**Fundamentals of Physics Lecture 1.**

**Kinematic and Dynamic of Translational Motion. Work and Power. Energy. Momentum and Impulse**

**Introduction**

The word ***physics*** comes from a Greek word meaning "**knowledge of nature**."

Physics attempts to describe the fundamental nature of the universe and how it works, always striving for the simplest explanations common to the most diverse behavior.

The goal of physics is to explain as many things as possible using as **few** laws as possible, revealing their underlying simplicity and beauty.

Physicists construct models to represent the world around them. These models form conceptual frameworks that permit us to reduce complex situations into simpler, more understandable forms.

In general, such models of physical systems take a mathematical form.

It is always understood that the models are by nature incomplete and, therefore, imperfect

Physics is an experimental science.

The acceptance of any physical theory depends on its success in predicting and explaining reproducible observations.

To understand physics, or any experimental science, we must be able to connect our theoretical description of nature with our experimental observations of nature.

This connection is made through quantitative measurements.

The mechanics is divided into two parts: **kinematics** and **dynamics.**

The word *kinematics* is derived from the Greek word *kinema,* meaning "motion" — the same root from which we get the word *cinema.* **Kinematics** describes the positions and motions of objects in space as a function of time but does not consider the causes of motion.

Kinematics provides the means for describing the motions of such varied things as planets, golf balls, and subatomic particles.

The **dynamics** studies of the causes of motion**.**

The causes and effects of motion are discussed for many seemingly different situations, but the techniques used are the same

1. **Kinematics of point particle.**

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| Motion is the changing of position of any body relative to other bodies.  The motion may be over a straight or curve line. Generally it is a curve line and called **mechanical trajectory**or **path** (green line on the figure).  The length of mechanical trajectory called **distance traveled** or **trip**.  Knowing of distance traveled isn’t enough. We must to know also a direction of motion. When something moves from one location to another, we say it undergoes a **displacement**. The vector of changing in position, including the sign of the change, is called the **displacement**(black arrow on the figure)**.** | Похожее изображение |

Any measurement of position, distance, or speed must be made with respect to a **reference frame**, or **frame of reference**.

In physics, we often draw a set of **coordinate axes**, for example Cartesian Coordinates as shown in Figure bellow, to represent a frame of reference. We can always place the origin 0, and the directions of the *x, y* and *z* axes, as we like for convenience. The *x, y* and*z* axes are always perpendicular to each other. The **origin** is where x = 0, y = 0 and z = 0

Cartesian Coordinates may be 1-dimensional, 2-dimensional and 3-dimensional

First we will consider motion of point particle.

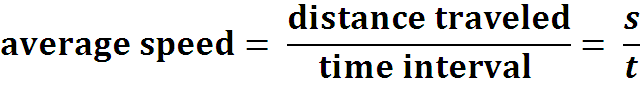
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| For 3-dimension motion it is useful to notate position of particle by radius-vector . Radius-vector has components to corresponding axes: rx = x; ry = y; rz = z.  If object changes its position the displacement is:  where are radius-vectors of initial position P1 and final position P2of the moving body respectively. | Картинки по запросу 3 dimension displacement Cartesian system | Похожее изображение |

Components of displacement to the axes are: Δrx = x2 - x1 Δry = y2 - y1 Δrz = z2 - z1

The symbol Δ(the Greek capital letter delta) is used to indicate a change in something - in this case, the position *r(x,y,z).* Thus Δr is the change in position*.*

The speed shows the distance traveled per unit of time. Speed is a scalar quantity, because distance traveled is scalar.

We define the **average speed*v***as the total distance, ***s***, traveled during a particular time divided by that time interval, ***t****:*



If the average speed is the same for all parts of a trip, then the speed is constant. The speed of a body is constant when it travels equal distances in any equal periods of time. This kind of motion called ***uniform motion.***For this case distance (trip) is simple: ***S = v∙t***

If the speed is changing, motion called nonuniform and we can find the instantaneous speed, taking the derivative from the distance with time:

In case nonuniform motion distance traveled between t1 and t2 moments must be found by taking integral:

Changing of **displacement** with time called **velocity**. Velocity is a vector insofar displacement is vector. Average velocity can be found:

Instantaneous velocity is defined to be a derivative of displacement with time:

For one dimension motion, for example over axis X:

or

Changing of velocity with time we call acceleration. Average acceleration is:

Instantaneous acceleration is first derivative of velocity with time or second derivative of displacement with time:

or

**Graphical representation of movement** (for simplicity we consider the one-dimensional motion)

Position-time graph

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| For the case of constant velocity (uniform motion):  The position-time curve is a straight line (as a present in Figure)and the slope is Δx/Δt*.* Thus we can determine the velocity from the slope of the line. Since the distance traveled is proportional to the time, we get the same numerical value for this ratio, Δx/Δt,no matter what interval of time we choose to consider. |  |
| Now consider nonuniform motion  We can define the instantaneous velocity for any point **A** as follows. We take ***Δt*** becomes vanishingly small. So the correspondent displacement **tends** to be a linear (approximately).  When ***Δt*** tend to zero the corresponding segment of curve tend to the **tangent** to the curve at that point.  The instantaneous velocity at point A is the slope of that tangent at that point, which is a straight line |  |
| The slopes at other points, such as В and С in Figure, are determined in the same way. Notice that in the immediate neighborhood of point B the displacement from the starting point is decreasing as time increases. Therefore, **ΔxB** is negative. The slope and the instantaneous velocity are both negative at point B. |  |

Velocity-time graph

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| In case uniform motion displacement is: ***S =Δx = v∙t***  How one can see from figure area under velocity-time graph is equal to displacement.  **We can extend this observation to state a general principle: The area** under any velocity-time curve between two times is equivalent to the **displacementduring that time** interval. |  |

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| We can divide the total time into small time intervals of duration *Δt*. Over each of these intervals we may approximate the velocity by a constant value, given by the average of the initial and final velocities for the interval.  The total displacement is then represented by the sum of all the areas of these rectangular strips, that is, the total area under the velocity-time curve. Thus    If Δt → 0, that is: |  |
| Velocity-time graph give as also opportunity to fined instantaneous acceleration.  Recall that the slope of a curved line at any point is determined by the line tangent to the curve at that point. This slope is equal to derivative of velocity with time, i.e. acceleration  Here Δ*v*should be taken as difference between any two points on the tangential line to the graph. |  |

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| Translational and rotational quantities compared | | | | | | |
| concept | translation | | connection | | rotation | |
| base quantities | **s**,**r** |  | **s** = | **θ** × **r** | **θ** |  |
| coordinate systems | **r** = | *x* **î** + *y* **ĵ** | *x* =  *y* =  *r*2 =  θ = | *r* cos θ *r* sin θ *x*2 + *y*2 tan−1 (*y*/*x*) | **r** = | *r* **r̂** + θ **θ̂** |
| velocity | **v** = | *d***r**/*dt* | **v** = | **ω** × **r** | **ω** = | *d***θ**/*dt* |
| acceleration | **a** = | *d***v**/*dt* = *d*2**r**/*dt*2 | **a** = | **α** × **r** − ω2**r** | **α** = | *d***ω**/*dt* = *d*2**θ**/*dt*2 |
| equations of motion | *v* =  *x* =  *v*2 = | *v*0 + *at* *x*0 + *v*0*t* + ½*at*2 *v*02 + 2*a*(*x* − *x*0) |  |  | ω =  θ =  ω2 = | ω0 + α*t* θ0 + ω0*t* + ½α*t*2 ω02 + 2α(θ − θ |

1. **Classic dynamic.**

**Force** is *an action capableof accelerating an object*.

Because *force* has direction as well as magnitude, it is a *vector quantity*. If several forces act simultaneously on the same object, it is the net force that determines the motion of the object. The *net* force is the *vector sum* of all forces acting on the object.

We often refer to the net force as the *resultant* force or the *unbalanced* force.

There are 4 (four) fundamental forces in the nature:

1. The gravitational force

2. The weak force.

3. The electromagnetic force

4. The strong force

A dropped stone falls because of the force of gravity. In this case the stone falls freely without being in contact with anything.

The *electromagnetic force* is responsible for holding atoms and molecules together and for the structure of matter.

The *strong force* is the attractive force that holds together the constituents of the atomic nucleus. It is sometimes called the *nuclear* force.

The *weak force* acts between all matter, but is so weak that it plays no direct part in ordinary observable behavior.It is, however, important in the interactions between subnuclear particles.

Current theories have been partially successful in *unifyingthe basic forces of nature*, so that we now understand the electric and weak force to be separate manifestations of one force, the **electroweak** force. Thus, according to one view, *there are only three*fundamental forces: *the gravitational force, the strong force, and the electroweak force*.

**Newton's first law**

A statement of Newton's first law, also known as the ***law of inertia***, in more concise language, is:

**A body has a constant velocity unless there is a net force acting on it.**

The special case of a body at rest corresponds to a velocity of zero.

In modern terms, **inertia** is the property of matter that causes objects to resist changes in motion.

(The word "inertia" is from the Latin word for "sluggish" or "inactive.“)

**mass** is a *quantitative measure of the inertia* of a body.

***We readily believe that a body at rest remains at rest unless some action is taken. It is not so easily seen from everyday experience that once a body is moving with nonzero constant velocity (constant speed in a straight line), it continues to do so without any additional outside effort.***

**Newton's second law**

Newton's first law describes what happens when the net force acting on an object is zero. In that case the object either remains at rest or continues in motion with constant speed in a straight line. Newton's second law describes the change of motion that occurs when a nonzero net force acts on the object.

*The original translation of* Newton's second law *was:*

***The alteration of* motion *is ever proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.***

Another one way to expresses the second law is:

**The acceleration of an object is directly proportional to the net force actingon it, and is inversely proportional to the object’s mass. The direction of theacceleration is in the direction of the net force acting on the object.**

- is the net force, applied to body.

We rearrange this equation to obtain the familiar statement of Newton’ssecond law:

or

In SI units, with the mass in kilograms, the unit of force is called the **newton** (N).One newton is the force required to impart an acceleration of 1m/s2 to amass of 1 kg. Thus 1N = kg∙m/s2

**Newton's Third law**

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| **Whenever one object exerts a force on a second object, the second objectexerts an equal force in the opposite direction on the first.** | Картинки по запросу newton's third law |

**Note carefully** that the two forces shown in Figure act on differentobjects. These two forces would never appear together in asum of forces in Newton’s second law. Why not? Because they act ondifferent objects.**The acceleration of one particular object must include *only* the forces on that *one* object.**

1. **Weight, the Force of Gravity. Friction.Static Equilibrium.**

All objects are attracted to the Earth. The attractive force exerted by the Earth onan object is called the **gravitational force**. This force is directed toward the centerof the Earth, and its magnitude is called the **weight** of the object.

Freely falling object experiences an acceleration **g**acting toward the center of the Earth. Applying Newton’s second law toa freely falling object of mass *m*, with **acceleration g** gives:

Therefore, the weight of an object, being defined as the magnitude of **Fg**, is given by

*W = mg*

Because it depends on *g*, weight varies with geographic location. Because *g*decreases with increasing distance from the center of the Earth, objects weigh lessat higher altitudes than at sea level.

Weight depends also on acceleration of the body.

If vertical acceleration is zero *W = mg.*  We call it weight at rest.

If vertical acceleration directed upward, then *W = m(g+a)*

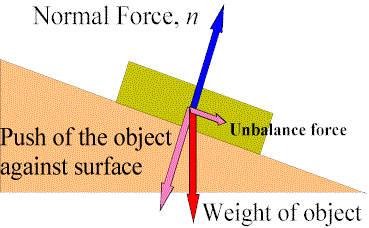
If vertical acceleration directed downward, then *W = m(g-a)*

If vertical acceleration is equal to free acceleration, that mean the body free falls, then*W = 0* and we call it *weightlessness*.

**Notice that body's mass would be *unchanged***.

When an object such as a brick *rests* on the ground, the gravitational force continues to act on the brick, even though it is not accelerating. According to Newton's second law, the *net force on the brick at rest must be zero*. There must be another force acting on the brick that opposes the gravitational force.

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| This force is provided by the ground. The force provided by the ground is perpendicular to the surface of contact and is known as the **normal force.**The normal force is simply the resistance of the ground to the motion of the brick acted upon by gravity. It is this normal force that keeps the brick from sinking into the ground. | Картинки по запросу The force provided by the ground is perpendicular to the surface of contact and is known as the normal force. |



**Frictional forces** generally oppose the motion of a body. These forces are also electromagnetic in origin.

Friction arises whenever one body slides over another. In this case wehave **dynamic or kinetic friction**.When an object slides along a rough surface, the force of kinetic friction actsopposite to the direction of the object’s velocity. The magnitude of the force ofkinetic friction depends on the nature of the two sliding surfaces. For givensurfaces, experiment shows that the friction force is approximately proportionalto the *normal force* between the two surfaces

*Ffr = μkN*

The term *μk*is called the *coefficient of kinetic friction*, and its valuedepends on the nature of the two surfaces.

Friction also arises whenever there isa tendency for motion, not necessarily motion itself. For example a blockthat rests on an inclined plane has a tendency to slide down the plane, sothere is a force of friction up the plane. Similarly, if you pull on a blockon a level rough road with a small force the block will not move. Thisis because a force of friction develops that is equal and opposite to thepulling force*F*. In this case we have **static friction**.

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| The static friction force is equal to the applied force *F*and is directed in the opposite direction. There is a maximum value of the static frictional force. If the applied force exceeds this value, the body begins to move. The magnitude of the force of static friction between any two surfaces in contactcan have the values:  *Fs*≤μ*sN*  where the dimensionless constant μ*s*is called the **coefficient of static friction**and *N*is the magnitude of the normal force exerted by one surface on theother. | Картинки по запросу static friction force |

There is also the rolling frictional force, but its consideration is not included in our present course.

1. **Work. Power.**

The word w*ork* has a variety of meanings in everyday language. But in physics, work is given a very specific meaning to describe what is accomplished when a force acts on an object, and the object moves through a distance. We consider only translational motion for now and, unless otherwise explained, objects are assumed to be rigid with no complicating internal motion, and can be treated like particles.

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| The **work** *W* done on a system by an agent exerting a constant force on the system is the product of the magnitude *F* of the force, the magnitude Δ*r* ofthe displacement of the point of application of the force, and *cos θ*, where *θ* is the angle between the force and displacement vectors:  *W = FΔrcosθ*  Or we can replace this equation as a dot product: | Похожее изображение |

**Work Done by a Varying Force**

If the force acting on an object is constant, the work done by that force can becalculated using Equation given above. But in many cases, the force varies in magnitude ordirection during a process.

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| The work done by a varying force can be determined graphically. To do so,we plot the component of force(*Fx*= *Fcosθ*) parallel to the direction of motion at any point as a function of distance *x*, as in Figure. We divide the distanceinto small segments Δ*x*. For each segment, we indicate the average of*Fx*by ahorizontal dashed line. Then the work done for each segment is*ΔW= Fx Δx* which is the area of a rectangle Δxwide and *Fx* high. | Картинки по запросу Work Done by a Varying Force |

The total work done tomove the object a total distance is the sum of the areas of therectangles.

If we subdivide the distance into many more segments, Δ*x*can be made smallerand our estimate of the work done would be more accurate. In the limit as Δ*x*approaches zero (d*x*→0), the total area of the many narrow rectangles approaches thearea under the curve. That is, *the* w*ork done by a* v*ariable force inmo*v*ing an object bet*w*een t*w*o points is equal to the area under the Fx*v*s. Δx*curve between those two points *xi*and *xf*.

That is integral:

The SI unit for work is the newton-meter or kg**.**m2/s2. This combination unit has also been given the name joule (J), in honor of James Prescott Joule (1818-1889), one of the great contributors to our understanding of energy: 1 joule (J) = 1 N**.** m = 1 kg**.**m2/s2

Other energy units:

1 BTU = 1.055.103 J (British thermal unit)

1 calorie = 4.187 J

1 kWh = 3.6.106 J

**Power.**In many cases it is useful to know not just the total amount of work being done, but how rapidly work is being done. For instance, if you have a motor that can provide only a certain amount of work in one day, and you wish to accomplish twice that much work, then you must either take two days for the job or get an additional motor. We define **Power** as the time rate of doing work; that is,

where ΔW is the amount of work done in the time interval Δt.

For instantaneous power we take derivative of work with time:

In SI units, work is measured in joules and time in seconds. The unit of power is the joule/second, a combination that has been given the name watt (abbreviated W):

1 joule/second = 1 watt. (W)

The measurement of power grew out of the need of early steam-engine builders to specify the properties of their engines. James Watt (1736-1819), the most inventive of these engine builders, developed the steam engine into an efficient, versatile engine that could be used to drive machinery.

Our definition of power applies to all types of work, whether mechanical, electrical, or thermal. However, we can rewrite the definition in a special way for mechanical work by simply rearranging terms. When a force acts on an object so that it moves with a speed *v,* we can calculate the power from the force and the speed. If we consider the force to be constant, the change in work is Δ*W = F Δx.* Then power becomes

so *P = Fv*

It can be shown that it is true for instantaneous power even when the force is not constant.

1. **Energy. Kinetic Energy.**

***Energy is the ability to do work.***

A compressed spring has energy because it may do work in returning to its uncompressed state. A falling body has energy because it may drive a stake into the ground upon striking it. Gunpowder, which may do work on exploding, has energy. An electrical battery has energy because it can turn an electric motor that does work.

A moving object can do work on another object it strikes. The energy of motion is called**kinetic energy**.

Suppose we consider a free body and subject it to a constant net force Fnet. This force may or may not be gravitational in origin.The work done on the body is W = *Fnet***.** *x.* If w*e* use Newton's second law: W = *ma***.** *x*

If the object is initially moving in the direction of Fnet with a speed v*1*then after moving through the distance *x* it will have a speed v2 given by the kinematic expression

After rearranging

This equation is known as the **work-energy theorem:** *The work done on a body by the* net force acting *on it is equal to the change in kinetic energy of the body.*

The quantity ½ *mv2*is given the name *kinetic energy* (KE). More specifically, this quantity is called the **translational kinetic energy.** A body of mass m moving with a speed *v* possesses a kinetic energy due to its translational motion that is given by

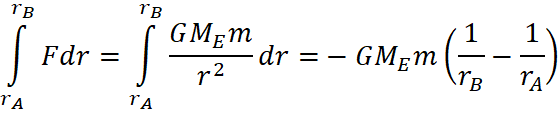
The SI units for kinetic energy are kg.m2/s2 or joules **(J)**, the same as the units for work.

1. **General Form of Gravitational Potential Energy.**

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| Suppose we wish to calculate the potential energy difference between points A and B, where A is at a distance *rA*from the earth's center and *В*is at a distance *rB*from the earth's center.  First we move the object along the path of constant radius from point A to a point C. Remember, work is done only when we exert a force through a distance to overcome the gravitational force. To move from С to B, we must apply a force to move the mass outward. The total work expended in going from С to В |  |

This force opposes the gravitational force given by Newton's law of gravitation

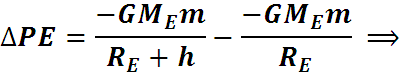
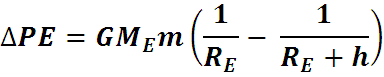
Insert this gravity force into the equation for the work done, we get

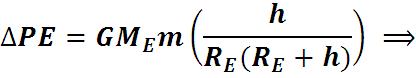
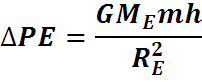




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| If we define the potential energy at any distance as    Then    and    Often we will choose ***r =* ∞** (infinity) to be the zero reference. | D:\XAZAR\Course Physics 1\1 Class 10 Lecture 8\92A-pic-earth-gpe.jpg |

We can show that two different expressions for the change in potential energy of a body give essentially the same answer for small changes in distance from the earth's surface.

The acceleration of gravity *g* is given by *g =* GME/R2, so:



1. **Conservation of Mechanical Energy.**

If the work done by a force on an object depends only on the initial and final positions of the object, then that force is a **conservative force.** The work is independent of the path taken.

If you move an object against a conservative force and return it to the starting place (***closed path***), the total work done is zero.

The *gravitational force, spring forceareconservative* forces.

For example, if you do an amount of work to lift a barbell from the floor, the same amount of work is done on you if you lower the barbell to its initial location.

We conclude, from the requirement that the work done be independent of the path taken, lides that conservative forces must be forces that depend only on position, rather than forces that may vary with time, speed of the object, or some other parameter.

**An important distinction between conservative and nonconservative forces is that we can write an expression for the potential energy for conservative forces.**

No such expression is possible for frictional forces, or for resistance of air to the motion of a body and the resistance of a liquid.

The sum of the body's kinetic energy and potential energy is its ***totalmechanical energy****.*



The value of the potential energy (PE) and kinetic energy (KE) may change, but their sum, the total energy (E), is a constant and does not change.

