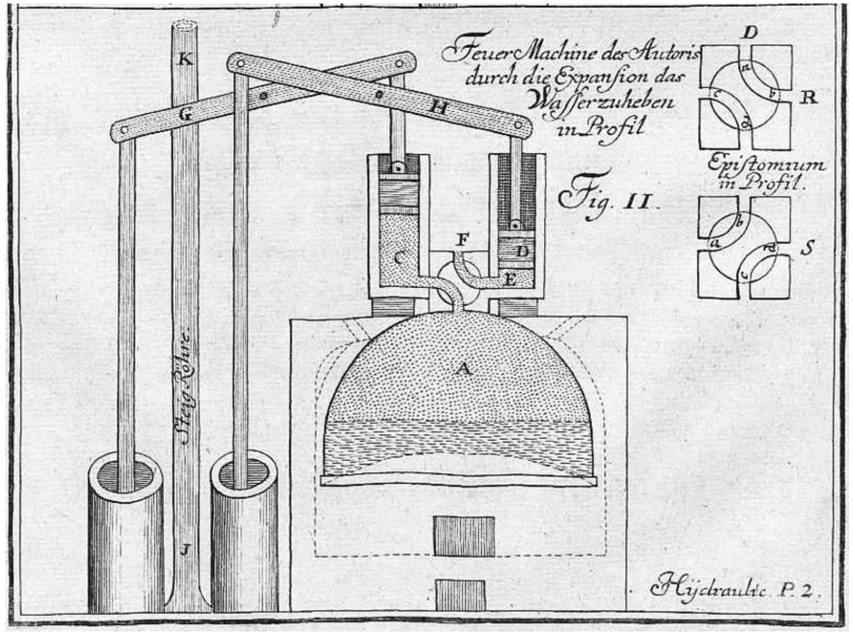
Concept check

I lift a 5kg chair over a distance of 2m (slowly and at constant speed).

1. No work is done.
2. 5 J of work are done.
3. 10 J of work are done.
4. 50 J of work are done.
5. 100 J or work are done.

Industrial revolution





Steam engines became practical at the end of the 18th century.

This fueled the industrial revolution. Starting in England manufacturing gets rationalized and factories develop. City populations grow and "for the first time in history, the living standards of the masses of ordinary people have begun to undergo sustained growth"*.

This also lead to a different perspective on physical processes and technology influences the directions of scientific thought.

*Lucas, Robert E., Jr. (2002). Lectures on Economic Growth. Cambridge: Harvard University Press. pp. 10910

Carnot

Steam engines had been invented by practical inventers, but much of the physics behind the operation of such a machine was unknown.

Sadi Carnot was the first person to really consider the theory of a steam engine carefully. His only publication Reflections on the Motive Power of Fire was both a breakthrough in the understanding of work and transformation of energy, and at the same time almost completely ignored.

Lord Kelvin (born William Thompson) rediscovered Carnot's results and later credited Carnot with the invention of the new science called "thermodynamics".

Much more about that in the next lecture.

Sadi Carnot
born 1796
died 1832

Helmholtz

Hermann v. Helmholtz
Physician
Physicist
*1821, †1894

Hermann Ludwig Ferdinand von Helmholtz was a German physician and physicist who made significant contributions to several widely varied areas of modern science.

Here we are interested in his observation of the heating up of decomposing bodies. Where did that heat come from? He followed the ancient Greek thesis "nothing comes from nothing" and decided that the heat must come from some other "living force" residing in the material and that this force gets transformed but not created or destroyed. We now call this "living force" **energy**.

He was able to show that for Newton's mechanics this could be given a specific definition.

Newton’s mechanics and kinetic energy

If I lift up a book I need to do work equal to the distance times the weight of the book or $E_p = mgh$. This work that I do to the book is still there, since I can use this book to lift something else. This form of energy is called **potential energy**.

If I drop the book, what is happening to the potential energy?
It obtains speed!
It gets transformed into another from of energy which we call kinetic energy. This is the energy the book has due to its speed. How much kinetic energy does a book have after it has fallen? Exactely the same amount as the original potential energy.

Quantiative expression for kinetic energy

From lecture 3 we know that for uniformly accelerate motion

$$x(t) = h - \frac{1}{2}gt^2 \tag{1}$$

So the time when $x = 0$ is given by

$$t = \sqrt{\frac{2h}{g}} \tag{2}$$

and the velocity is then given by

$$v = gt = g\sqrt{\frac{2h}{g}} = \sqrt{2gh} \tag{3}$$

But $E = mgh$, so $gh = E/m$ and we get

$$v = \sqrt{\frac{2E}{m}} \tag{4}$$

which we can rewrite as

$$\text{kinetic energy} = \left(\frac{1}{2}\right) \times (\text{object's mass}) \times (\text{square of object's speed})$$

or

$$E_k = \frac{1}{2}mv^2$$

This kinetic energy is defined such that (neglecting air resistance) the gravitational energy at the beginning gets exactly transformed into kinetic energy at the end.