*If the forces act in given system are all conservative, the sum of the kinetic and potential energy is a constant.* This statement is the **law of conservation of mechanical energy.**

Etotal = constant

Those laws of nature that state that some quantity is the same before and after an event or interaction are called *conservation laws.*

Because conservation laws allow us to consider quantities, such as energy, that do not change during an event, we do not need to know the details of the interaction. We simply deal with the value of the conserved quantity before and after the interaction. Moreover, the fact that some quantities are conserved, and some are not, tells us something about nature itself.

1. **Linear momentum. Impulse. Newton's Laws and the Conservation of Momentum.**

The concept of momentum is extremely important in physics. Whenever we examine a moving object, we must consider both: its mass and its velocity. The **linear momentum** of a body with mass m, traveling with velocity **v,** is defined to be the product of the mass and the velocity. Momentum is associated with an object's translational motion. Since mass is a scalar quantity and velocity is avector quantity, their product, momentum (which we designate with the letter **p),** is a vector quantity:

Early we introduced Newton's second law in the form

Remind that acceleration is the derivative of velocity with time:

This is a more general form of Newton's second law. Where **Fnet** is the net force applied to an object*.*

We can rewrite this equation

The quantity on the left, **F**dt*,* is called the **impulse.** It is the product of the force **F** and the time interval dtover which the force acts. Changing of momentum is equal to impulse.

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| Even though the force occurs very briefly, the force is not usually constant over the time interval. For this reason, we often replace the force with the average force over the time of interaction ∆t. | Картинки по запросу impulse of a force | D:\XAZAR\Course Physics 1\1 Class 12,13 Lecture 9,10\impulsive force2.jpg |

If a system of mass m is subject to zero net external force, Newton's second law states that the rate of change of momentum with time is zero.

***The System's momentum remains constant when the net external force acting on it is zero****.* That is, if

Then:

1. **Conservation of Momentum in head-on collisions.**

For a collision involving two bodies, the **conservation law** can be expressed symbolically as



unprimed quantities stand for values before the collision and primed quantities stand for values after the collision.

**Note that we do not need to know anything about the details of the collision mechanism itself.**

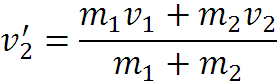
The rule holds for collisions between hard elastic bodies, such as billiard balls or glass spheres, as well as for collisions between soft bodies that do not "bounce" upon colliding, such as blobs of putty. These cases in which the two objects stick together are an important class of collisions, known as perfectly inelastic collisions.

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| First, let's simplify our discussion to just **head-on**, or **one-dimensional**, perfectly inelastic collisions.  so that they move only in one direction means that the vector equation for momentum conservation reduces to a single one - dimensional algebraic equation: |  |

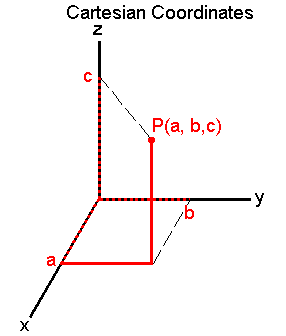
If the collision is perfectly inelastic, the two bodies stick together and *v'1 = v'2*. We can immediately determine the final velocity in terms of the masses and the initial velocities.

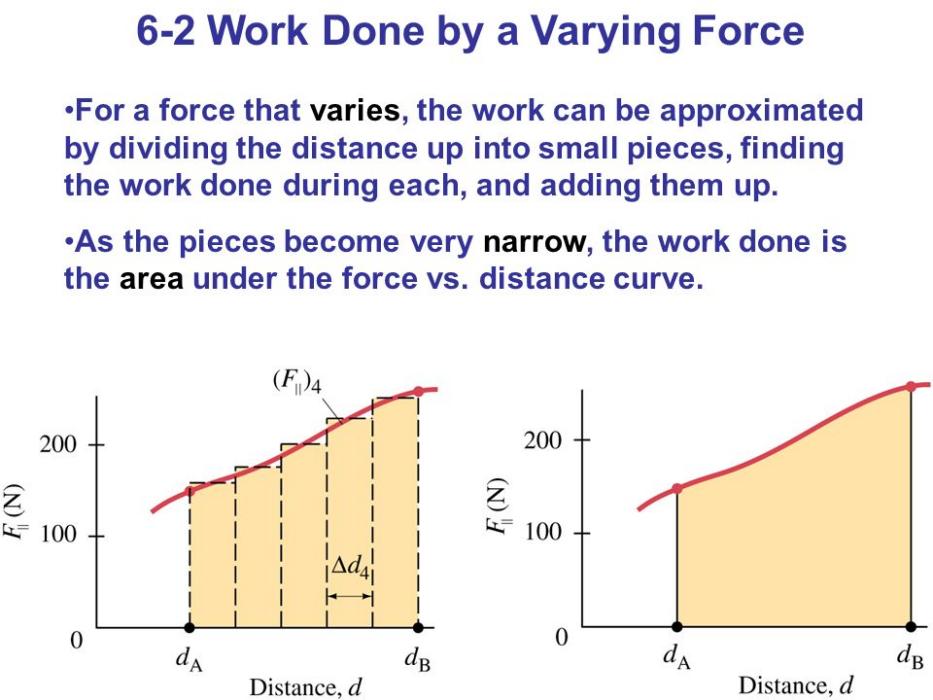


Solving for the final velocity v'2, we get



In collisions that are not perfectly inelastic, knowing the masses and initial velocities is not enough to determine the final velocities. We need more information. For example, for elastic collisions we mast to use the law of conservation of energy.





**Fundamentals of Physics Lecture 2. Kinematics and Dynamics of Rotational motion.**

1. **Uniform Circular Motion.**

Consider a point particle moving along a circular path of radius r with constant speed *v.* A particle moving in this manner is said to undergo **uniform circular motion.**

By a "***point particle***" we mean an object of negligible size and constant mass.

As we learned in our study of kinematics, a particle's speed is determined by measuring the distance traveled along its path and dividing by the elapsed time.

|  |  |
| --- | --- |
| Although the dot moves along its circular path with a constant speed*,* its *instantaneous velocity vector v*is constantly changing because the *direction* of its motion is *constantly changing*. Hence the instantaneous acceleration, which is in the same direction as Δ**v***,* is directed radially toward the center of the circular path. |  |
| Therefore *a particle* moving *with constant speed around a circle is always accelerated toward the center.* In this special case, the particle has uniform circular motion, and its acceleration is always perpendicular to the velocity. This acceleration is called the **centripetal** (center-seeking) **acceleration.**  Nevertheless, the velocity is always tangential to the circle and the acceleration always points to the center of the circle.  Magnitudeof centripetal acceleration is: | D:\XAZAR\Course Physics 1\1 Class 9 Lecture 7\6EXpa.png |

Suppose that we know an object's period T, which is the time it takes the object to complete one revolution around its circular path. During this time, the object travels with constant speed *v* along a distance equal to the circumference of the circle,

*vT = 2πr*

Upon rearranging, we get:

We can insert this expression into equation for centripetal acceleration to get the centripetal acceleration in terms of ***r***and *T*

The **frequency***f* is the number of complete revolutions, or cycles, an object makes per unit of time. The frequency *f* is the reciprocal of the period T. If an object takes a time T to complete one revolution around the circle, then the number of revolutions per unit time, the frequency, is

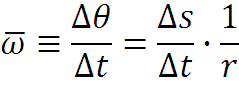
*f = 1/T*

The SI unit of frequency is the **hertz**, abbreviated Hz: 1 Hz = 1 s-1

The expression for the centripetal acceleration in terms of the frequency:

*ac = 4π2f2r*

The position of a point in circular motion with tangential velocity *v* at a constant radial distance *r* from the center of the circle may be given by the angle θ. This angle is defined in terms of the arc length *s* and the radius *r*:θ= *s*/*r*. *The rate of changeof* this *angle* is the **angular velocity ω.** The average angular velocity ω is

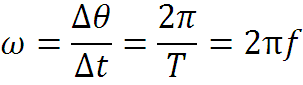


When the time interval is very small, Δs/Δt becomes the instantaneous speed v. Then the instantaneous angular velocity ω becomes

We can express the centripetal acceleration in terms of the angular velocity

*ac = ω2r*

When the change in time Δt is one period, the change in angle corresponds to one complete revolution or 2π rad. Thus we can also express the angular velocity as



Since ω is directly proportional to *f*  and has the dimension of inverse time, it is often called the **angular frequency**. The two names for ω may be used interchangeably. We will use these terms again in describing rotations and oscillations.

We have just seen that an object of mass *m* moving in a circular path with a uniform speed ***v***is accelerated becausethe direction of itsinstantaneous velocity is continuously changing.

By Newton's second law, the net forceacting on the object is in the same direction as the observedacceleration. This net force is given the special name **centripetal force** because it is directed toward the center of the circle.

It is this net force that causes the motion of the object to be circular; without the centripetal force, the object would travel in a straight line and not in a circle.

1. **Torque.**

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| Consider a door hinged at one edge. We can pull on it in several ways.  However, the most effective way to open the door is to grab the edge of the door farthest from the hinges and pull at right angles to the door.  The quantity measuring how effectively a force causes rotation is called **torque**. The torque **τ** about the point О is defined as  *τ≡ rF sin θ*,  where r is the distance from the axis to the point of force **F** application and θ is the angle between force vector and displacement **r**. Rewrite it in vector form: | | D:\XAZAR\Course Physics 1\1 Class 12,13 Lecture 9,10\open door 2.jpg | |
| **The lever arm** is defined as the perpendicular distance from the axis of rotation to the **line of action** of the force. From the geometry, we see that the lever arm is  *L = r sin θ*.  Therefore we can say that the torque is the product of force times the lever arm:  *τ= FL* | | **View on the door from the top** | |
| Figure shows two forces F1 and F2 generating torques. In both cases the forces are at right angles r. Although the resulting torques have the same magnitude, they tend to cause rotations in opposite directions. Thus torque is really a vector quantity, with both *magnitude* and *direction*. The *direction is along the axis of rotation*. |  | |  |

**The units of torque** are the units of length multiplied by the units of force. Thus the SI units for torque are the **newton-meter (N·m).**

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| The direction of the torque points along the direction a *right-handed screw* will move if **r** is rotated by **F**.    Figure on the right shows an alternative way of establishing this direction. | D:\XAZAR\Course Physics 1\1 Class 12,13 Lecture 9,10\torque vector.gif |

1. **Moment of Inertia and Rotational Kinetic Energy.**

Rotational motion is not always uniform and may having tangential acceleration as well as radial (centripetal) acceleration.

The rotating body has kinetic energy due to its rotary motion, and this kinetic energy equals the work done in causing body begins to rotate.

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| Suppose the mass is initially moving with tangential (linear) speed **v1**, and is subject to a force that is always perpendicular to the fixed length *r*. This force is tangent force, not centripetal.  The work done moving the mass through a small arc *ds* about the axis is:  *dW = F∙ds = m∙a∙ds*  In the same time we find the work done here is  dW = ½ mv22 - ½ mv12  where v1 and v2 are the initial and final tangential velocities. We may express these tangential velocities with the angular velocities through **v = r ω**, thus: |  |

Lets notate as *I = mr2*- moment of inertia of point body when it rotates over the circle with radius *r.* In this notation work done is:

The work done is equal to the change of rotational kinetic energy, where the *rotational kinetic energy* is defined by:

Compare with kinetic energy of translational motion:

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| The moment of inertia of the ***extended rigid body*** depends both on the mass and on the geometry, or shape of the body***.*** We can calculate the moment of inertia of an extended body by summing the moments of inertia of each small element of the body, obtaining the moment of inertia of the whole.  Moment of inertia I, defined as follows:    the **moment of inertia of the object depends on the** masses of the particles making up the object and their distances from the rotation axis. | Похожее изображение |

Except for a few simple cases, the techniques of calculus are needed to perform the summation.

What is a Moment of Inertia?

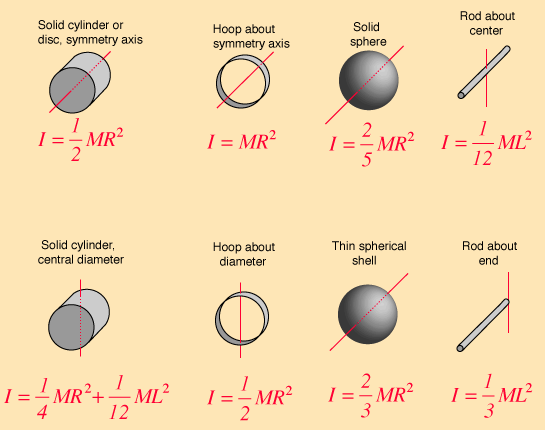
• It is a measure of an object’s resistance to changes to its rotation. Moment of inertia is the rotational analogue to mass (inertia).

• Also defined as the capacity of a cross-section to resist bending.

• It must be specified with respect to a chosen axis of rotation.

• It is usually quantified in kg∙m2

**Some Formula for Moment of Inertia of Bodies with Regular Shape**



1. **Steiner's theorem (parallel-axis theorem).**

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| The calculation of moments of inertia of an object about an arbitrary axis can becumbersome, even for a highly symmetric object. Fortunately, use of an importanttheorem, called the **parallel-axis theorem (Steiner's theorem),** often simplifies the calculation.  Suppose the object in Figure rotates about the *z* axis. The moment of inertia does not depend on howthe mass is distributed along the *z* axis(as we can see, the momentof inertia of a cylinder is independent of its length). That is the reason why we take planar object as example.  The moment of inertia about *z*axis can be found by formula:  I = ICM + mD2  Where Dis the distance between axis *z* and axis through the centre of mass. | Похожее изображение |

1. **Angular Momentum. Conservation of Angular Momentum.**

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| Suppose you have a wheel mounted on an axle on which it is free to turn. To set the wheel turning you need to apply a torque to it about its axle to overcome the wheel's inertia. Once the wheel is set in motion, it continues to rotate at constant angular velocity until another torque is applied.In both cases, a torque causes the angular velocity to change. This situation is analogous to the application of a force to a body to change its linear velocity.  Throughout this Lecture we have seen that if we use the appropriate angularvariables, the kinematic and dynamic equations for rotational motion are analogousto those for ordinary linear motion. We saw in the previous Section,for example, that rotational kinetic energy can be written as which isanalogous to the translational kinetic energy. | D:\XAZAR\Course Physics 1\1 Class 12,13 Lecture 9,10\wheel_axle.jpg |

In like manner, the linearmomentum*p = mv*, has a rotational analog. It is called **angular momentum**, *L*.

The angularmomentum is

where *I* is the moment of inertia and *ω*is the angular velocity about the axis ofrotation. The SI units for *L* are: kg∙m2/s which has no special name.

Newton’s second law we have rewritten in more generally in terms of momentum:

In a similar way, the rotational equivalent of Newton’s second law can be written also interms of angular momentum:

where is the τnet - net torque acting to rotate the object.

The angular momentum *L* of rotating point particle related with its linear momentum *p* with formula:

The direction of angular momentum is defined in a manner similar to the way in which we defined the direction of the torque

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Angular momentum is an important concept in physics because, undercertain conditions, it is a conserved quantity. We can see from equationsecond law for rotational motion that ifthe net torque on an object is zero = 0, then

equals zero. That is angular momentum*L* does not change. This is the **law of conservation of angular momentum** fora rotating object:

**The total angular momentum of a rotating object remains constant if the nettorque acting on it is zero.**



The law of conservation of angular momentum is one of the great conservationlaws of physics, along with those for energy and linear momentum.

1. **Angular Acceleration.**

The specialcase when the moment of inertia is constant, this equation can be written as follows:

Here α is angular acceleration:

Angular acceleration is a physical quantity, which present changing of angular velocity with time.

In case when the net torque is not equal zero means that the magnitude of linear velocity doesn't stay constant. This is not uniform circular motion. Changing of linear velocity with magnitude can be explained by tangent acceleration. The body receives this acceleration from the tangential force. It is the tangential force that changes the speed of rotation. And it is the tangential force that gives the body the unbalanced torque.

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| This tangential acceleration is  The instantaneous acceleration of the point ***a***is the vector sum of the radial acceleration ***ac*** and the tangential acceleration ***at***: |  |

1. **Rotational Equilibrium.**

**A pair of forces**, such as F1 and F2, that are equal in magnitude but opposite in direction and not lying along the same line is called a **couple.**The couple applies a torque about О equal to the sum of the torques due to the individual forces.

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| Note that although the forces are in opposite directions, they tend to rotate the body in the same direction about O    However, since F1 = F2 = F, we may write  **τ= sF** | D:\XAZAR\Course Physics 1\1 Class 12,13 Lecture 9,10\couple1.jpg |

There are two conditionsfor equilibrium:

1) The **first** condition for equilibrium is**condition for translationalequilibrium**.

The net force acts on the body is zero:

2) The **second** condition for equilibrium is**condition forrotational equilibrium**.

However, an object in translational equilibrium may still rotate. For example a **pair of forces**, such as F1 and F2, that are equal in magnitude but opposite in direction and not lying along the same linediscussed before may object to rotate.

If we want to keep the object from rotating, we must subject it to another torque of the same magnitude but in the opposite direction. We may thus conclude that for a body to be in rotational equilibrium the sum of the torques must be zero, or:

Example of **Steiner's theorem (parallel-axis theorem).**

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| Похожее изображение | Похожее изображение |

**General Physics Lecture 3. Harmonic oscillations. Waves.**

**1. Harmonic oscillations and their characteristics.**

*Periodic* motion, the repeating motion of an object in which it continues to return to a given position after a fixed time interval. The repetitive movements of such an object are called *oscillations.*

For a system to oscillate it is necessary to have a **restoring force**, i.e. a force that brings the system back towards its equilibrium position when the system is displaced away from equilibrium.

We will focus our attention on a special case of periodic motion called ***simple harmonic motion****.* All periodic motions can be modeled as combinations of simple harmonic motions. Understanding oscillations is the first step in understanding the behavior of waves. Simple Harmonic Motion (SHM) are called oscillations, in which physical quantity fluctuates as a sine (or cosine).

Harmonic oscillations of any quantity ***S*** can be described by equation of type

*S* = *A* cos(*ωt* + *φ* ) or *S* = *A* sin(*ωt* + *φ* )

where, A -amplitude (maximum value) of S; ω - angular frequency; φ - initial phase.

Quantity S may be a displacement, speed, acceleration, kinetic energy, potential energy, electric energy, magnetic energy and so on.

The time taken to complete one full oscillation is called the **period**, *T*. The number of full oscillations per second is called **frequency** *f* of the oscillations. Since we have one oscillation in a time equal to the period *T*, the number of oscillations per second is 1/*T* and so: *f* =1/*T*

Relation between frequency an angular frequency is: *ω = 2πf*

Relation between period an angular frequency is: *ωT = 2π*

The main characteristics of SHM are:

• the period and amplitude are constant

• the period is independent of the amplitude

• the displacement, velocity and acceleration are sine or cosine functions of time.

The defining property of all simple harmonic oscillations is that the magnitude of the acceleration of the body that has been displaced away from equilibrium is proportional to the displacement and the direction of the acceleration is towards the equilibrium position. Mathematically these two conditions can be stated as:

*a = - ω2∙x* (1)

Recall that, by definition, *a* = *dv/dt* = *d*2*x/dt* 2, so we can express Equation (1) as

*or* (2)

Equation (2) is called **oscillation equation.**

Functions *x* = *A* cos(*ωt* + *φ*) or *x* = *A* sin(*ωt* + *φ*) are a solution types of the differential equation (2). Solution of equation (2) may be also represented by exponential function:

because

where imaginary unit. Euler's formula state that:

**2. Mass-spring system**

As a model for simple harmonic motion, consider a block of mass *m* attached to the end of a spring, with the block free to move on a frictionless, horizontal surface. When the spring is neither stretched nor compressed, the block is at rest at the position called the **equilibrium position** of the system, which we identify as *x=* 0

|  |  |  |
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| When the block is displaced to a position *x,* the spring exerts on the block a force that is proportional to the position and given by **Hooke’s law**:  *Fs* = - *kx*  We call *Fs* a **restoring force** because it is always directed toward the equilibrium position and therefore *opposite* the displacement of the block from equilibrium.  When the block is displaced from the equilibrium point and released, it is undergoes an acceleration  *F = ma*.  So we get:  *- kx = ma or* (3)  That is, the acceleration of the block is proportional to its position, and the direction of the acceleration is opposite the direction of the displacement of the block from equilibrium. Systems that behave in this way are said to exhibit **simple harmonic motion.**  If we compare (3) with (1) and (2) we can see that *k/m = ω2* and it represents angular frequency of block-spring system. | Похожее изображение | |
| Let’s now find a mathematical solution to Equation, that is, a function *x*(*t*) that satisfies this second-order differential equation and is a mathematical representation of the position of the particle as a function of time. We seek a function whose second derivative is the same as the original function with a negative sign and multiplied by ω2. The trigonometric functions sine and cosine exhibit this behavior, so we can build a solution around one or both of them. The following cosine function is a solution to the differential equation:  *x* = *A* cos(*ωt* + *φ* ) | | Картинки по запросу block-spring system |

where A - amplitude of oscillations; - angular frequency

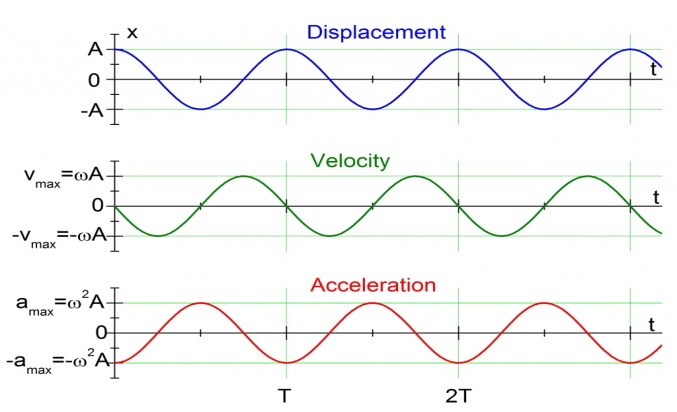
Period of oscillations of block-spring system:

Frequency of oscillations of block-spring system:

Firth derivative of position-time function *x(t)* is a velocity:

Second derivative of position-time function *x(t)* is an acceleration:

The constant angle φ is called the **phase constant** (**or initial phase angle**) and, along with the amplitude *A*, is determined uniquely by the position and velocity of the particle at *t* = 0. If the particle is at its maximum position *x* = *A* at *t* = 0, the phase constant is φ = 0 and the graphical representation of the motion is as shown in Figure. The quantity (ω*t* + φ) is called the **phase** of the motion. Notice that the function *x*(*t*) is periodic and its value is the same each time ω*t* increases by 2π radians.



**3. Simple Pendulum**

Another typical example of an harmonic oscillation is provided by the simple pendulum, i.e. a point mass suspended to a vertical string of constant length *l* fixed to a rigid support. When the mass is displaced slightly sideways and then released, the mass begins to oscillate. In an oscillation the motion is repetitive, i.e. periodic, and the body moves back and forth around an equilibrium position.

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| The forces acting on the ball are the tension force **T** exerted by the string and the gravitational force *m***g**. The tangential component *mg sinθ* of the gravitational force always acts toward θ = 0, opposite the displacement of the ball from the lowest position. Therefore, the tangential component is a **restoring force**, and we can apply Newton’s second law for motion in the tangential direction:  *ma = F = - mg sinθ*  When the angle *θ* is sufficiently small, sin*θ* may be approximated by the angle *θ* in radians:  sin *θ* ≈ *θ*, for small *θ*. |  |

From the picture we can see that *θ =x/l* , where *x* is displacement

So:

*ma = - mg sinθ ≈ -mgθ = - mgx/l*

After canceling on *m,* equation can be written:

*a = = - (g/l)∙ x*

or

Where

Period of simple pendulum:

Frequency of simple pendulum:

**1. Damped free mechanical oscillations**

The oscillatory motions we have considered so far have been for ideal systems, that is, systems that oscillate indefinitely under the action of only one force, a linear restoring force. In many real systems, nonconservative forces such as friction or air resistance also act and retard the motion of the system. These forces we will call ***retarding force***. Consequently, the mechanical energy of the system diminishes in time, and the motion is said to be *damped.*

Attenuation of oscillations in electrical systems circuits is caused by heat losses, energy losses to radiation of electromagnetic waves, as well as heat losses in dielectrics and ferromagnets due to electric and magnetic hysteresis.

One common type of retarding force is the force which proportional to the speed of the moving object and acts in the direction opposite the velocity of the object with respect to the medium. This retarding force is often observed when an object moves through air, for instance. Because the retarding force can be expressed as ***R* =** -*b***v** (where *b* is a constant called the ***retarding coefficient***) and the restoring force of the system, for example, is -*kx*, we can write Newton’s second law as

(1)

The solution to this equation requires mathematics that may be unfamiliar to you; we simply state it here without proof. When the retarding force is small compared with the maximum restoring force—that is, when the damping coefficient *b* is small—the solution to Equation (1) is

(2)

This result can be verified by substituting Equation (2) into Equation (1).

Here A=Aoe-(b/2m)t is a amplitude of damped oscillations; ω - the angular frequency of damped oscillation is

It is convenient to express the angular frequency of a damped oscillator in the form

where *ωo2 = k/m* represents the angular frequency in the absence of a retarding force (the **undamped** oscillator, i.e. b=0) and is called the **natural frequency** of the system.

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| Any system with exponentially decreasing amplitude is known as a **damped oscillator.** The dashed red lines in Figure, which define the *envelope* of the oscillatory curve, represent the exponential factor in Equation (2). This envelope shows that the amplitude decays exponentially with time. |  |

**4. Forced oscillations. The differential equations of forced mechanical oscillations.**

We have seen that the mechanical energy of a damped oscillator decreases in time as a result of the retarding force. It is possible to compensate for this energy decrease by applying a periodic external force that does positive work on the system. At any instant, energy can be transferred into the system by an applied force that acts in the direction of motion of the oscillator. For example, a child on a swing can be kept in motion by appropriately timed “pushes.” The amplitude of motion remains constant if the energy input per cycle of motion exactly equals the decrease in mechanical energy in each cycle that results from retarding forces.

A common example of a forced oscillator is a damped oscillator driven by an external force that varies periodically, such as *F*(*t*) = *F*o cos ω*t*, where *F*o is a constant and ω is the angular frequency of the driving force.

Modeling an oscillator with both retarding and driving forces as a particle under a net force, Newton’s second law in this situation gives:

and finally:

(8)

Equation (8) is the differential equation of forced oscillations. In mathematics there is the theorem that the general solution of the inhomogeneous linear second-order differential equations with constant coefficients will be the sum of two expressions: x = xo+ x1

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| xo - general solution of the homogeneous equation, when the right side is zero  x1 - any particular solution of the inhomogeneous equation  In this situation, the solution of Equation (8) is:  (9)  where  and  After the driving force on an initially stationary object begins to act, the amplitude of the oscillation will increase. After same sufficiently period of time, when the energy input per cycle from the driving force equals the amount of mechanical energy transformed to internal energy for each cycle, a steady-state condition is reached in which the oscillations proceed with constant amplitude. |  |

Superposition of equation (9) finally get a function:

x=Acos(ωt + φ) (10)

where

(11)

where *ωo2 = k/m* - natural frequency of the undamped oscillator (*b* = 0). Equations (10) and (11) show that the forced oscillator vibrates at the frequency of the driving force and that the amplitude of the oscillator is constant for a given driving force because it is being driven in steady-state by an external force.

The differential equation for forced electromagnetic oscillations with external voltage Vm cos ωt as a driving force has a form:

**5. Resonance.**

For small damping (*b*/2*m < ωo* or δ *< ωo*), the amplitude is large when the frequency of the driving force is near the natural frequency of oscillation, or when ω ≈ ωo. The dramatic increase in amplitude near the natural frequency is called **resonance.**

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| More precise **resonance frequency is**:  resonance amplitude is  When ω→0, amplitude approaches limit value which is called statistic deviation:  When ω→∞, amplitude approaches zero. |  |

In case weak damping when δ2 <<ωo2 resonance amplitude

where Q - Quality factor (Q*-* factor), Ao - statistic deviation. Thus, the larger the Q factor, the greater the amplitude of the resonance.

How can be seen from figure amplitude of resonance decreases with decreasing Q factor and increasing of δ. Also the frequency of resonance slightly decreasing with increasing of δ.

The rate at which work is done on the oscillator by **F** equals the dot product **F∙v**; this rate is the power delivered to the oscillator. Because the product **F**∙**v** is a maximum when **F** and **v** are in phase, we conclude that at resonance, the applied force is in phase with the velocity and the power transferred to the oscillator is a maximum. Thus, the oscillations of the force outstrip the oscillations of the system by a phase π/2.

A resonant vibration you may have experienced is the “singing” of telephone wires in the wind. Machines often break if one vibrating part is in resonance with some other moving part. Soldiers marching in cadence across a bridge have been known to set up resonant vibrations in the structure and thereby cause it to collapse. Whenever any real physical system is driven near its resonance frequency, you can expect oscillations of very large amplitudes.

**1. Wave process. Transverse and longitudinal waves. Wave graphs and wave properties. Wave front and wave ray.**

If excite oscillations at any point in the medium (solid, liquid or gaseous) then because the interaction between the particles of the medium, these oscillations are transmitted from one medium point to another at a rate that depends on the properties of the medium.

In considering the oscillations we are not take into account the detailed structure of the environment; medium is regarded like something continuously distributed in space and has elastic properties.

Wave processes is the process of propagation of oscillations in a continuous medium. When the wave propagates particles of the medium oscillate around their equilibrium positions and do not move after wave. With a wave only state of the vibrational motion and its energy is transmitted from one particle to another.

**The main property of all waves is energy transfer without the transfer of matter.**

The propagation of disturbances in an elastic medium are called *elastic (or mechanical) waves*.

The elastic wave is called harmonic if the oscillations of medium particle are harmonic.

A traveling wave or pulse that causes the points of the disturbed medium to move perpendicular to the direction of propagation is called a **transverse wave.**

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| A traveling wave or pulse that causes the elements of the medium to move parallel to the direction of propagation is called a **longitudinal wave.** |  |

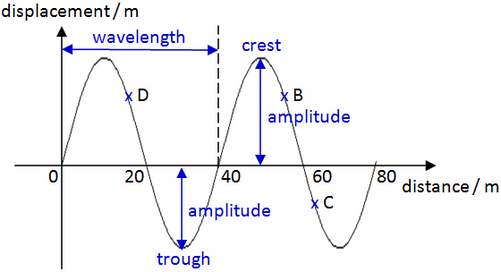
Consider harmonic wave travels at the speed v along the OX axis. Denote the displacement of medium points by y =y (x, t). For a given time t relation between the displacement of the particles and the distance x of the particles from the oscillation source O can be represented as a ***wave graph*.**

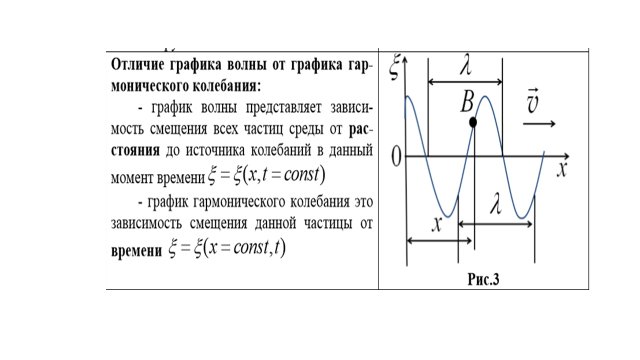
|  |  |
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| Wave graph differs from the graph of the harmonic oscillation:   * the *waves graph* represents dependency of the displacement of all the medium particles on the distance from oscillations source for the specific time y = y (x, t = const). Curve represents a snapshot of the wave at some specific time *t*. * the *graph of harmonic oscillations* is the dependence of the displacement of one specific particle from the time y = y(x = const, t). | https://img06.rl0.ru/b28de822d322e8361f989bbf71796b24/c361x280/www.sengpielaudio.com/WavesSinusodialTimeDistance.gif |

It is important to differentiate between the motion of the wave and the motion of the elements of the medium.

A point in Figure at which the displacement of the element from its normal position is highest is called the **crest** of the wave. The lowest point is called the **trough.** The distance from one crest to the next is called the **wavelength** λ (Greek letter lambda). More generally, the wavelength is the minimum distance between any two identical points on adjacent waves as shown in the next Figure.

If you count the number of seconds between the arrivals of two adjacent crests at a given point in space, you measure the **period** *T* of the waves. The period of the wave is the same as the period of the simple harmonic oscillation of one element of the medium. The same information is more often given by the inverse of the period, which is called the **frequency** *f*. In general, the frequency of a periodic wave is the number of crests (or troughs, or any other point on the wave) that pass a given point in a unit time interval. The frequency of a sinusoidal wave is related to the period by the expression





The frequency of the wave is the same as the frequency of the simple harmonic oscillation of one element of the medium. The most common unit for frequency, as we learned before, is s-1, or **hertz** (Hz). The corresponding unit for *T* is seconds.

We can give another definition of wavelength, linking it with the velocity of the wave.

Wavelength is the distance which is covered by a harmonic wave for a time equal to the period of oscillation T.

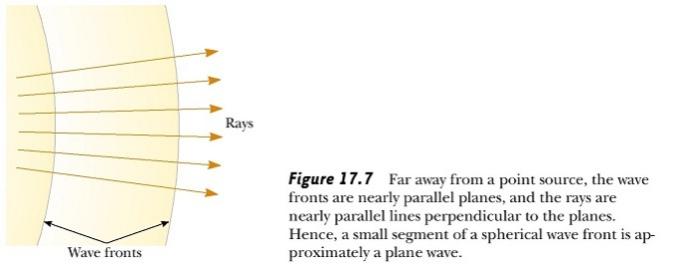
as *f= 1/Т* we also have:

where ω - angular frequency.

The wave is called a **traveling** wave, if all points of the wave move in space at a constant speed.

The locus of points which wave reaches at some instant of time t and oscillating with the same phase called the **wave front**. These points can be represented in the form of an imaginary surface.

In general, the set of points oscillating with the same phase is called the wave surface. The wave front is also one of the wave surfaces. The number of Wave surfaces are countless, but the wave front is the only. (Sometimes all wave surfaces called wave front.) The wave is called **plane (flat)** if its wave surfaces are a set of planes parallel to each other. The wave is called **spherical** if its wave surfaces have the form of concentric spheres.



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| https://img05.rl0.ru/346baa76e3962434c8fd553a054d82dd/c680x387/www.kshitij-iitjee.com/Study/Physics/Part2/Chapter17/41.jpg | |
|  |  | |

The wave **rays** are a lines that are perpendicular to the wave surface and tangent to it at each point coincides with the direction of wave propagation.

**2. Wave function**

*a) Wave function of plane wave*

Consider the sinusoidal wave, which shows the oscillations of the wave point at *position x* = 0. Because the wave is sinusoidal, we expect the wave function at this point to be expressed as

*y* (*0*, t) = *A* cos *ωt*,

where y - displacement of the point; *A* - the amplitude and *ω* - the angular frequency.

Oscillations of point B, situated at distance x from the origin will be described by the same function, but it oscillations is delayed on time *τ = x/*v, because wave needs this time is to reach point B. Equation for oscillations of particle that lie in a plane passing through the point x is given by

*y (x, t) = A cos ω (t - x*/v*)*

In general wave function has a form:

where φo - initial phase of wave and - phase of wave.

We can express the wave function in a convenient form by defining other quantitie, the **angular wave number** *k* (usually called simply the **wave number**)

(1)

The wave number shows how many wavelengths fit a distance equal to the length of 2π units. Wave function can be rewritten:

*y (x, t) = A cos (ωt - kx +φo)* (2)

Also we can use more advanced form

(3)

*b) Wave function of spherical wave*

(4)

where Ao - amplitude of the wave at its origin point; x - is the distance from the origin to the certain point. As it is seen amplitude of spherical wave decrease with distance according to law A = Ao/x.

**3. Phase speed of a wave.**

The **phase speed** of a [wave](https://en.wikipedia.org/wiki/Wave" \o "Wave) is the rate at which the [phase](https://en.wikipedia.org/wiki/Phase_(waves)" \o "Phase (waves)) of the wave [propagates in space](https://en.wikipedia.org/wiki/Wave_propagation" \o "Wave propagation). Any given phase of the wave (for example, the [crest](https://en.wikipedia.org/wiki/Crest_(physics)" \o "Crest (physics))) will appear to travel at the phase speed. The phase velocity is given in terms of the [wavelength](https://en.wikipedia.org/wiki/Wavelength" \o "Wavelength) λ and [period](https://en.wikipedia.org/wiki/Wave_period" \o "Wave period) T as

Equivalently, in terms of the wave's [angular frequency](https://en.wikipedia.org/wiki/Angular_frequency" \o "Angular frequency) ω, which specifies angular change per unit of time, and [wavenumber](https://en.wikipedia.org/wiki/Wavenumber" \o "Wavenumber) (or angular wave number) k, which represents the proportionality between the angular frequency ω and the linear speed (speed of propagation) νp,

To understand where this equation comes from, consider a basic [sine wave](https://en.wikipedia.org/wiki/Sine_wave" \o "Sine wave), A cos (kx−ωt). After time t, the source has produced ωt/2π = ft oscillations. After the same time, the initial wave front has propagated away from the source through space to the distance x to fit the same number of oscillations,

kx = ωt.

Thus the propagation velocity is

v = dx/dt = ω/k.

**4. Wave equation.**

Wave propagation in a homogeneous isotropic medium, in general, is described by the wave equation. The wave equation is a linear second odder differential equation in partial derivatives. For the plane wave propagates through the OX axis wave equation has a form:

(5)

Solution of wave equation (5) is any wave function, for example (2), (3) or (4)

Wave equation in 3 dimensions usually written in form:

(6)

where we use Greece letter ξ (ksi) to denote the displacement of points of medium.

This equation often write by using Laplace operator or Laplacian:

(7)

Solution of wave equation (6) or (7) has a form such as:

*ξ (r, t) = A cos (ωt - kr +φo) or*

where Ao - amplitude of the wave at its origin point; r - is the distance from the origin to the certain point. As it is seen amplitude of spherical wave decrease with distance according to law A = Ao/r. First two equations for plane waves and third one - for spherical.

**5. The Rate of Energy Transfer by Sinusoidal Waves.**

The medium with propagating wave has certain energy. The **energy density** at each point of the medium is determined by the formula:

(8)

where ρ= m/V - density of the medium; A -amplitude and ω - angular frequency of wave.

This energy is delivered from the oscillation source at different points of the medium wave itself. Thus wave transports energy.

The amount of energy carried by a wave through a surface per unit time ΔΦ = ΔW/Δt is called **energy** **flux** through the surface. To characterize the energy flow in different points of the space medium, we introduce a vector quantity called the **energy flux density**.

(9)

ΔΦ - energy flux

ΔA⊥- area perpendicular to the propagation of wave

Δt - time range

*ΔW=wΔA⊥vΔt*

Substitute this equation in (9) we get

*j = wv* (10)

Combine (10) with (8) we can write for **energy flux density**:

(11)

**General Physics Lecture 4. Fluid Mechanics**

A **fluid** is a collection of molecules that are randomly arranged and held together byweak cohesive forces and by forces exerted by the walls of a container.

The attractive force between molecules that acts to hold a fluid together is called cohesion. The attractive force between unlike molecules - say, between water and glass - is called adhesion.

Both liquids andgases are fluids.

In our treatment of the mechanics of fluids, we’ll be applying principles and analysismodels that we have already discussed. First, we consider the mechanics of a fluid at rest,that is, ***fluid statics****,* and then study fluids in motion, that is, ***fluid dynamics***.

1. **Pressure. Hydrostatic Pressure.**

The pressure ***P*** is the ***force acts per unit area:***

In SI it is given the name Pascal for pressure unit. Pa= N/m2. *Another units of pressure and their relationship with Paskal*:

|  |  |
| --- | --- |
| **Name** | **Value**  **(N/m2 = Pa)** |
| **1 bar** | **1.00 ∙ 105** |
| **1 atmosphere (atm)** | **1.01 ∙ 105** |
| **1 mm Hg** | **1.33 ∙ 102** |

|  |  |
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| Consider an upright cylinder containing a liquid. A force acts on the bottom of the cylinder as a result of the weight of the liquid inside. The pressure of the liquid on the bottom is:  where **m** is the mass of the liquid, **A** is the area of the bottom of the cylinder, and **g** is the acceleration of gravity. Note that although force is a vector quantity, pressure is a scalar. | D:\XAZAR\Course Physics 1\1 Class 17,18 Lecture 12,13\Figure_12_04_01a.jpg |

It is convenient to use the concept of density when discussing pressure. The density of a substance, d, was defined as its mass per unit volume d = m/V. Pressure can be written in term density

*P = dgh (hydrostatic pressure)*

We can now see that pressure is directly proportional to both the density and the depth of the liquid

1. **Pascal’s Principle.**

***The pressure applied at one point in an enclosed fluid is transmitted undiminished to every part of the fluid and to the walls of the container.***

Pascal's principle holds for gases as well as for liquids, with some minor modifications due to the change in volume of a gas when the pressure is changed.