Concept check

I drop a 1kg weight from a height of 1 m to the floor.

What is the initial potential energy (wrt the floor)?
(a) 0; (b) 10 J; (c) 1 J; (d) 10 N;

What is the initial kinetic energy?
(a) 0; (b) 10 J; (c) 1 J; (d) 10 N;

What is the kinetic energy just before the book hits the floor?
(a) 0; (b) 10 J; (c) 1 J; (d) 10 N;

What if the potential energy just before the book hits the floor?
(a) 0; (b) 10 J; (c) 1 J; (d) 10 N;

What about after it has hit the floor?

Concept check

How much kinetic energy do I have if I run with 2m/s compared to when I run with 1 m/s?

(a) the same kinetic energy;
(b) twice the kinetic energy;
(c) four times the kinetic energy;
(d) eight times the kinetic energy;

Concept check

If I throw a ball up with a velocity of 10 m/s it will rise to a height of 5 m.

How fast do I have to throw the ball so that it will rise to a height of 10 m?

(a) 10 m/s;
(b) 20 m/s;
(c) 30 m/s;
(d) 40 m/s;

Energy conservation

So far we have neglected air resistance, and that is clearly not always a good approximation. Helmholtz was thinking about a much deeper concept of **always** conserving energy.

There are different kinds of energy: gravitational energy, kinetic energy, elastic energy, thermal energy, electromagnetic energy, radiant energy, chemical energy, nuclear energy.

Joule's energy conservation: 1847 lecture

You see, therefore, that living force (kinetic energy) may be converted into heat, and that heat may be converted into living force, or its equivalent attraction through space. All three therefore — namely, heat, living force, and attraction through space (to which I might also add light, were it consistent with the scope of the present lecture) – are mutually convertible into one another. In these conversions nothing is lost . . . . We can therefore express the equivalence in definite language applicable at all times and under all circumstances. Thus the attraction of 817 lb. through the space of one foot is equivalent to, and convertible into, the living force possessed by a body of the same weight of 817 lb. when moving with the velocity of eight feet per second, and this living force is again convertible into the quantity of heat which can increase the temperature of one pound of water by one degree Fahrenheit.

James Prescott Joule
born 1818
died 1889

Law of conservation of Energy

The total energy of all participants in any process remains unchanged throughout that process. That is, energy cannot be created or destroyed. Energy can be transformed (changed from one form to another), and it can be transferred (moved from one place to another), but the total amount stays always the same.

This law is as true as any general rule ever gets. It is correct in any situation yet observed. It even holds where Newton's laws are no longer applicable.

Definition of Potential energy

Define the potential energy of an object as the amount of work it takes to bring the object to a certain height:

$$\text{gravitational energy} = \text{weight} \times \text{height}^*$$

You can use that energy to do work.

---

*Where the height is measured from some reference point, e.g. the floor.

Work-Energy principle

Work is an energy transfer. Work reduces the energy of the system doing the work and increasing the energy of the system on which work is done, both by an amount equal to the work done.

Energy conservation in β -decay

When scientists observed β-decay (a nucleus emits an electron) it was observed that energy was not conserved.
Maybe there was a new particle? Tried to capture this in lead, but no success.
This was the situation of 1914 - 1930. By 1929 physicists like Niels Bohr suggested that maybe energy was not conserved in nuclear reactions.
Wolfgang Pauli hypotesized a particle that interacted so weakly that it could not be captured in the lead. It was eventually found (more about that in a later lecture) and called the *neutrino*.

True story about a Fargo inventor

About a year ago I was visited by a Fargo inventor that had developed (conceptually) a machine that will solve our energy problems by generating energy in a renewable process that needed not external fuel cell. He was looking for funding from the Navy for his research.

Would you write him a letter of support?

I met him later and he told me that he had been successful in obtaining funding for his research.

Energy efficiency

Often only a small part of the energy can be transformed to do useful energy. Think of using the chemical energy in a sandwich to carry a chair upstairs. We define energy efficiency as:

$$\text{Energy efficiency} = \frac{\text{useful output energy}}{\text{total input energy}}$$

It is usually expressed as a percentage. The efficiency of a typical human muscular activity is only about 10%.

Power

What is the difference between walking and running up a flight of stairs? The same amount of work is done, but there is a difference:

$$\text{power} = \frac{\text{work done}}{\text{time to do it}}$$

The unit is $J/s = W$ or a Watt.