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| Some Applications of Pascal's principle:  1) hydraulic lift: P1 = P2  A2>A1  F1 = P1 A1; F2 = P2 A2  **F2> F1** | | | D:\XAZAR\Course Physics 1\1 Class 17,18 Lecture 12,13\car_hoist_hydraulic.gif | |
| 2) pressure-measuring devices | D:\XAZAR\Course Physics 1\1 Class 17,18 Lecture 12,13\Tire-Pressure-Gauge-Dimensions.jpg  Tire gauge with a spring-loaded piston | D:\XAZAR\Course Physics 1\1 Class 17,18 Lecture 12,13\utube.gif  Liquid Manometer | | D:\XAZAR\Course Physics 1\1 Class 17,18 Lecture 12,13\Figure_12_06_04a.jpg  The Torricelli experiment |

1. **Archimedes’s Principle.**

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| A body, whether completely or partially submerged in a fluid,is buoyed upward by a force that is equal to the weight of the displaced fluid.  ***Fbuoyant = dfluid∙g∙Vsubmerged***  Buoyant force depends only on the volume of the submerged object, not on its mass or density. It depends of the density of environment  1. Of course, if body is denser than fluid, the buoyant force alone cannot support it and body would sink to the bottom.  2. If the fluid has a densitygreater than that of the body, it would float. | D:\XAZAR\Course Physics 1\1 Class 17,18 Lecture 12,13\pressure-gradient-buoyancy.jpg |

Blimps, hot-air balloons, and other lighter-than-air craft furnish another example of Archimedes' principle. They float in the air just as a submerged fish floats in the water. The blimp obviously has individual parts that will not float in air.

However, the ***average*** density of the whole craft, including passengers, must be less than the density of air to accomplish an unpowered takeoff. To meet this requirement in a practical way, the blimp contains a large volume of helium. The same type of observation can be made about large ships, which float even though they are made of steel and carry dense objects. The explanation is that the average density of the entire ship, including all of the air spaces, is less than the density of water.

1. **Streamlines and Equation of Continuity.**

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| Consider the flow of a fluid.First assume fluid1) is incompressible 2) has no internal friction, 3) has no viscosity. Figure shows a fluid flowing.  If the neighboring layers of fluid move past each other smoothly, each small element of fluid follows a path called a streamline.  If we draw all of the streamlines from the boundary of region A to some later position B, we outline a tube of flow (stream tube). | Картинки по запросу streamline and tube of flow |

Fluid particles cannot flow into or out of the sides of this tube; if they could, the streamlines would cross one another.

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| The smooth streamline flow is known as **laminar** flow.  When the fluid exceeds a certain critical velocity, the flow is no longer laminar but becomes **turbulent** and is characterized byan irregular, complex motion. | D:\XAZAR\Course Physics 1\1 Class 17,18 Lecture 12,13\laminar_turbulent_flow.gif |
| Let us consider an incompressible fluid flowing steadily through a tube from a region of cross-sectional area ***A1*** to a region of area ***A2***.  If the density of the fluid is ***d,*** then the mass of fluid that flows into the tube in time ***Δt*** is ***d∙v1A1Δt.*** Similarly, the mass of fluid that flows out of the tube through ***A2*** in the same time ***Δt*** is ***d∙ v 2 A2 Δt .*** Since the mass of fluid entering is the same as the mass leaving:  ***d∙ v 1A1Δt = d ∙v 2 A2 Δt*** |  |

Divide out the density ***d*** because it is constant for an incompressible fluid we get

***v 1A1 = v 2 A2***

This equation is called the **equation of continuity** and will be useful throughout our discussion of fluids in motion. It states that the flow of material (mass) through a tube of changing cross section is constant when the density of the fluid does not change.

Notice that the product***vA*** is the volume rate of flow. In SI units the volume rate of flow is measured in m3**/**s.

1. **Bernoulli’s Equation.**

As a fluid moves through a region where its speed or elevation above the Earth’s surface changes, the pressure in the fluid varies with these changes. Consider the flow of a segment of an ideal fluid through a nonuniform pipe in a time interval Δ*t* as illustrated in Figure. We have added two features: the forces on the outer ends of the ΔV portions of fluid and the heights of these portions above the reference position *h=* 0.

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| We calculate the work done on a small element of fluid moving along a tube of flow and then use the work - energy theorem to equate the change in kinetic energy to this work.  To move a small element of fluid through a distance of***Δx1*** at region 1 requires an amount of work ***P1 A1Δx1 =P1 ΔV.*** (Amount of volume *ΔV* is equal at both regions, according with equation of continuity.)  At the same time, the same amount of fluid (given by ***ΔV =A2Δx2***) moves a distance***Δx2*** at region 2. The work in this case is ־***P2 A2Δ***x2***=***- ***P2ΔV***. The negative sign indicates that the element of fluid at region 2 moves against the force due to the pressure of the fluid to its left.  Net work is: ***W = (P1 - P2)ΔV*** | Похожее изображение |

This work is spent to changing of potential energy and kinetic energy of ***m*** amount of fluid.

Recall that mass of fluid ***m = ρΔV,*** where ρ - is a density of fluid

If we divide each term by the portion volume Δ*V* this expressionreduces to

Rearranging terms gives



This expression is called **Bernoulli's equation**. It describes the relationship of a fluid's pressure, velocity, and height as it moves along a pipe or other tube of flow.

First summand in Bernoulli's equationis called static pressure (*P*), second summand - dynamic pressure *(½ρv2*) and third summand - hydrostatic pressure (*ρgh*)

Remember, that Bernoulli's equation is valid only for:

1) incompressible fluids of 2) negligible viscosity in 3) laminar flow.

Under these conditions, Bernoulli's equation expresses conservation of energy in a moving fluid.

Let us consider a horizontal pipe (h1 = h2)

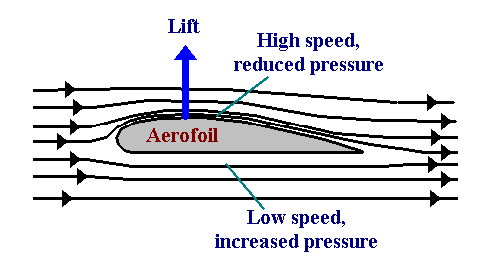


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| The equation of continuity tells us that the fluid flows more rapidly in a constricted region of the pipe. If we combine the equation of continuity with Bernoulli's equation we get that when a moving fluid enters a narrower section of pipe, its speed increases but the pressure on the fluid decreases.  If *v*2 is greater than *v*1, then P2 is smaller than ***P1*** | Картинки по запросу streamline and tube of flow |

Bernoulli's equation gives us methods to measure velocity of flow and different kinds of pressure of flow.

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| ***Venturi meter***  D:\XAZAR\Course Physics 1\1 Class 17,18 Lecture 12,13\venturi.gif | Похожее изображение |

Bernoulli's equation help to explain how airplanes can fly and why they are not fall.



1. **Viscosity and Poiseuille’s Law.**

Viscosity is a property of a fluid that indicates its internalfriction. The more viscous a fluid, the greater the force required to cause one layer of fluid to slide past another.

Viscosity is what prevents objects from moving freely through a fluid, or a fluid from flowing freely in a pipe.The viscosity of gases is less than that of liquids.

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| The viscosity of different fluids can be expressed quantitatively by a *coefficientof* v*iscosity*, h (the Greek lowercase letter eta), which is defined in thefollowing way. A thin layer of fluid is placed between two flat plates. One plateis stationary and the other is made to move as on Figure. The fluid directly incontact with each plate is held to the surface by the adhesive force between themolecules of the liquid and those of the plate. | Похожее изображение |

Thus the upper surface of thefluid moves with the same speed *v* as the upper plate, whereas the fluid in contactwith the stationary plate remains stationary. The stationary layer of fluid retardsthe flow of the layer just above it, which in turn retards the flow of the next layer,and so on. Thus the velocity varies continuously from 0 to *v,* as shown. Theincrease in velocity divided by the distance *l*over which this change is made—equalto *v/l*—is called the v*elocity gradient*(more exactly*dv/dx*).

To move the upper plate requires a force,which you can verify by moving a flat plate across a puddle of syrup on a table.For a given fluid, it is found that the force required, *F*, is proportional to theareaof fluid in contact with each plate, *A*, and to the speed, *v,* and is inverselyproportional to the separation,*l*, of the plates. For different fluids,the more viscous the fluid, the greater is the required force. The proportionalityconstant for this equation is defined as the coefficient of viscosity,h

or

Solving forh

The SI unit for h is N∙s/m2 = Pa∙s (pascal ∙ second). Viscosities are often given in centipoise (1cP = 10-3 Pa∙s)

Viscosity increases with decreasing temperature.

If there were no viscosity in horizontal pipe of uniform cross section, the pressure in a moving fluid would be constant.

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| Viscosity acts like a sort of friction (between fluid layersmoving at slightly different speeds), so a pressure difference between the ends ofa level tube is necessary for the steady flow of any real fluid, be it water or oil in apipe, or blood in the circulatory system of a human.  The French scientist J. L. Poiseuille (1799–1869), who was interested in thephysics of blood circulation (and after whom the “poise” is named), determined howthe variables affect the flow rate of an incompressible fluid undergoing laminarflow in a cylindrical tube. | Похожее изображение |
| His result, known as **Poiseuille’s equation**, is:    where ***Q* = *v*A** is the volume rate of flow in m3/s,  ***η*** is the coefficient of viscosity,  ***R*** is the radius of the pipe,  ***L*** is the separation between the test points. | Похожее изображение |

If ***R*** and ***L*** are given in meters and the pressure is given in pascals, the unit of the coefficient of viscosity ***η*** is the pascal-second (Pa**.**s).

Poiseuille's law is often used experimentally to determine the coefficient of viscosity of a liquid.

Poiseuille’s equation tells us that the flow rate *Q* is directly proportional tothe “pressure gradient,” and it is inversely proportional to the viscosityof the fluid. This is just what we might expect. It may be surprising, however,that *Q* also depends on the *fourth* power of the tube’s radius. This means that forthe same pressure gradient, if the tube radius is halved, the flow rate is decreasedby a factor of 16!

1. **Stokes’s Law.**

An object moving through a fluid experiences a resistive force, or drag, that is proportional to

* the viscosity of the fluid ***η***
* speed***v***(if the object is moving slowly enough)

For spherical object of radius ***r***, the force is:

***F = 6πηrv***

where ***η*** is the coefficient of viscosity. This equation is known as **Stokes's law.**

Stokes’s law can be used to measuring the viscosity of the fluid.

1. **Terminal Velocity.**

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| Consider a small solid sphere of radius ***r*** dropped into the top of a column of liquid.  At the top of the column the sphere accelerates downward under the influence of gravity.  However, there are two additional forces, both acting upward:   * the constant buoyant force * velocity-dependent retarding force.   When the sum of the upward forces is equal to the gravitational force, the sphere travels with a constant speed***vt ,*** called the **terminal velocity**. | D:\XAZAR\Course Physics 1\1 Class 17,18 Lecture 12,13\terminal-velocity.jpeg |

To determine this speed, we write the equation for the equilibrium of forces:

***W = Fgra*v *= Fbuoyancy + Fdrag***

***Fgrav =* 4/3 *πr3ρg;***

***Fbuoyancy =* 4/3 *πr3ρ*'*g;***

***Fdrag = 6πηrvt***

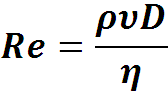
where ***ρ*** *and* ***ρ*'**are density of the sphere and liquid respectively.

Combining these equations, we get the terminal velocity:



1. **Laminar and Turbulent Flow.**

The ratio of the inertial force to the viscous force, called the ***Reynolds number,*** is a useful parameter for describing fluid flow and for determining the onset of turbulence. It is given by



where ρ and η are the density and viscosity of the fluid, ***v*** is the velocity of the object, and L is a length characteristic of the moving object, or diameter of the tube.

Reynolds numbers:

* less than about 2000 correspond to laminar flow
* greater than 3000 correspond to turbulent flow
* at values between 2000 and 3000 the flow is unstable and may change back and forth from one type of flow to another.

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| D:\XAZAR\Course Physics 1\1 Class 17,18 Lecture 12,13\laminar_flow.jpg | D:\XAZAR\Course Physics 1\1 Class 17,18 Lecture 12,13\dns-zoom.jpg |

(\* For Additional reading)

An important class of effects occurs whenever an object moves more rapidly than we assume it does for the case in which Stokes's law holds.

As long as the speed is low enough so that the fluid flows smoothly around the object, the retarding force, or drag, is proportional to the speed:

***F= bv***

*b* - proportionality coefficient.

But when the speed becomes so great that the **streamline flow breaks** up and the **fluid swirls** around in eddies, the drag becomes more nearly proportional to the square of the velocity. The retarding force can then be represented as a sum of two terms:

***F = bv + cv2***

where ***b*** and ***c*** are constants determined for each case being considered.

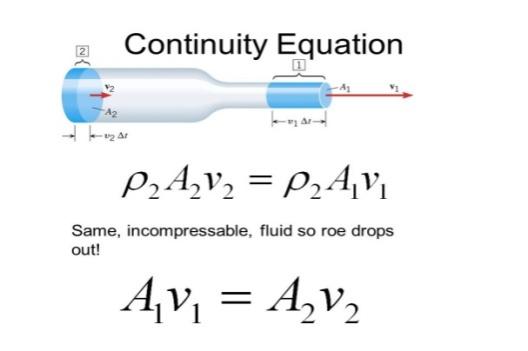
An object falling from rest through the air begins its fall with acceleration equal to the acceleration of gravity. The retarding force increases as the object's speed increases, so that the acceleration decreases and eventually becomes zero. The resulting constant velocity is the terminal velocity *v*t, at which the downward force of gravity is opposed by a retarding force of equal magnitude due to the air resistance:

***mg = bvt + cvt2***

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| In many cases of practical interest, the constant ***b*** is so small that the term ***bvt*** can be neglected. In that case the terminal velocity may be written as | Картинки по запросу fast motion of sport car | D:\XAZAR\Course Physics 1\1 Class 17,18 Lecture 12,13\parachute2.jpeg |

One of the objects of contemporary automobile design is to reduce the drag coefficient in order to improve fuel economy.

On the other hand, the design objective for a parachute is to have drag coefficient so that the descent is slow.



**General Physics Lecture 5. Kinetic theory. Thermal physics.**

1. **Temperature and Thermometry**

In everyday life, **temperature** is a measure of how hot or cold something is. A hotoven is said to have a high temperature, whereas the ice of a frozen lake is said tohave a low temperature.

Many properties of matter change with temperature. For example, most materialsexpand when their temperature is increased.

Instruments designed to measure temperature are called **thermometers**.There are many kinds of thermometers.

The basis of thermometry is that some physical properties vary with temperature in a quantitative and repeatable fashion.

Some of these thermometric properties are the volume of a gas or liquid, the length of a metallic strip, the electrical resistance of a conductor, and the light-transmitting properties of a crystal.

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| The choice of a particular thermometer depends primarily on the range of temperatures to be studied.  Any thermometer, whether liquid-in-glass or one that depends on other thermal properties, must be calibrated to make it a useful instrument.  In order to measure temperature quantitatively, some sort of numerical scale mustbe defined. The most common scale today is the **Celsius** or **centigrade** scale. In theUnited States, the **Fahrenheit** scale is common. The most important scale in scientificwork is the absolute, or Kelvin, scale. | D:\XAZAR\Course Physics 1\1 Class 20 Lecture 14\averillfwk-fig05_025.jpg |

(Recall by yourself the formula for transfer from one scale to another)

1. **Thermal equilibrium and The zeroth law of thermodynamics**

If two objects at different temperatures are placed in thermal contact (meaningthermal energy can transfer from one to the other), the two objects will eventuallyreach the same temperature. They are then said to be in **thermal equilibrium**. Forexample, you leave a fever thermometer in your mouth until it comes into thermalequilibrium with that environment; then you read it. Two objects are definedto be in thermal equilibrium if, when placed in thermal contact, no net energyflows from one to the other, and their temperatures don’t change.

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| Experiments indicate that  **if two systems are in thermal equilibrium with a third system, then they are inthermal equilibrium with each other.**This postulate is called the **zeroth law of thermodynamics**. It has this unusualname because it was not until after the first and second laws of thermodynamicswere worked out that scientists realized that this apparently obvious postulate needed to be stated first. | D:\XAZAR\Course Physics 1\1 Class 21 Lecture 15\three-cans.jpgD:\XAZAR\Course Physics 1\1 Class 21 Lecture 15\th010206p.gif |

1. **Ideal gas.Gas laws.**

Any gas that obeys the relationships derived from assumptions below at all temperatures and pressures is called an **ideal gas:**

* 1. A sample of gas consists of many identical molecules. In this context "many" means so many that one could not hope to trace out their individual paths.
  2. The molecules are very far apart in comparison to their size; that is, the total volume of the molecules is negligible when compared with the size of their container.
  3. The direction of motion of any molecule is random; on the average, no direction is preferred above another and the molecules move with a variety of speeds.
  4. The molecules are treated as if they were hard spheres. This assumption, which gives rise to the name "billiard ball model," means that there are no forces acting between molecules except when the molecules collide and that the collisions are elastic. In addition, we treat collisions with the walls of the container as elastic collisions.
  5. The molecules obey Newton's laws of motion.

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| **Boyle's law**states that if **the temperature T doesn’t change, the pressure exerted by a gas is inversely proportional to the volume in which it is enclosed.**  **PV = constant** (if T = constant)  Where P is the gas pressure, V its volume, and the value of the constant depends on the initial conditions.  A complete statement of Boyle's law includes the condition that both the temperature and the amount of gas must be held constant. | D:\XAZAR\Course Physics 1\1 Class 23,24 Lecture 16,17\boyle1ga.gif |

Alternatively, Boyle’s law may be written

**P1V1 = P2V2**

where the subscripts 1 and 2 refer to different physical states of the same sample of gas with the temperature held constant.

**The Law of Charles**

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| The Frenchman Jacques Charles (1746–1823) found that when the pressure is nottoo high and is kept constant, the volume of a gas increases with temperature ata nearly linear rate, as shown in Figure.  V = Vo(1+βT)  where V is the volume at temperature *T* and V0 and β are constants. The experimental result is that β is the same for all gases. If *T* is measured in degrees Celsius, β has the experimental value of 1/273.15°C. |  |

However, all gases liquefy at lowtemperatures (for example, oxygen liquefies at-183oC), so the graph cannot beextended below the liquefaction point.

Nonetheless, the graph is essentially astraight line and if projected to lower temperatures, as shown by the dashed line,it crosses the axis at about -273oC. Such a graph can be drawn for any gas, and a straight line results whichalways projects back to -273oC at zero volume. This seems to imply that if a gascould be cooled to -273oC, it would have zero volume, and at lower temperaturesa negative volume, which makes no sense. It could be argued that -273oC is the lowest temperature possible; indeed, many other more recent experimentsindicate that this is so. This temperature is called the **absolute zero** of temperature.Its value has been determined to be -273.15oC.

Absolute zero forms the basis of a temperature scale known as the **absolutescale** or **Kelvin scale**, and it is used extensively in scientific work. On this scalethe temperature is specified as degrees Kelvin or, preferably, simply as **kelvins** (K)without the degree sign.

Thus we state:

***The* v*olume of a fixed quantity of gas is directly proportional to the absolute temperature* w*hen the pressure is kept constant*.** This is known as**Charles’s law**, and is written

or (if *P* = constant)

where the subscripts 1 and 2 refer to different physical states of the same sample of gas with the preture held constant.

A third gas law, known as **Gay-Lussac’s law**, after Joseph Gay-Lussac(1778–1850), states that:

***At constant* v*olume, the absolute pressure of a fixed quantity of a gas is directly proportional to the absolute temperature*:**

or (if *V* = constant)

where the subscripts 1 and 2 refer to different physical states of the same sample of gas with the volume held constant.

1. **The Equation of state of Ideal Gas.**

Boyle's law and the law of Charles and Gay-Lussac are special cases more general expression called the**ideal gas law.** It can be inferred from them and is usually written

PV = nRT

An equation that links the pressure, volume, and temperature of a sample of matter is called an**equation of state.**

Here, as before, P, V, and T stand for pressure, volume, and temperature, respectively.

**R** is a constant that is the same for all gases, and so is called the **universal gas constant.** If pressure is measured in the SI unit of Pascals, volume in cubic meters, and temperature in Kelvins, then**R** has the value

*R =* 8.314 Joule/mole⋅K.

The **quantity of gas**, measured in moles, is given by **n**.

A **mole** is the amount of material whose mass in grams is numerically equal to the molecular mass of the substance.

The “mole” is an official SI unit for the amount of substance. One **mole**(abbreviated mol) is the amount of substance that contains 6.02∙1023objects(usually atoms, molecules, or ions, etc.). This number is called *A*v*ogadro’s number*(*NA*). Its value comes from measurements. The mole’sprecise definition is the number of atoms in exactly 12 grams of carbon-12.

We will often speak of the relative masses of individual atoms and molecules - what we call the **atomic mass** or **molecular mass**, respectively. (The terms *atomic*w*eight* and *molecular* w*eight* are sometimes used.) These masses are based onarbitrarily assigning the most abundant form of carbon atom,12C, the atomicmass of exactly 12.0000 **unified atomic mass units** (u). In terms of kilograms,

1u = 1.6605∙10-27 kg.

The average atomic mass of hydrogen is 1.0079 u, and the values for otheratoms are as listed in the Periodic Table of elements.

***IDEAL GAS LAW in terms of molecules***

Since the total number of molecules, *N*, in a gas is equal to *NA* times the numberof moles (*N = nNA*), then the ideal gas law can be written in terms of the number of molecules present:

or

*PV = NkT*

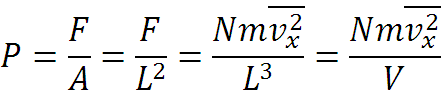
where *k = R/NA*is called the **Boltzmann constant** and has the value

1. **The Kinetic-Theory of gas. The Kinetic-Theory Definition of Temperature.**

In the kinetic theory of gases, we assume that a gas consists of many particles. Here "many" means so numerous that we cannot hope to trace out their individual paths. If we do not treat the molecules individually, then we must determine their average behavior. This implies that we need to develop a statistical theory that includes the rules of probability.

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| We start by considering an ideal gas confined to a cubical box with sides of length *L.*  Consider a molecule of mass *m* moving parallel to the *x* axis in the positive direction.  The average momentum change per unit time at face *A* is    The total force due to N molecules is    where the bar indicates, as before, the average of that quantity. | D:\XAZAR\Course Physics 1\1 Class 23,24 Lecture 16,17\gas_molecules.gif |

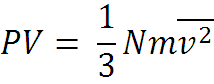
By dividing both sides of the equation by the area of the face A = L2, we have the pressure P:



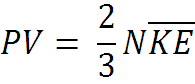
or



Because  we get:



Sincethe average kinetic energy per molecule is *1/2 mv2*, we have:



The quantities on the left-hand side of these equations are macroscopic (large-scale) quantities. The quantities on the right-hand side are microscopic (molecular-scale) variables. We have derived an expression linkingthe microscopic,andgenerallyunobservable,properties of molecules, such as their masses and speeds, with the easily observed large-scaleproperties, such as pressure and volume.

Combine the last equation with equation of state of ideal gas

From here we can state that:

This equation tells us that:

**The average translational kinetic energy of molecules in random motion in anideal gas is directly proportional to the absolute temperature of the gas.**

The higher the temperature, according to kinetic theory, the faster the moleculesare moving on average. This relation is one of the triumphs of kinetic theory.

1. **The Barometric Formula**

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| We wish to find an expression for pressure as a function of height.  Starting at some point in midair, the change in pressure associated with a small change in height can be found in terms of the weight of the air. If we take an arbitrary gas column with intersection area S and height h, then the weight of this column is given by:  F=mg=ρgV=ρghS,  whereρis the gas density. | Похожее изображение |

Then the gas pressure is expressed by the following formula:

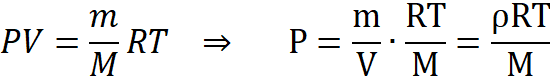
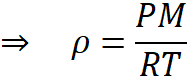
P= F/S= ρghS/S=ρgh.

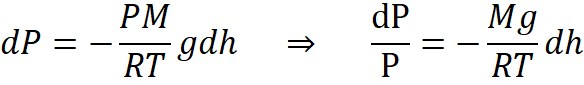
Now imagine such a column in the atmosphere and separate a thin layer of air with the height dh. It’s clear that such a layer causes the pressure change by the value of

*dP=−ρgdh.*

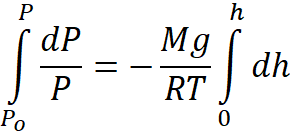
We have put the minus sign because the pressure must decrease as the altitude increases.

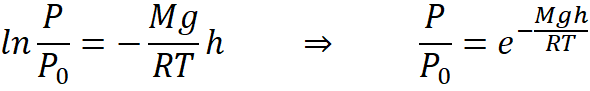
Considering atmospheric air as an ideal gas, we can use the ideal gas law to express the density ρ through pressure P:



We obtain a differential equation describing the gas pressure P as a function of the altitude h. Integrating gives the equation:





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| where we use, that *M/R =m/k*    where P0 - the pressure at height h = 0  P - the pressure at height h = z  m - the mass of one molecule  g - free fall acceleration  *k* - the Boltzmann constant  *e* - an irrational number with a value approximately equal to 2.718. | | Картинки по запросу barometric formula |
| Похожее изображение | http://hyperphysics.phy-astr.gsu.edu/hbase/Kinetic/imgkin/barf2.gif | |

We may also express this equation in terms of the number density n, the number of molecules per unit volume. We can do so because at constant temperature, the pressure and density of an ideal gas are proportional. Thus



This equation also is called the*barometric formula.* It gives the number of molecules per unit volume as a function of height **z** in our idealized atmosphere.

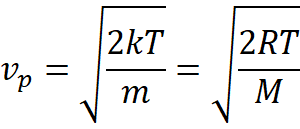
1. **Distribution of Molecular Speeds.**

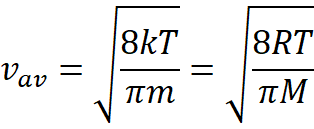
We have considered only the average speeds of molecules. However, there are times when we need to know the distribution of the molecular speeds in a gas.

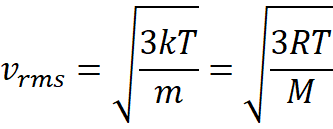
By distribution we mean a mathematical expression that tells us what fraction of the molecules have speeds in a given range.

The problem of the distribution of molecular speeds was first solved by James Clerk Maxwell (1831-1879) in 1860. Maxwell's significant contribution was the introduction of statistical ideas into classical mechanics.

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| The **Maxwell-Boltzmann distribution** function:    where *f(v)* is the fraction of molecules that have speeds between *v* and*v + Δv.*  m - the mass of one molecule  T - temperature  *k* - the Boltzmann constant  *e* - an irrational number | D:\XAZAR\Course Physics 1\1 Class 23,24 Lecture 16,17\KinTheoryGas05.gif |

Most probable speed:

Average speed:

 Root mean squired speed:

|  |  |
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| Figure represents speed distribution curves for different temperatures. The peak in each curve shifts to the right as *T increases, indicating that the average speed increases with increasing* temperature, as expected.  Because the lowest speed possible is zero and the upper classical limit of the speed is infinity, the curves are asymmetrical. | D:\XAZAR\Course Physics 1\1 Class 23,24 Lecture 16,17\maxwell.jpg |

The speed distribution curves for molecules in a liquid are similar to those shown in Figure. We can understand the phenomenon of evaporation of a liquid from this distribution in speeds, given that some molecules in the liquid are more energetic than others. Some of the faster-moving molecules in the liquid penetrate the surface and even leave the liquid at temperatures well below the boiling point.

The molecules that escape the liquid by evaporation are those that have sufficient energy to overcome the attractive forces of the molecules in the liquid phase. Consequently, the molecules left behind in the liquid phase have a lower average kinetic energy; as a result, the temperature of the liquid decreases.

Hence, evaporation is a cooling process. For example, an alcohol-soaked cloth can be placed on a feverish head to cool and comfort a patient.

**Fundamentals of Physics Lecture 6. Heat and Calorimetry. Thermodynamics.**

1. **Internal energy. The First Law of Thermodynamics. State variables. Reversible and irreversible processes.**

A **thermodynamic system** is any collection of objects considered together; the rest of the universe is the environment of the system.

A thermodynamic system interacts with its surrounding environment by heat transfer and/or work.

As a result of this energy exchange with the environment, the system's internal energy may change. By **internal energy** ***U*** we mean the total kinetic and potential energy associated with the internal state of the atoms composing the system.

Be sure you understand the differences among *temperature*, *internal energy,* and *heat.*

**Temperature** is a measure of the warmth of an object; as we said in previous lecture, on an atomic level it is determined by the average random kinetic energy of the object's atoms.

**Internal energy** is the sum of the kinetic and potential energies of the internal motion of all the atoms in the object.

**Heat** is the transfer of energy to or from an object either by changing the kinetic energy of the atoms (changing an object's temperature) or by changing the potential energy of the atoms (changing an object's phase).

In the usual formulation of the first law of thermodynamics, we consider the transfer of heat into a system, the work performed by the system, and the change in the system’s internal energy. If we let *Q* be the net amount of heat flowing into a system during some process and W be the net work done *by* the system, then conservation of energy gives

*Q = W + ΔU*

where ΔU is the change in the system’s internal energy, W - work done by a system.

Upon rearranging, we find: *ΔU = Q – W*

In words:

**The change in internal energy of a system equals the difference between the heat taken in by the system and the work done by the system.**

Let's us apply first law to various isoprocesses.

**Isothermal process.** If the temperature of a system does not change during a process**.** For ideal gas it means no changing in internal energy *ΔU =0*.

Therefore, from the first law, the heat absorbed by the system must equal the work done by the system:

Q = W

**Adiabatic process.** No heat enters or leaves the system during process, then the system is perfectly isolated from its environment.

A good approximation to an adiabatic process is anything that happens so rapidly that heat does not have time to flow in or out of the system, as in the rapid compression of air in a tire pump.

If Q = 0 the first law is:

ΔU = - W

Thus the change in internal energy is the negative if the positive work done by the system.

Note that most processes in nature are neither strictly adiabatic nor strictly isothermal, but we can approximate many processes by treating them as one or the other, or as one followed by the other.

**Isochoric process (or isovolumetric).** A process in which the volume of the system does not change.Heating a gas in a tightly sealed container is an example of such a process.

In a process that goes forward at constant volume, no displacement can take place, so the work done by the system is zero. Then, from the first law, we have only two terms:

Q = ΔU

Any heat added to the system goes into increasing its internal energy.

**Isobaric process.** The pressure does not change during a process.

One example of an isobaric process is the boiling of water in an open container. Since the container is open, the process occurs at constant atmospheric pressure. At the boiling point, the temperature of the water no longer increases with the addition of heat; instead there is a change of phase from water to steam.

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| In case of constant pressure work done by a gas can be found easily. Figure shows a cylinder of gas fitted with a piston. If the gas pushes the piston out an amount *Δx,* the increment of work done F*Δx* can be written in terms of the pressure *P* and the change in volumeΔV:    *W = PΔV*  And the first law gives:  *Q = PΔV + ΔU*  Heat delivered to the system goes to increase its internal energy and produce some work. | D:\XAZAR\Course Physics 1\1 Class 21 Lecture 15\Figure_16_02_04a.jpg |

**A state variable.** A state variable is a physical property that characterizes the state of a system independently of how that particular state is reached.

For example, a cup of tea that is at room temperature has the same temperature whether it cools from boiling temperature or is heated from freezing temperature; temperature T is a state variable. Pressure P and volume V are also state variables.

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| Under some conditions, two state coordinates completely specify the thermodynamic state of a system.  Then we can represent any possible state by a point on a two-dimensional plot.  Transfer the system from one state to another can be realized by a variety of ways, transferring the amount of heat to the system and produce the work over system. Therefore, the amount of *heat Q* added to or released by a thermodynamic system is not a state variable, it depends on transfer path.  Although the *work W* done by a system often does involve state variables, such as *"W=PΔV* " done by a gas, work itself is not a state variable. | D:\XAZAR\Course Physics 1\1 Class 21 Lecture 15\images.jpg |

An interesting aspect of the first law is that it asserts that the *internal energy* of a system is a state variable. The internal energy difference between the heat into a system and the work done by that system does not depend on the details of how that heat was added or how that work was done.

An important goal of thermodynamic studies is to consider systems in different thermodynamic states and follow the changes in the state variables as the systems undergo changes. However, thermodynamic state variables are meaningful only for systems in equilibrium. For example, when a large sample of gas undergoes a rapid expansion, the temperature and pressure may fluctuate from place to place within the gas.

In a **reversible** process, the system undergoing the process can be returned to its initial conditions along the same path on a *PV* diagram, and every point along this path is an equilibrium state. A process that does not satisfy these requirements is **irreversible.**

**A reversible process** is a process in which the system is very nearly in equilibrium all the time.

A reversal of the controlling factors causes the system to exactly retrace its path in the opposite direction, back to its initial state.

Alternatively, we can say that a reversal of the controlling factors causes a reversal of the energy transformation. There is no wasted energy.

Reversible processes are allowed by the first law of thermodynamics and *we will* use *them as* examples of how to think about thermodynamic processes.

However, a reversible process cannot take place **if friction or any other form of energy loss** is present.

That is, each of the processes (say, during expansion of the gases against a piston) was done so slowly that the process could be considered a series of equilibrium states, and the whole process could be done in reverse with no change in the magnitude of work done or heat exchanged. A real process, on the other hand, would occur more quickly; there would be turbulence in the gas, friction would be present, and so on. Because of these factors, a real process cannot be done precisely in reverse—the turbulence would be different and the heat lost to friction would not reverse itself. Thus, real processes are **irreversible**.

1. **Heat Transfer. Calorimetry. The Molar Specific Heats of Gases.**

Heat transfer takes place in three ways: conduction, convection, and radiation.

In table you can find comparison between these processes.

|  |  |  |
| --- | --- | --- |
| **Conduction** | **Convection** | **Radiation** |
| Relatively slow process | A more rapid process | A still more rapid |
| Heat energy is transferred without any net movement of the material itself. | Is accomplished through the mass motion or flow of some fluid | Realize by electromagnetic radiation (as a light radiation) |
| Environment is necessary. Not occur in a vacuum. | Environment is necessary. Not occur in solids and vacuum. | This process requires neither contact nor mass flow, nor any environment, and can pass through empty space (a vacuum). |

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| **Conduction.** Suppose we imagine a wall of uniform material, which separates a warm room from a cold one. After a period of time, a steady temperature change occurs across the wall and a steady flow of heat goes from the warmer room to the cooler one. The time rate at which heat flows *(ΔQ/Δt)* through the wall is proportional to the area *A,* proportional to the temperature difference (T2 - T1), and inversely proportional to the thickness L of the wall. | D:\XAZAR\Course Physics 1\1 Class 20 Lecture 14\Conduction_2.JPG |

*K* - the **thermal conductivity [**W/m·K]

A **–** area

L - thickness L of the wall

T2 and T1 – the wall temperature on the hot and cold side, respectively

A high thermal conductivity indicates a good heat conductor; a low thermal conductivity indicates a good heat insulator.

The effectiveness of insulation is rated by another quantity, called **thermal resistance**, or *R* value. The **R value** is the ratio of a material's thickness to its thermal conductivity: R ≡ L/K

**Radiation.** The rate at which an object radiates energy is proportional to its surface area A and to the fourth power of its absolute temperature T. The total energy radiated from an object per unit time is

P = σeAT4 the **Stefan-Boltzmann** law

*σ* *=* 5.67 x 10 -8 W·m-2K-4 is the Stefan-Boltzmann constant,

e - is a constant called the *emissivity.* The emissivity is a dimensionless number between 0 and 1 that describes the nature of the emitting surface. The emissivity is larger for dark, rough surfaces and smaller for smooth, shiny ones.

For example. The book in your hand is radiating, but it is also absorbing radiation from its surroundings. If the book (or other object) is at a temperature **T** and its surroundings are at a different temperature **Ts**, the net energy gained (or lost) by the book is given by

Pnet = σeA(T4 – Ts4)

where ***A*** is the surface area of the book.

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| **Convection.** Because of the mathematical complexities, the details of convection will be left to more advanced work. | D:\XAZAR\Course Physics 1\1 Class 20 Lecture 14\convection.bmp |

**Calorimetry.** The measurement of quantities of heat exchanged, a process known as *calorimetry,* was introduced in the late 1700s.

The **specific heat capacity**, or simply the **specific heat,** is **the heat required per unit mass to change the temperature of a substance by one Kelvin.**

The amount of heat Q required to warm an object of mass m by raising its temperature ***ΔT*** is given by

**Q = mc *ΔT***

The units of specific heat is J/kg·K.

When we use this convention, *ΔT* is always Tfinal - Tinitial. A negative value of *ΔT* means that heat has left the body.

**Heat capacity,** which is the amount of heat required to change an object’s temperature by 1K.

**Q = C *ΔT***

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| The transformation from one physical state to another takes place with *no change in temperature* and is called a change of phase.  The heat absorbed or released with a phase change is called the **heat of transformation** (sometimes the *latent heat of transformation)* L, and this heat defined as the ratio of the amount of heat Q absorbed (or released) to the mass m of material undergoing the phase change:  **L = Q/m.**  We can express the heat absorbed (or released) in terms of L:  **Q = m·L**  Heats of transformation are expressed in units of [J/kg]. | D:\XAZAR\Course Physics 1\1 Class 20 Lecture 14\heat and temp phase change graph.gif |

If the phase change is from the solid to the liquid phase (or from the liquid to the solid), we refer to the **heat of fusion;** for the liquid-vapor phase change we use the term **heat of vaporization.** The energy added (or removed) in the form of the heat of transformation goes into rearranging the internal structure of the substance.

For example, when a solid becomes a liquid, energy is required to overcome the forces that keep the material in the solid state.

In the case of gases, it is convenient to use a molar specific heat (sometimes called the molar heat capacity), which is the heat needed to raise one mole of a substance through one Kelvin. We will mark molar specific heat as **C**.

We saw that the relationship between the change in temperature *ΔT* of a mole n with specific heat *C* and the heat added Q is

Q = nCΔT

However, for a gas, we must define two specific heats. The amount of heat needed to raise the temperature of a gas by one degree depends on whether the volume of the gas is kept constant or allowed to expand.

We therefore introduce Cv, the **molar specific heat at constant volume,** and Cp, the **molar specific heat at constant pressure.**

Use the first law of thermodynamics.

Q = ΔU + W

If the volume does not change, then no mechanical work is done by the gas and all the heat goes into changing of internal energy. Thus

Q = ΔU

The heat added is related to the temperature change by

Q = *nC*vΔT

Comparison of these two equations gives

*ΔU =* nCv *ΔT.*

For an ideal gas, the internal energy is due solely to the kinetic energy of the molecules. Thus the change in internal energy may be obtained from:

3/2nRΔT = nCvΔT

This equation can be simplified to give

Cv = 3/2R = 12.47 J/mol·K

**Note** that our model assumes elastic collisions and does **not** consider **rotations** **or vibrations** of the molecules.

If the expansion is carried out at constant pressure the first law of thermodynamics is

*ΔU = Q - P ΔV*

We know that:

*ΔU = nC*v *ΔT* Q = *nCp ΔT P ΔV = nR ΔT*

Substitution of these equations in the first law of thermodynamics gives

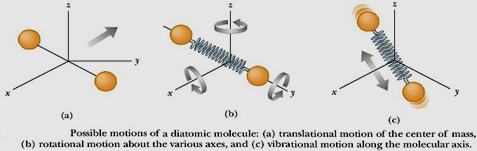
*nC*v *ΔT = nCp ΔT - nR ΔT*

Upon simplification we see that *Cp -* Cv = R.

For an ideal gas, we can see that Cp = 5/2 R = 20.79 J/mol·K.

Generally for ideal gas it is assumed that molecules are monatomic and the sole contribution to the internal energy of a gas is the translational kinetic energy of molecules in 3 dimensions.

However, diatomic molecules can also rotate about 2 axes and vibrate relative center of mass of molecule



Recall that the Equipartition energy theorem states that at equilibrium each degree of freedom contributes, on the average, ½ *kT* of energy per molecule. For diatomic molecules:

*i*tran = 3 translational freedom degree;

*i*rot = 2 rotational freedom degree;

*i*vib = 1 vibrational freedom degree.

Total degree of freedom: *i* = *i*tran + *i*rot + 2*i*vib

Here we take in total degree of freedom vibrational degrees of freedom 2 times, because of vibration consist of 2 energies: kinetic and potential.

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| Therefore:  and  The ratio of these heat capacities is a dimensionless quantity γ given by: γ = CP/Cv  However, how we observe in experiments, activated degree of freedom depends on temperature. For example CV for diatomic hydrogen H2 gas at temperatures below 200 K is 3/2R, at range 250 K to 750 K is 5/2R and at temperatures above 1000 K is 7/2R. |  |

1. **Adiabatic process.**

An **adiabatic process** is one in which no energy is transferred by heat between a system and its surroundings.

For example, if a gas is compressed (or expanded) rapidly, very little energy is transferred out of (or into) the system by heat, so the process is nearly adiabatic. Another example of an adiabatic process is the slow expansion of a gas that is thermally insulated from its surroundings.

All three variables in the ideal gas law (*P*, *V*, and *T)* change during an adiabatic process.

First Law of Thermodynamics for adiabatic process:

Q = 0 dU = - W

Let’s imagine an adiabatic gas process involving an infinitesimal change in volume *dV* and an accompanying infinitesimal change in temperature *dT*. The work done by the gas is: *W =* *P dV*.