Estimates

What is your power output while running up a flight of stairs?
If the energy efficiency of this process is 10%, what is your (chemical) power input?

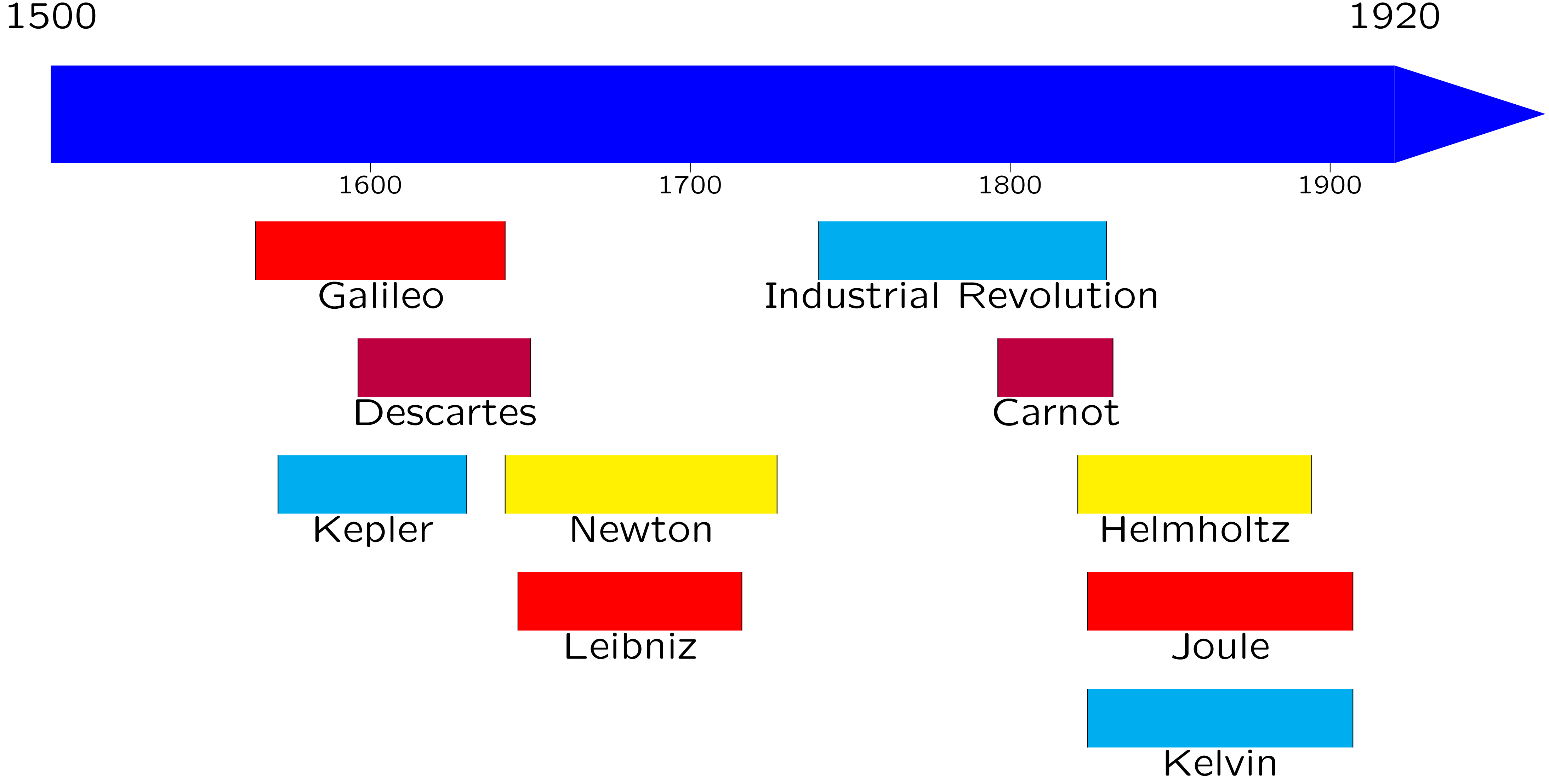
Concept check

You press a 500N weigh from the shoulders up to arms' length, a distance of 0.8m during a period of 2 seconds.

How much work did you do?

What is your power output?

Timeline



1500

1920

1600

1700

1800

1900

Galileo

Industrial Revolution

Descartes

Carnot

Kepler

Newton

Helmholtz

Leibniz

Joule

Kelvin

Summary

- Work = Fd
- Kinetic energy $E_k = (1/2)mv^2$
- Gravitational energy $E_g = mgh$
- Law of energy conservation
- Work energy principle
- Forms of energy
- efficiency & power