Because the internal energy of an ideal gas depends only on temperature, the change in the internal energy in an adiabatic process is the same as that for an isovolumetric process between the same temperatures,

*dU =* *nCV dT* dU = - W *nCV dT = -PdV*

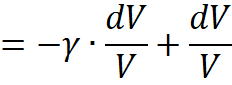
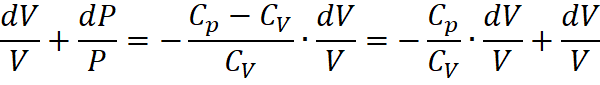
Taking the total differential of the equation of state of an ideal gas, *PV =* *nRT*, gives

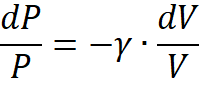
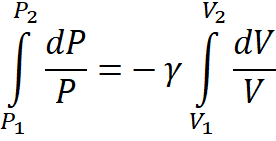
*P dV +* *V dP* = *nR dT*

Eliminating *dT* from these Equations, we find that

*P dV* + *V dP =-RPdV/CV*

Substituting *R =* *CP* - *CV* and dividing by *PV* gives



|  |  |
| --- | --- |
| ln *P2/P1 =* - ln (*V2/V1)γ*  which is equivalent to    or *P1* ∙*V1γ = P2*∙*V2γ =Constant*  Because γ > 1, the *PV* curve is steeper than it would be for an isothermal expansion, for which *PV* = constant. | Картинки по запросу The PV diagram for an adiabatic expansion |

By the definition of an adiabatic process, no energy is transferred by heat into or out of the system. Hence, from the first law, we see that ΔU is negative (work is done *by* the gas, so its internal energy decreases) and so Δ*T* also is negative. Therefore, the temperature of the gas decreases (*T2* < *T1*) during an adiabatic expansion. Conversely, the temperature increases if the gas is compressed adiabatically.

Using the ideal gas law, we can express Equation of adiabatic process as

*T1* ∙*V1(γ-1) = T2*∙*V2(γ-1) =Constant*

|  |  |
| --- | --- |
| *PV* curves for Isothermal, Adiabatic, Isochoric and Isobaric Processes | A comparison of the final temperatures with the initial |
| Картинки по запросу The PV diagram for an adiabatic expansion | Картинки по запросу The PV diagram for an adiabatic expansion |

**Fundamentals of Physics Lecture 7. Calorimetry. Real gases.**

1. **Heat engines**

A **heat engine** is a device that takes in energy by heat and, operating in a cyclic process, expels a fraction of that energy by means of work. For instance, in a typical process by which a power plant produces electricity, a fuel such as coal is burned and the high-temperature gases produced are used to convert liquid water to steam. This steam is directed at the blades of a turbine, setting it into rotation. The mechanical energy associated with this rotation is used to drive an electric generator. Another device that can be modeled as a heat engine is the internal combustion engine in an automobile. This device uses energy from a burning fuel to perform work on pistons that results in the motion of the automobile.

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| It is useful to represent a heat engine schematically as in Figure. The engine absorbs a quantity of energy |*Qh*| from the hot reservoir. For the mathematical discussion of heat engines, we use absolute values to make all energy transfers by heat positive, and the direction of transfer is indicated with an explicit positive or negative sign. The engine does work *W*eng (so that *negative* work *W* = -*W*eng is done *on* the engine) and then gives up a quantity of energy |*Qc*| to the cold reservoir.  The **thermal efficiency** *e* of a heat engine is defined as the ratio of the net work done by the engine during one cycle to the energy input at the higher temperature during the cycle: | Картинки по запросу Schematic representation of a heat engine. |

This Equation shows that a heat engine has 100% efficiency (*e* = 1) only if |*Qc*| = 0, that is, if no energy is expelled to the cold reservoir. In other words, a heat engine with perfect efficiency would have to expel all the input energy by work. Unfortunately, for example, a good automobile engine has an efficiency of about 20%, and diesel engines have efficiencies ranging from 35% to 40%.

1. **The Carnot Cycle and the Efficiency of Engines**

It was important to regulate an engine to develop its maximum power output and to determine what that output was.

Watt accomplished this with a technique he developed and used privately for many years. Though steam engines were considerably improved by Watt and others, the basis for understanding the general principles of heat engines did not come until 1824, when the French engineer Sadi Carnot (1796-1832) published a treatise on this subject.

In doing so, Carnot formulated the basic ideas of thermodynamics. He said that *all* movements were ultimately due to heat. It made no difference whether they occurred in natural phenomena, such as rain, storms, earthquakes, and volcanoes, or in mechanical devices such as steam engines.

Carnot proposed an ideal heat engine that operates cyclically and reversibly between two temperatures.

The ideal Carnot engine sets an upper limit on the efficiency of all real engines, including steam engines, Diesel and gasoline (Otto) engines, jet engines, and nuclear reactors. Furthermore, studies of the theoretical Carnot engine indicate some of the factors that affect the efficiency of real engines.

**Carnot engine consists:**

1. Cylinder containing the working substance.
2. A hot body of infinite thermal capacity, called a *heat reservoir,* supplies heat. (This reservoir can be approximated by any source of heat)
3. The cold body, called a *heat sink,* is also of infinite thermal capacity so that it can absorb heat without raising its own temperature. (This sink can be approximated by any large body, such as the ocean)

The **Carnot cycle** consists of four reversible processes, two isothermal and two adiabatic:

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| *Step 1.* We start the cycle with the cylinder in contact with the heat reservoir, where the working substance (gas) takes in an amount of heat Qh at a high temperature TH.  *Step 2.* The cylinder is then moved to the insulating body, where the heat input is zero. The load on the piston is reduced and the gas is allowed to expand, this time along an adiabatic curve (B to C).  *Step 3.* Next the cylinder is moved to the heat sink. Here the gas undergoes an isothermal contraction (С to D) in which an amount of heat Qc expelled to the cold reservoir at temperature Tc. | *D:\XAZAR\Course Physics 1\1 Class 21 Lecture 15\therm_carnot_fig1.jpg* |

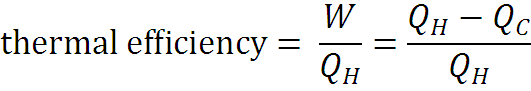
*Step 4.* In the final step of the Carnot cycle, the cylinder is moved back to the insulating body. The load on the piston is increased and the gas undergoes an adiabatic compression (D to A).

By the first law of thermodynamics, the work done must equal the net heat flow into the cylinder:

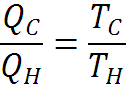
W = QH - QC

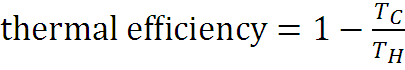
Where QH and QC are taken to be positive quantities. The process is shown schematically in.

We define the **thermal efficiency** of any system, such as a machine, to be the ratio of the work done to the heat input:



For an ideal gas the internal energy is proportional to the Kelvin temperature.

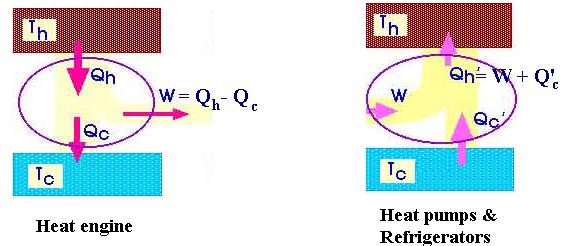




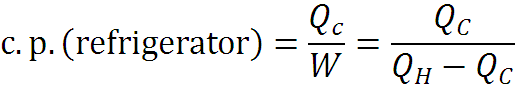
1. **Heat Pumps and Refrigerators**

By reversing the direction of the Carnot cycle, we can put work into the system and transfer heat from a low temperature to a higher one. A system operated in this manner is called a **refrigerator.**

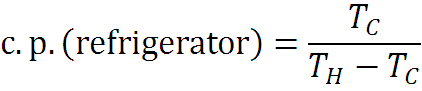
An air conditioner is a refrigerator that is designed to take heat from within a house and exhaust it to the outdoors. When such a system is reversed so that it cools the outdoors and delivers heat to the inside of the house, it is called a **heat pump.**



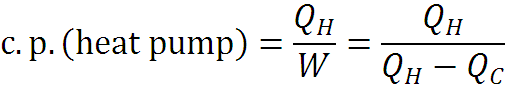
The coefficient of performance (c.p.) of **refrigerator**:



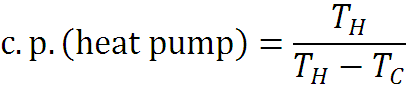
with ideal gas as the working substance, this becomes

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The coefficient of performance of a **heat pump** is defined to be the ratio of the heat delivered inside the house (the high temperature reservoir) to the work supplied:



In terms of temperatures, the coefficient of performance becomes



1. **The Second Law of Thermodynamics.**

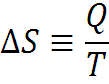
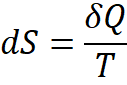
**There are three formulations of the second law:**

1. **Clausius statement of the second law:** Heat cannot, by itself, pass from a colder to a warmer body.
2. **Kelvin statement of the second law:** It is impossible for any system to undergo a cyclic process whose *sole* result is the absorption of heat from a single reservoir at a single temperature and the performance of an equivalent amount of work.
3. **Entropy and second law of thermodynamics.**

We can gain additional insight into the meaning of the second law of thermodynamics by considering it from a standpoint first introduced by Clausius in 1850. He introduced a new thermodynamic state variable called***entropy****,* which has two Greek roots and means much the same as "turning into “.

**Entropy** is a measure of how much energy or heat is unavailable for conversion into work.

When a system at Kelvin temperature *T* undergoes a *reversible* process by absorbing an amount of heat Q, its increase in entropy ΔS is

 or 

Notice that we are defining entropy for a reversible process, which does not occur in nature. However, for our purposes, we can use this definition for processes that are approximately reversible.

3. A more generalization principle, discovered by Clausius:***In any process the entropy of the system increases or remains constant.***

(This is another way of expression of the *second law*.) Entropy remains constant only in the case of reversible processes.

If we have two bodies at different temperatures - say, a hot stove and a block of ice - we can connect a heat engine between them and extract useful work.

If, instead, we place the two bodies in direct thermal contact, they will come to thermal equilibrium. In agreement with the first law of thermodynamics, the total energy content of the stove and the ice is the same before contact as that of the stove and water (melted ice) after they have been placed in contact.

However, once they reach equilibrium, we cannot separate them again and expect to extract work from them with a heat engine. Something has changed, even though the total energy has not. What has changed is the availability of the energy to do work. An increase in entropy means a decrease in the energy available to do work, not a decrease in the total energy.

Ludwig Boltzmann (1844-1906) showed that an increase in the entropy of a system or substance corresponds to an increased degree of disorder (chaos) in the atoms or molecules composing the substance. The most probable—that is, the most statistically favored arrangement of molecules is the one with the most molecular disorder.

If the entropy principle is true throughout the universe, we can envision sometime in the far distant future when everything m the universe will have reached a uniform temperature. No heat could flow, no work could be done, and no change in energy or motion could take place. Neither engines nor plants nor animals would be able to extract energy. This possible occurrence is often called the***heat death of the universe****.*

There are several approaches to solving, or at least lessening, the problem of thermal pollution. One approach in which active research is going on is the development of alternative energy sources. The techniques being studied include the harnessing of wind power, tidal power, solar power, ocean temperature differences, and a host of other ingenious ideas. A second approach to reducing thermal pollution involves measures for saving energy, from better building insulation to smaller, more efficient cars.

1. **The Van der Waals Equation.**

The agreement between the observed and predicted behavior of real gases is good near atmospheric pressure and ordinary temperatures.

Deviations from the predictions are greatest when the pressure is very great or the temperature is very low.

At the extremes of these conditions, the gases condense to liquids.

We can take account of certain types of molecular interactions and of the nonzero size of the molecules by making modifications to the equation of state of an ideal gas.

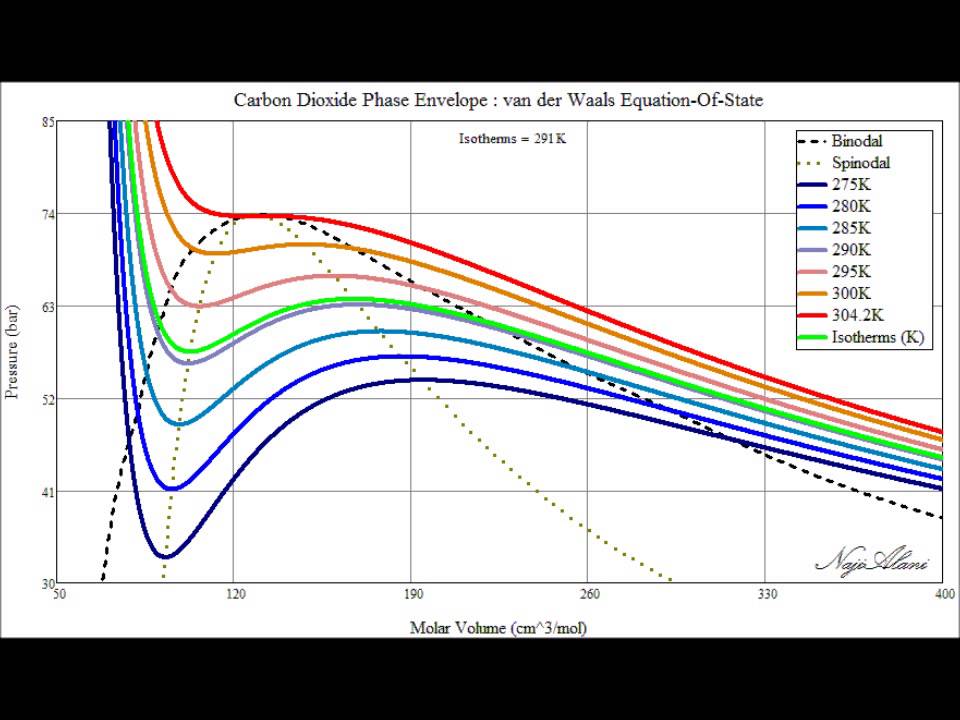
The first major step in this direction was taken in 1873, when the Dutch physicist J. D. van der Waals (1837-1923)

(P + *a*n2/V2)(V – nb) = nRT

This equation, called the **van der Waals equation.** The constant *b* is called the covolume and *nb* is of the order of magnitude of the volume actually occupied by the molecules.

The interaction between the molecules is taken into account in a very general way by the constant *a.* Both ***a*** and***b*** must be determined experimentally and are different for different gases.

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| Numerous attempts have been made to improve on the van der Waals equation. Many of these have brought better agreement, but not necessarily better understanding.  The difficulty of accurately representing the intramolecular forces is one of the principal difficulties. There is also the basic problem, mentioned before, that the laws of classical physics are not entirely correct for such small dimensions.  The lines of constant temperature are called isotherms. | | D:\XAZAR\Course Physics 1\1 Class 23,24 Lecture 16,17\Van_der_Waals_isotherms.gif |
| Картинки по запросу superheated liquid | Похожее изображение | |



**Fundamentals of Physics Lecture 8. Basic principles of electricity.**

1. **Electric charge. Coulomb’s law.**

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| The Greek word for amber is *electron*, and it is from this root word that we get our word electricity.  As we study electricity, we still use the concepts of mechanics, especially such ideas as the **conservation of energy** and the relationship between force and acceleration. | Картинки по запросу Электризация |

In fact, the nongravitational forces that were studied in mechanics, such as friction and Hooke's law, are actually due to electrical forces between molecules and atoms.

In solids the mobile charges are negative **electrons**. When electrons are removed from an object, positive charges remain. These consist of the nuclei of the atoms that make up the material. In solids the positive charges are not mobile.

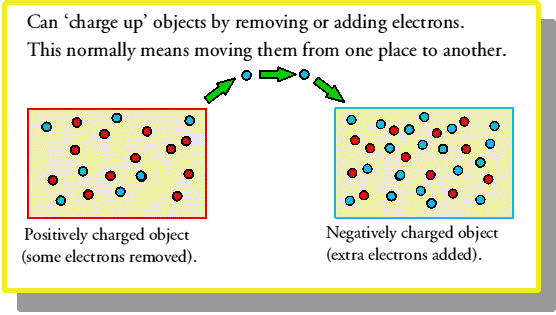
In liquids and gases, however, positive charges, too, are free to move.

On the electrical properties materials are divided into 3 groups:

1. A **conductor**is a material through which charge may flow easily;
2. An **insulator**is a material through which charge flows poorly or not at all.
3. A **semiconductors**, which are materials that are neither good conductors nor good insulators, but show a behavior intermediate between the two. All modern electronics is based on semiconductors

Macroscopic objects are nearly always electrically neutral. They have neither excess negative nor excess positive charge.

* we can give them a negative charge by adding extra electrons
* we can make them positive by removing electrons
* no charge is removed from any object except by being transferred to another object.



Law of conservation of charge: ***the total amount of electric charge* in *the universe remains constant***

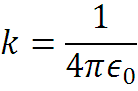
q1 + q2 + q3 + …+ qn = const

*single* *charges can be neither created nor destroyed.* This principle is one of the fundamental observations of nature, equal in importance to the conservation laws for energy, momentum, and angular momentum.

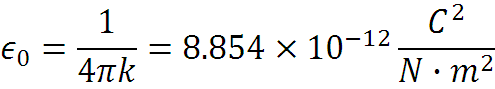
No violations of this principle have ever been observed. **Charges can be created** (and destroyed) **only in pairs of equal magnitude and opposite sign.**

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| In his experiments on electrical forces, Coulomb charged two small pith balls (pith is a light, spongy material from the center of plant stems) and measured the force between them  Coulomb: "The repulsive force between two small spheres electrified with the same type of electricity is inversely proportional to the square of the distance between the centers of the two spheres."  Coulomb also verified the inverse-square distance law for the attractive force between unlike charges.  The electrostatic force also depends on the product of the charges. Thus the magnitude of the force between two point charges is    where *q1* and *q2* are the values of the two charges, *r* is the separation between them, and *к* is a proportionality constant. This relationship is known as **Coulomb's law.** | **To measure the relatively small electrostatic forces, Coulomb used a torsion balance.** The torsion balance measured the electric force on the charged spheres in the same way that *Cavendish’s balance* measured the gravitational force. |
| The force is directed along the line joining the two charges. If both *q1* and *q2* arepositive, their product is positive and so *F* is positive, indicating a repulsive force. Similarly, if both charges are negative, *F* is again positive and the force is again repulsive.  However, if one charge is positive and the other negative, then *F* is negative, indicating an attractive force.  The force F1,2 exerted on charge q1 by charge q2 is equal in magnitude and opposite in direction to the force F2,1 exerted on charge q2 by charge q1  The SI unit for charge, the **coulomb** (C), is derived from the ampere. If we measure the amount of charge in coulombs and the separation in meters, then Coulomb’s law correctly gives the force in newtons if |  |

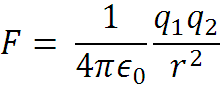
It is often convenient to define the constant in Coulomb's law to be



The quantity *ε₀*is known as the **permittivity of free space** and has the value



When the permittivity constant is used, Coulomb's law takes the form



The most fundamental unit of charge in nature is the charge of an electron or proton. This quantity is denoted by e, the elementary charge, which has the value

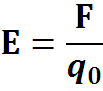
*e =*1.602⋅10-19*C*

Thus it takes about 6.24⋅1018 electrons to make one coulomb of charge.

Experimentally, it has been found that electrical charge always occurs in multiples of the elementary charge ***e***. For this reason we say that charge is *quantized;* that is, it occurs only in integer multiples of ***е****.*

1. **Electric field. Superposition principle.**

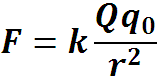
We define the **electric field E** at a point in space as the force **F** per unit charge exerted on a small positive **test charge** q0 placed at that point:



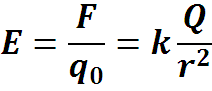
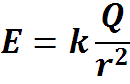
We choose the test charge q0 to be very small so that its presence does not distort the field being measured.

Thus the units of electric field are newtons per coulomb, N/C. The direction of the field vector is the direction of the force on a positive test charge.

Field of a single point charge Q that is isolated from other charges. The magnitude of **F** is



The magnitude of the electric field at point *r* is

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| If Q is a positive charge, then the field is directed radially away from it. If Q is negative, the direction of the field is toward it.  The relative number of lines of force is proportional to the magnitude of the force and hence to the strength of the field.  In an electrostatic field, lines of force always begin at positive charges and end at negative charges.  **Superposition of Electric Field**  Three charges produce an electric field in space. The field measured at point P is the vector sum of the individual fields. Net force acting to the test charge ***q0*** at point P is:    The electric field at P is found by dividing the force by the ***q0,*** obtaining |  |

In other words, the electric field resulting from several point charges is just the superposition of their individual fields.

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| **D:\XAZAR\Course Physics 2\electric-lines-of-force-mutual-repulsion.jpeg**  **Lines of electric field near two equal charges.** | **Lines of electric field near two equal but opposite charges.** |

1. **Electric Flux and Gauss’s law.**

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| The **electric flux** through a small portion of surface area ∆Ais the product of the magnitude of the electric field |E|, the magnitude of the surface area ∆A**,** and the cosine of the angle *θ* between the direction of the field and the direction of the normal to the surface. The electric fluxis then:  *ΔΦE = EΔAcosθ*  It is more convenient to use the area vector to describe the flux. |  |
| The area vector **A** is equal to the product of the area and normal vector **n,** where the normal vector is a unit vector perpendicular to the surface.  For non uniform field and complex shape of area we have to divide area to small elements. By using this we state that element of Electric flux *dΦE* is dot product of vector of electric field intensity and vector of Area element ***dA***: | ÐÐ°ÑÑÐ¸Ð½ÐºÐ¸ Ð¿Ð¾ Ð·Ð°Ð¿ÑÐ¾ÑÑ area vector physics |
| Summing the contributions of all elements gives an approximation to the total flux through the surface:  Where we take integral over all surface A.  We are often interested in evaluating the flux through a *closed surface,* defined as a surface that divides space into an inside and an outside region so that one cannot move from one region to the other without crossing the surface. | Картинки по запросу Electric flux |

The *net* flux through the surface is proportional to the net number of lines leaving the surface, where the net number means *the number of lines leaving the surface minus the number of lines entering the surface.* If more lines are leaving than entering, the net flux is positive. If more lines are entering than leaving, the net flux is negative. Using the symbol of an integral over a closed surface, we can write the net flux Φ*E* through a closed surface as:

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| Consider a point positive charge + q and spherical surface centered about the charge. The lines of electric field emerging from this charge *+ q* pass through the surface. The number of field lines passing through the surface is independent of the radius of the surface. Also we can see that electric field is equal at all points and perpendicular to the surface, so *θ = 0* and *cosθ = 1.* | ÐÐ°ÑÑÐ¸Ð½ÐºÐ¸ Ð¿Ð¾ Ð·Ð°Ð¿ÑÐ¾ÑÑ gauss law |

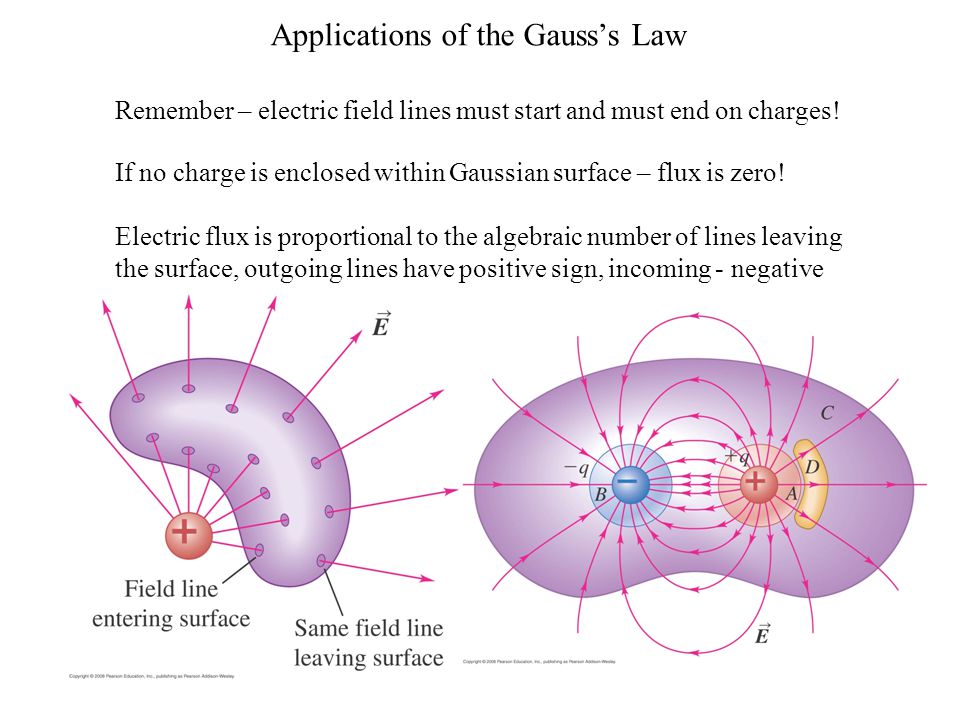
The integral over surface is equal to the area of sphere: *A* = *4πr2*. We know that the magnitude of the electric field everywhere on the surface of the sphere is

Substitute these in flux we get:

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| Gauss proved the law for a closed surface of any shape.  **The net electric flux through any (real or imaginary) closed surface is directly proportional to the net electric charge enclosed within that surface.**  Where Q - is net electric charge within surface. | Картинки по запросу Electric flux |

Gauss's law stands as one of the fundamental laws of electricity. The surface (usually imaginary) used for application of Gauss's law is often called a **Gaussian surface.**

The net amount of electric flux that passes through an arbitrary closed surface is directly related to the amount of electric charge inside that surface.



Gauss's law to prove an important assertion: **An excess charge placed on a conductor resides entirely on its outer surface.**

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| For example, if an excess charge is placed on an isolated conductor of any arbitrary shape, the charge sets up a field within the conductor. This field causes the mobile charges within the conductor to move about until the internal field reduces to zero. When the internal field reaches zero, the charge stops moving and the system is in static equilibrium. Thus for a charged conductor in equilibrium, the electric field inside the conductor must be zero.  The dashed line represents a Gaussian surface just inside the surface of a charged conductor, shown here in cross section. We can use Gauss's law to show that when a charged conductor has reached electrical equilibrium, any excess charge on the conductor must reside on its outer surface. |  |

1. **Electric potential. Equipotential surfaces.**

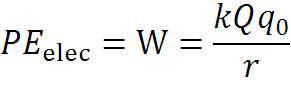
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| We develop the idea of electric potential by analyzing the work that is done and the change in energy that occurs when a charge is moved in an electric field. To move charge *q0* from *rB* to *rA*, electrostatic field applies a force and work done is: |  |

If the test charge is released from rest at *rB*, it will be in motion as it passes *rA* and will therefore have kinetic energy. From conservation of energy, we know that this kinetic energy must come from somewhere, which means that the work given by formula corresponds to an increase in potential energy of the test charge. Since the interaction is electrical we call this ***electrical potential energy.*** The work given by this equation corresponds to an increase in potential energy of the test charge.

The electrostatic force is a **conservative** force, just like the gravitational force, so the *work done does not depend on the path of the charge, but only on its starting and ending positions.*

The formula gives us the *difference* in electrical potential energy between two points in space due to a point charge. In establishing a zero of potential energy, we are free to pick any absolute reference potential that suits our convenience.

Traditionally, we choose the zero of potential to correspond to the case in which the charges are infinitely separated, that is, for *rA* = ∞. With this choice, the **electrical potential energy** of the test charge *q0* located a finite distance ***r*** away from a source charge Q is

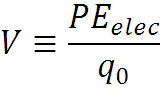


For a positive charge Q, the electrical force on a positive charge *q0* is repulsive and the potential energy is positive. However, if Q is negative, resulting in an attractive force between Q and *q0,* the electrical potential energy is negative.

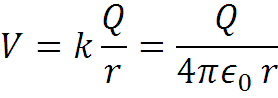
When the charges have the same sign the potential energy is positive and when the charges have unlike signs the potential energy is negative.

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| For example.  (a) A test charge *q0* located a distance *rA* from a source charge +*Q*.  (b) The test charge is moved a distance ∆*r* closer to source charge *Q,* which results in a change the potential energy.  Work done is negative (displacement directed opposite to force). Potential energy increase. |  |

We define the **electric potential** V at a point in an electric field as the electrical potential energy divided by the magnitude of the test charge *q0:*



The electric potential due to a point charge Q is obtained from the potential energy by dividing by *qo,*



If the charge Q is positive, the potential is positive, and if *Q* is negative, the potential is negative.

The electric potential at any point in space is defined to be the work per unit charge required to bring a charge from infinity to that point.

The unit of electric potential is the volt: **1 volt = 1 joule/coulomb.**

The electric potential due to two or more point charges is easily obtained. From the principle of superposition of forces, the work done in bringing a test charge from infinity can be separated into parts associated with the individual forces due to each single charge. The total work is the sum of these individual contributions. Because electric potential is a scalar, not a vector quantity, the potential at a given point in space is just the algebraic sum of the potential due to the separate source charges.

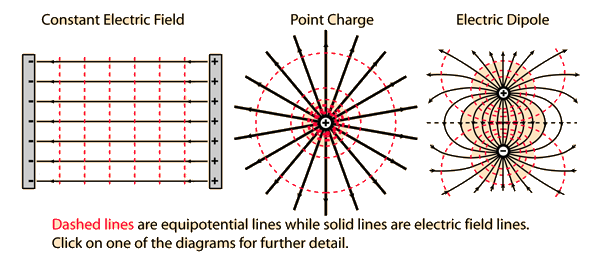
*Vtot = V1 + V2 + ... + Vn*

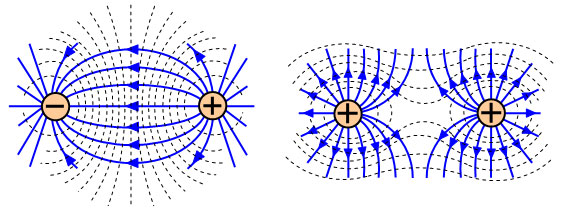
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| **Potential difference (Voltage)**  Often, the quantity of interest is not the absolute potential, but the potential difference between two points. The **electric potential difference** is the ratio of the work required to move a charge from one point to another to the magnitude of the charge. The potential difference between points *A* and В is | ÐÐ¾ÑÐ¾Ð¶ÐµÐµ Ð¸Ð·Ð¾Ð±ÑÐ°Ð¶ÐµÐ½Ð¸Ðµ |

Since the potential is measured in volts, the potential difference is also measured in volts. For this reason we often refer to a potential difference as a voltage.

Many times, the potential difference is taken with reference to the *ground* (earth), which we generally choose as the zero potential.

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| A test charge q0 changes potential energy when moving along a radial path away from a fixed charge Q, but not when moving in a circular path about Q. The circular path is an equipotential line.    Any surface for which all points are at the same potential is called an **equipotential surface.** |  |





Each equipotential surface represents a different potential, decreasing in magnitude with increasing distance from the source charge. The choice of specific potentials is arbitrary; An equipotential surface can be drawn through any point in the field.

Equipotential surfaces may be drawn corresponding to any given configuration of electric field. We construct the contours of the equipotential surfaces by making them everywhere perpendicular to the electric field vector (or lines of force).

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| **Electric Potential Gradient**  We can determine the electric field from the knowledge of the potentials.  For example, suppose we wish to move a test charge **q0** from one equipotential surface to another along a path *dr.*If the potential increases by d*V***,** we must do an amount of work:  *dW = qodV*  If the path is perpendicular to the equipotential surfaces, then it must lie along the direction of the electric field present in that region of space. | ÐÐ¾ÑÐ¾Ð¶ÐµÐµ Ð¸Ð·Ð¾Ð±ÑÐ°Ð¶ÐµÐ½Ð¸Ðµ |

So, we can also calculate the work done in terms of the force due to that field:

we find that:

or



The quantity **dV/dr**is called the **electric potential gradient.** (See additional information on the end of fail.) It is the rate of change of the electric potential with distance, that is, the change in potential with unit distance. The potential gradient is a vector whose magnitude is equal to the magnitude of the electric field and whose direction is opposite to the direction of the electric field. Thus the electric field is equal to the negative of the potential gradient.

In SI units the electric field is given in volts per meter (V/m).

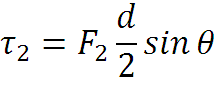
**Fundamentals of Physics. Lecture 9.** **Capacitance and Capacitors**

1. **Conductors and insulators. Electric field in medium.**

There are three kinds of materials relative electric properties:

1. Conductors. Conduct electric current. How we have seen from Gauss's law electric field in conductors is equal zero.
2. Insulators (dielectrics). They don't conduct electric current. Electric field in dielectrics decreases (see below)
3. Semiconductors. Conduct electric current but less than conductors.
4. **Electric dipoles. Dielectrics. Polarization of dielectrics.**

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| Many common electrical situations involve two equal but opposite charges separated by a fixed distance. This combination of charges is called **an electric dipole**.  A net ***torque*** arises that causes the dipole to rotate so as to align along the direction of the field  The situation is illustrated in the picture where the clockwise torque generated by Coulomb force acting to the positive charge about the center of dipole:    Similarly, the torque resulting from the force on the negative charge is also clockwise and is given by: | The forces acting on an electric dipole in a uniform electric field cause it to rotate. |



Total torque:



The force *F* is given by *qE*. This leads to:



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| The product ***qd*** is usually given the name ***dipole moment*** and for electric dipoles is often represented by the letter ***p***  If we define the dipole moment as a vector of magnitude p with direction from the negative to the positive charge, then the torque is the product of the dipole moment *p*, the field *E*, and the sine of the angle between them: | Direction of the dipole moment *p* of two opposite charges of magnitude *q* separated by a distance *d* |

The direction of the rotation produced by the torque rotates ***p***into alignment with ***E (right hand rule)****.*



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| When a dipole is placed in an external electric field, a torque acts to align it with the field.  For example, consider the behavior of a free dipole P1 interacting with the field of a dipole P2 fixed in space. The free dipole then rotates into alignment with the field of the fixed dipole.  It follows that we must do work to rotate the dipole to some position other than alignment along the field direction. We can, therefore, associate a potential energy with the orientation of the dipole in the field. | | | C:\Documents and Settings\sazakov\Desktop\15.28.jpg |
| If we consider the position in which the dipole is perpendicular to the field as the reference position, then the potential energy decreases when the dipole rotates into the direction of the field and increases when the dipole rotates in the opposite direction. The potential energy is:  *PE = -p∙E∙cosθ* | C:\Documents and Settings\sazakov\Desktop\15.29.jpg | (a) Polar molecules are randomly oriented in the absence of an electric field, (b) In the presence of an electric field the dipoles become partially aligned along the direction of the field. | |

1. **Capacitance and Capacitors.**

Any system of two conductors placed near each other but separated by an insulator can store more charge than can an isolated conductor

The important measure of these devices is their capacity to store charge, in time they became known as capacitors. A *capacitor* is a device for storing charge.

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| Capacitors come in many shapes and sizes, made from a variety of materials.  Capacitors, which evolved from early devices for storing charge, are part of most common electronic circuits, from the tuning circuit in your radio to the ignition system in your car. Their operation can be understood by building on the ideas of electric charge and electric potential.  The **capacitance** С of a capacitor is defined as the ratio of the quantity of charge stored on it to the potential difference V between the conductors. | D:\XAZAR\Course Physics 2\Picture Lecture 3,4\Capacitors Variable-capacitor.jpg |

The magnitude of the capacitance is a constant for each particular capacitor and depends only on the geometrical shape of the capacitor and on the nature of the insulating material between the conductors.

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| When the charge is measured in coulombs and the potential in volts, the capacitance is measured in **farads** (F): **1 farad = 1 coulomb/volt.**  The farad is a large unit. Many practical capacitors have values of microfarads (μF), nanofarads (nF), or even picofarads (pF). | *The circuit symbol for a capacitor* |

Because, for a given capacitor, the value of the capacitance is fixed, we can rearrange the previous equation to show the linear relationship between the charge stored and the voltage on the capacitor:

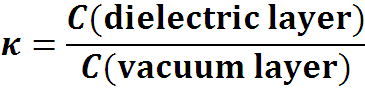
*q= CV*

Thus, if the potential difference between the plates is increased, the charge stored on the capacitor is also increased. Similarly, if you need to store a large charge with only a small applied voltage, then you need a large capacitance.

The formula of capacitance for a parallel-plate capacitor:

is appropriate only when there is a vacuum between the capacitor plates.

When a nonconducting (electrically insulating) material is inserted between the plates, the capacitance increases, even though the area and separation remain constant. The ratio of the new capacitance to the capacitance in a vacuum is called the **dielectric** **constant** (Greek letter kappa):



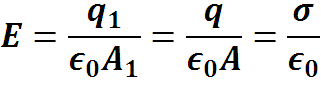
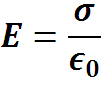
Materials that do not conduct electric charge are also known as **dielectrics.**

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| (a) The field of a parallel-plate capacitor without any material between the plates,  (b) An induced charge on the surfaces of an insulating material placed between plates generates a field within the material opposite in direction to the original field,  (c) The net field between the plates is reduced, leading increased capacitance.  For a parallel-plate capacitor, the effect of adding an insulating layer of dielectric constant к that fills the space between the plates is to modify the previous equation so that it becomes |  |

Thus the value of a capacitor depends on the area of the plates, the dielectric constant of the insulating material, and the thickness of the dielectric layer.

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| **Electric Field of a Parallel-Plate Capacitor**  According to Gauss's law, the flux is proportional to the charge enclosed by the cylinder. For this alignment there is no flux through the curved side of the cylinder. Thus all the flux must emerge through the end of area The statement of Gauss's law becomes    Where A1 is the area of the end of the cylinder, ql is the charge within, and εo is the proportionality constant **(permittivity of free space)**. |  |

For a flat plate we expect the charge to be uniformly distributed over the surface. In that case the ratio of charge to area is constant and can be taken as equal to the total charge *q* on the plate divided by its total surface area A. The ratio of q/A is called the **surface charge density**, usually denoted by **σ**. Thus the magnitude of the field is

**Capacitors in Combination**

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| Let's add in the circuit **the capacitor**. We learned before that capacitance is proportional to the area of the plates of a parallel-plate capacitor. Thus if we could double the area we would double the capacitance.  The voltage *V* supplied by the battery appears across each capacitor. The charge on each capacitor depends on this voltage, and the capacitance of each is determined from the equation *С* = *q/V.* | ÐÐ°ÑÑÐ¸Ð½ÐºÐ¸ Ð¿Ð¾ Ð·Ð°Ð¿ÑÐ¾ÑÑ capacitors connected in parallel | ÐÐ°ÑÑÐ¸Ð½ÐºÐ¸ Ð¿Ð¾ Ð·Ð°Ð¿ÑÐ¾ÑÑ capacitors connected in parallel  The equivalent capacitance *Cp* of **capacitors connected in parallel** is  ***Cpar = C1 + C2 + ... + Cn*** |

Suppose instead of joining the capacitors in parallel we join them end-to-end **in series** across the battery.

The first capacitor becomes charged, it induces an equal charge in the second capacitor, which in turn induces an equal charge in the third capacitor.

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| Since the capacitors permit no flow of charge between their plates, there is no net charge within the region marked by the colored rectangle. The magnitude of the charge is the same on each plate of each capacitor. (That is, there is no net charge in the region marked by the colored rectangle).  All of the capacitors must have the same charge *q: q1 = q2 = q3= q*  Conservation of energy (Kirchhoff's voltage rule) requires that the sum of the individual capacitor voltages be equal to the total voltage supplied by the battery:  ***V = V1 + V2 + ... + Vn***  Replacing the individual voltages by their equivalents in terms of q/C, we find that: |  |

For capacitors connected in parallel, the voltage is the same across each capacitor, while for capacitors connected in series, the charge is the same on each capacitor.

1. **Energy Stored in Capacitors. Electric energy density.**

A test charge *q* placed in this constant field experiences a force *F = qE*. If the charge moves through the distance *d* from the positive to the negative plate, the work done by the field is

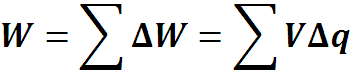
*W = Fd* *= qEd.*

This amount of work is equal to the loss of electric potential energy by the test charge.

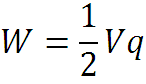
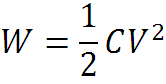
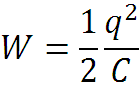
The energy stored on the capacitor may be considered as electrical potential energy, which can be released when the capacitor is discharged by connecting a conducting path between its plates.

We can think of capacitors as devices for storing energy or as devices for storing electric charge.

The total work done in charging the capacitor from zero to a voltage V is the sum of the work needed to transfer each amount of charge Δq:



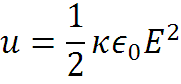
The energy required charging an initially uncharged capacitor to a potential difference V and charge ***q*** is:

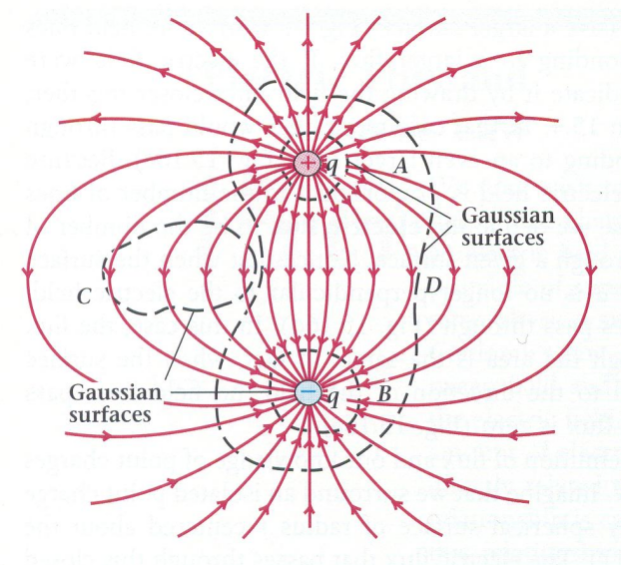
We have seen that, when fringing can be ignored, the electric field within a parallel-plate capacitor is uniform; that is, it is the same at all points between the plates. Thus the ***energy density* u**, the stored energy per unit volume, should also be uniform.

where ***Ad*** is the volume between the plates.

If we substitute the relationships *C* = κεoA/d and *E = V/d* the **energy density** becomes



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| Похожее изображение | ÐÐ°ÑÑÐ¸Ð½ÐºÐ¸ Ð¿Ð¾ Ð·Ð°Ð¿ÑÐ¾ÑÑ gauss law |



**Fundamentals of Physics Lecture 10. Electric Current and Resistance. Kirchhoff's Rules.**

* We will use the concepts of charge, field, and potential to study charges in motion, or current electricity.
* Electric currents move along closed conducting paths called circuits.
* To understand how circuits work, we will use the laws of **conservation of charge** and **conservation** **of energy**, fundamental laws that apply to all electric circuits.

1. **Electric current and electromotive force.**

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| The electric current is an ordered motion of charged particles.  We define **electric current** to be the rate at which electric charge passes through a surface of cross-section of conductor. If Δqis the amount of charge that passes through this surface in a time interval Δ*t*, the **average current** *I* is equal to the charge that passes through cross-section areaper unit time: |  | (a) Random motion of an electron through a metal when no electric field is present. After many collisions, the electron remains close to its original position  (b) Motion of the electron in a metal when an electric field is present. Notice the net drift of the electron in the direction opposite to the electric field. |

If the rate at which charge flows varies in time, the current varies in time; we define the **instantaneous current** *I* as the limit of the average current as Δ*t* →0:

current is the first derivative of charge with the time

For the present, we consider only the case in which the charge always flows in the **same direction** and at the **same rate**. This is called **direct current** or **dc.**

The dimension of electric current is charge per unit of time, and the SI unit for current is the **ampere** (abbreviated A). Ampere is a one of the basic units in SI. The unit for charge is the coulomb, so

**1 coulomb = 1 ampere** × **1 second**

The source of such current could be a battery. In particular, a battery provides a potential difference, or voltage, V between its terminals. The corresponding electric field causes charges to move within the wire, thus generating the electric current.

Electrical energy can be released from a battery (or other source of electrical energy) only when the current has a complete conducting path available from one side of the potential difference to the other. We call this conducting path a **complete circuit.**

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| By convention, the direction associated with the current in a circuit is the direction in which **a positive charge** would move in the potential provided by the batters. Thus the current in the external circuit is said to be directed **from the positive terminal to the negative terminal of the battery**  In solids, such as wires, the mobile charges those are actually free to flow, and therefore make up the current, are the **negatively charged electrons**. Consequently, the motion of the electrons is opposite to the conventional direction assigned to the current. |  | (a) The direction of electric current is the direction of motion of positive charge  (b) The motion of electrons is opposite to the motion associated with the current. |

However, since a flow of positive charges in one direction is equivalent to a flow of negative charges in the opposite direction, **we use the convention of positive current in almost all cases**.

Although the current consists of the motion of discrete charges, the number of them is so large that we may **ignore** this **granularity** and consider the current to be a smooth, continuous flow of charge.

Average speed of translation through the conductor is called the *drift velocity,* and ranges from a few hundredths of a millimeter per second to several centimeters per second for copper wires in ordinary situations

The potential difference that appears between the terminals of a battery when no current is present is called the **electromotive force** or **emf.** (This **emf** is *not* a force, despite its name.)

Emf is equal to a work done to transfer of a unit charge over complete circuit.

Unit of emf is one volt (V).

1. **Resistance. Ohm’s law. Resistivity and conductivity.**

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| The ratio of the applied voltage to the resulting current is defined to be the resistance R of the material:  Resistance is the ability of a material to resist the flow of charge when it is subject to a given potential difference. Formula above is a Ohm's law (in integral form)  If *V* is measured in volts and *I* in amperes, then resistance has the unit of volt per ampere, which is called an **ohm** (abbreviated **Ω**)*.* |  |

The resistance of a wire must be proportional to its length *L* and inversely proportional to its cross-sectional area *A*

The constant of proportionality ρ is the electric **resistivity.** In SI units, resistivity is given in ohm-meters (Ω⋅m).

For most metals the resistivity increases with increasing temperature

For some materials, over narrow ranges, the change in resistivity is approximately proportional to the change in temperature.

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Reciprocal to resistivity quantity called conductivity σ = 1/ρ. Its SI unit is siemens per meter (S/m).

Current density *j* is a current per unit area of cross-section of conductor. Its can be defined by formula:

where *E* is an electric field in the conductor. In SI current density measured in A/m2. Formula above represent Ohm's formula in differential form.

1. **Power and energy in electric circuits. Joule’s law.**

As the current passes through the device (for example lamp), charges are moving from a higher potential to a lower one. Energy is being lost from the battery and converted (in the filament of the lamp for example) into heat and light. The amount of energy released by a charge *q* as it falls through the potential *V* across the lamp is *W* ***= qV*.** Since the potential is constant, the rate at which energy is released, or the power *P*, is

or, *P = VI*

Eliminating of current give:

Eliminating of voltage give:

Unit of power in SI is watt = joule/second

When an electric current passes through a resistor, electric energy is irreversibly transformed to thermal energy.

*Q = I2 RΔt*

This equation is known as integral **Joule's law.** Differential form of **Joule's law:**

***w = σE2***

where σ – conductivity and E – electric field.

1. **Direct current circuits. Batteries and circuit elements. Simple resistive circuits.**

Direct current (DC) is the flow of electricity in a single direction, from the positive to the negative terminals (potential poles). The direct current always flows in the same direction, distinguishing it from the alternating current (AC). Batteries are some of the main sources of direct current (DC), but many other sources also exist such as bridge rectifiers in power supply, solar panels, etc.

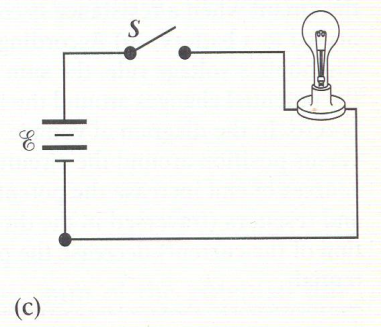
If the battery is connected to an external resistance R (called a load resistor), the current through the circuit depends on the emf *ε* and the total resistance,

where *r* - is an internal resistance of emf.

The potential difference across the terminals of the battery is the **terminal potential difference**, abbreviated TPD. It is the emf reduced by the voltage drop across the internal resistance *r*. Thus the TPD has a value:

Some concepts:

* One side of the circuit is maintained with a zero potential difference with respect to the earth and is called the *ground potential .*
* The other side of the circuit is called the "hot" side.
* A current will pass through any conducting object that simultaneously contacts the hot side of the circuit and a conducting path to ground.



(a) A circuit with one side grounded. The symbol for ground is shown, (b) Conditions for a short circuit. When the switch S is closed, the current passes through the switch instead of going through the lamp, (c) An open circuit. With the switch S open there is no current through the lamp.

Occasionally, electric equipment experiences a type of failure in which an alternative unwanted conducting path allows large currents. Such a path is usually called a *short circuit* because the current is not flowing through the desired circuit but instead passes through a parallel "shorter" path of lower resistance. The result of a short circuit is frequently a high current, since for a given potential difference, a lower resistance leads to a higher current.

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| **Simple resistive circuits:**  (a) A simple resistive circuit with one resistor connected across the potential of two batteries.  (b) Two resistors connected in series across the same batteries. The current is the same in each resistor connected in series |  |

The equivalent resistance of the **n** resistors connected *in series* is

*Rs = R1 + R2 +...+ Rn*

Current*: Is = I1 = I2 =...= In*

Voltage*: Vs = V1 + V2 +...+ Vn*

The equivalent resistance of **n** resistors connected *in* *parallel* is

Current*: Ip = I1 + I2 +...+ In*

Voltage*: Vp = V1 = V2 =...= Vn*

An important point to remember concerning series and parallel connection of resistors is that for series connection the *current through* the resistors is the same, and for parallel connection the voltage *across* the resistors is the same.

1. **Kirchhoff’s rules.**

There are two Kirchhoff’s rules:

1. Kirchhoff’s rule for currents (sometimes called Kirchhoff ’s first law, or Kirchhoff's junction law)
2. Kirchhoff’s voltage rule (sometimes called Kirchhoff’s second law or Kirchhoff ’s loop rule )

**1. Kirchhoff's current rule: The algebraic sum of the currents into the junction is zero.**

where n is a number of junctions. **This law is a consequence of charge conservation.**

In other words, the sum of the incoming currents equals the sum of the outgoing currents.

**The *sum of the currents flowing into the junction must equal the sum of the currents leaving the junction.***

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| The current entering the junction *are I1, I2 and the currents leaving the junction is I3.* Whatever charge enters the junction must exit the junction and so the sum of the currents into a junction equals the sum of the currents leaving the junction.  *I1+I2 - I3= 0*  *I1+I2 =I3* |  |

**Note. Number of equations can be written is equal n - 1, where n –number of junctions (nods) in the circuit.**

**2. Kirchhoff's loop rule:** the sum of the **emf** in any closed loop is equivalent to the sum of the potential drops in that loop

where ***n*** is number of emf in chosen loop and ***k*** is number of resistors in chosen loop.

The loop law is a consequence of energy conservation. This method is best used for complicated multi-loop circuits.

**Note. Number of equations can be written is equal m - 1, where m –number of loops in the circuit.**

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| How to use second law: Draw a loop through the circuit and put an arrow on it. This indicates the direction in which we will **go around** the circuit. Now follow *the loop starting at anywhere point. As we travel* along the circuit we calculate the quantity of ΣƐ and Σ*V, i.e. the sum of the voltages* across each cells and potential drops on resistors that the loop takes us through, according to the rules: |  |

Sign of emf and potential drop (positive or negative) should be taken according the rules given in the picture and described below:

For an imaginary traversal of a loop we use the following convention:

1. The EMF Ɛ is positive (+) if the current generated by it is co-directed with the selected **going around.**
2. The EMF Ɛ is negative (-) if the current it creates is oppositely directed to the selected direction of **going around.**
3. The potential difference is taken as positive (+*IR)* if the selected current direction and the direction of **going around** arecoincide.
4. The potential difference is taken as negative (-*IR)* if the selected current direction and the direction of **going around** areopposite.

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| **Example.**  When we are applying the first rule we get:  for junction at point ***a:*** for junction at point ***d:***  *I2 + I3 = I1 I1 = I2 + I3*  It is seen that this equations are same and we can take only one.  When we are applying second rule we get:  For upper loop: For bottom loop:  -ε1- ε2 = *I1R1+ I2R2* ε2+ε3 = - *I2R2 +I3R3* | C:\ADNSU\loops.jpg |

**Fundamental of Physics Lecture 11. Magnetic Field**

**1. Magnetic field**

In our study of electricity, we described the interactions between charged objects in terms of electric fields. Recall that an electric field surrounds any electric charge. In addition to containing an electric field, the region of space surrounding any *moving* electric charge also contains a **magnetic field.** A magnetic field also surrounds a magnetic substance making up a permanent magnet.

The direction of the magnetic field **B** at any location is the direction in which a compass needle points at that location. As with the electric field, we can represent the magnetic field by means of drawings with *magnetic field lines.* Themagnetic field lines of a bar magnet can be traced with the aid of a compass. Notice that the magnetic field lines outside the magnet point away from the North Pole and toward the South Pole. One can display magnetic field patterns of a bar magnet using small iron filings.

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| When we speak of a compass magnet having a north pole and a south pole, it is more proper to say that it has a “north-seeking” pole and a “south-seeking” pole. This wording means that the north-seeking pole points to the north geographic pole of the Earth, whereas the south-seeking pole points to the south geographic pole. Because the north pole of a magnet is attracted toward the north geographic pole of the Earth, the Earth’s south magnetic pole is located near the north geographic pole and the Earth’s north magnetic pole is located near the south geographic pole. |  |

We can quantify the magnetic field **B** by using our model of a particle in a field, like the model discussed for gravity and for electricity. The existence of a magnetic field at some point in space can be determined by measuring the **magnetic force F***B* exerted on an appropriate test particle placed at that point. If we perform such an experiment by placing a particle with charge *q* in the magnetic field, we find the following results:

* The magnetic force is proportional to the charge *q* of the particle.
* The magnetic force on a negative charge is directed opposite to the force on a positive charge moving in the same direction.
* The magnetic force is proportional to the magnitude of the magnetic field vector **B.**

We also find the following results, which are *totally different:*

* The magnetic force is proportional to the speed *v* of the particle.
* If the velocity vector makes an angle u with the magnetic field, the magnitude of the magnetic force is proportional to sin u.
* When a charged particle moves *parallel* to the magnetic field vector, the magnetic force on the charge is zero.
* When a charged particle moves in a direction *not* parallel to the magnetic field vector, the magnetic force acts in a direction perpendicular to both **v** and **B**; that is, the magnetic force is perpendicular to the plane formed by **v** and **B**

Despite this complicated behavior, these observations can be summarized in a compact way by writing the magnetic force in the form

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| (1)  which by definition of the cross product is perpendicular to both **v** and **B**.  Right-hand rules or right-screw rule are used for determining the direction of the cross product **v**×**B** and determining the direction of **F***B* |  |

The magnitude of the magnetic force on a charged particle is

*F = q v B sinθ*

where θ is the smaller angle between **v** and **B**. From this expression, we see that *F* is zero when **v** is parallel or antiparallel to **B** (θ = 0 or 180o) and maximum *Fmax* when **v** is perpendicular to **B** (θ = 90o, sinθ =1). We can define magnetic field by formula:

(2)

Let’s compare the important differences between the electric and magnetic versions of the particle in a field model:

• The electric force vector is along the direction of the electric field, whereas the magnetic force vector is perpendicular to the magnetic field.

• The electric force acts on a charged particle regardless of whether the particle is moving, whereas the magnetic force acts on a charged particle only when the particle is in motion.

• The electric force does work in displacing a charged particle, whereas the magnetic force associated with a steady magnetic field does no work when a particle is displaced because the force is perpendicular to the displacement of its point of application.

From the last statement and on the basis of the work–kinetic energy theorem, we conclude that the kinetic energy of a charged particle moving through a magnetic field cannot be altered by the magnetic field alone. The field can alter the direction of the velocity vector, but it cannot change the speed or kinetic energy of the particle.

The SI unit of magnetic field is the newton per coulomb-meter per second, which is called the **tesla** (T):

1 T = N/(A∙m)

**2. Motion of a charged particle in a uniform magnetic field. Lorentz's force.**

Now consider the special case of a positively charged particle moving in a uniform magnetic field with the initial velocity vector of the particle perpendicular to the field. Let’s assume the direction of the magnetic field is into the page as in Figure. The particle in a field model tells us that the magnetic force on the particle is perpendicular to both the magnetic field lines and the velocity of the particle. As the particle changes the direction of its velocity in response to the magnetic force, the magnetic force remains perpendicular to the velocity. As we found in our previous course, if the force is always perpendicular to the velocity, the path of the particle is a circle.

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| The **centripetal acceleration** required to keep the particle in a circle orbit is provided by the interaction of the moving charge with the magnetic field. Centripetal acceleration with the acceleration due to the magnetic fields  (3)  So a charged particle moving perpendicular to a magnetic field travels in a circle of radius  (4)  The angular speed of the particle is  (5) | The cross symbol (×) on the figure represent the tail-ends of magnetic field lines directed into the page. |

The period of the motion (the time interval the particle requires to complete one revolution) is equal to the circumference of the circle divided by the speed of the particle:

(6)

These results show that the angular speed of the particle and the period of the circular motion do not depend on the speed of the particle or on the radius of the orbit. The angular speed ω is often referred to as the **cyclotron frequency** because charged particles circulate at this angular frequency in the type of accelerator called a ***cyclotron (*A cyclotron is a device that can accelerate charged particles to very high speeds.*)***

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| If the initial velocity of the charged particle has a component *parallel* to the magnetic field **B**, instead of a circle, the resulting trajectory will be a ***helical*** *path.*  **Lorentz's force**  In the presence of both electric field **E** and magnetic field **B**, the total force on a charged particle is  (7)  This is known as the **Lorentz’s force** |  |

**3. Magnetic Force Acting on a Current-Carrying Conductor**

The current is a collection of many charged particles in motion. If a magnetic force is exerted on a single charged particle when the particle moves through a magnetic field, thus a current-carrying wire also experiences a force when placed in a magnetic field. The resultant force exerted by the field on the wire is the vector sum of the individual forces exerted on all the charged particles making up the current. The force exerted on the particles is transmitted to the wire when the particles collide with the atoms making up the wire.

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| The total magnetic force on the segment of wire of length *L* is  We can write this expression in a more convenient form by noting that the current in the wire is *I =* *nqvA.* Therefore,  (8)  where **L** is a vector that points in the direction of the current *I* and has a magnitude equal to the length *L* of the segment. | Картинки по запросу A segment of a current-carrying wire in a magnetic field |
| This expression applies only to a straight segment of wire in a uniform magnetic field. Now consider an arbitrarily shaped wire segment of uniform cross section in a magnetic field as shown in Figure. It follows from Equation (8) that the magnetic force exerted on a small segment of vector length *d***s** in the presence of a field **B** is  (9) | Картинки по запросу A segment of a current-carrying arbitrarily shaped wire in a magnetic field |

To calculate the total force **F** acting on the wire shown in Figure, we integrate Equation (9) over the length of the wire:

where *a* and *b* represent the endpoints of the wire.

**4. The Hall Effect**

When a current-carrying conductor is placed in a magnetic field, a potential difference is generated in a direction perpendicular to both the current and the magnetic field. This phenomenon, first observed by Edwin Hall (1855–1938) in 1879, is known as the *Hall effect.*

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| The arrangement for observing the Hall effect consists of a flat conductor carrying a current *I* in the *x* direction as shown in Figure. A uniform magnetic field **B** is applied in the *y* direction. If the charge carriers are electrons moving in the negative *x* direction with a drift velocity **v***d*, they experience an upward magnetic force **F***B* = *q***v***d* x **B**, are deflected upward, and accumulate at the upper edge of the flat conductor, leaving an excess of positive charge at the lower edge. This accumulation of charge at the edges establishes an electric field in the conductor and increases until the electric force on carriers remaining in the bulk of the conductor balances the magnetic force acting on the carriers. | Картинки по запросу The Hall Effect |

The electrons can now be described by the particle in equilibrium model, and they are no longer deflected upward.

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| A sensitive voltmeter connected across the sample as shown in Figure can measure the potential difference, known as the **Hall voltage** Δ*V*H, generated across the conductor.  If the charge carriers are positive and hence move in the positive *x* direction (for rightward current) as shown in Figures, they also experience an upward magnetic force *q***v***d* ×**B**, which produces a buildup of positive charge on the upper edge and leaves an excess of negative charge on the lower edge. | Картинки по запросу The Hall Effect |

Hence, the sign of the Hall voltage generated in the sample is opposite the sign of the Hall voltage resulting from the deflection of electrons. The sign of the charge carriers can therefore be determined from measuring the polarity of the Hall voltage.

In deriving an expression for the Hall voltage, first note that the magnetic force exerted on the carriers has magnitude *qvdB.* In equilibrium, this force is balanced by the electric force *qE*H, where *E*H is the magnitude of the electric field due to the charge separation (sometimes referred to as the *Hall field*). Therefore,

*qvdB= qE*H and *vdB= E*H

If *d* is the width of the conductor, the Hall voltage is

Δ*V*H *= E*H*d* = *vdBd* (10)

Therefore, the measured Hall voltage gives a value for the drift speed of the charge carriers if *d* and *B* are known.

We can obtain the charge-carrier density *n* by measuring the current in the sample. From equation current we can express the drift speed as

where *A* is the cross-sectional area of the conductor. Substituting this Equation into Equation (13) gives

(11)

Because *A* = *td*, where *t* is the thickness of the conductor, we can also express Equation (14) as

(12)

where *R*H = 1/*nq* is called the **Hall coefficient.** This relationship shows that a properly calibrated conductor can be used to measure the magnitude of an unknown magnetic field.

Because all quantities in Equation (15) other than *nq* can be measured, a value for the Hall coefficient is readily obtainable. The sign and magnitude of *R*H give the sign of the charge carriers and their number density.

**5. The Biot-Savart's law.**

Shortly after Oersted’s discovery in 1819 that a compass needle is deflected by a current-carrying conductor, Jean-Baptiste Biot (1774–1862) and Felix Savart (1791–1841) performed quantitative experiments on the force exerted by an electric current on a nearby magnet. From their experimental results, Biot and Savart arrived at a mathematical expression that gives the magnetic field at some point in space in terms of the current that produces the field.

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| That expression is based on the following experimental observations for the magnetic field *d***B** at any point associated with a length element *d***s** of a wire carrying a steady current *I* (Figure):  • The magnitude of *d***B** is inversely proportional to *r*2, where *r* is the distance from *d***s** to *Point.*  • The vector *d***B** is perpendicular both to *d***s** (which points in the direction of the current) and vector **r** directed from *d***s** toward *Point.* | Картинки по запросу The Biot-Savart-Laplace law |

• The magnitude of *d***B** is proportional to the current *I* and to the magnitude *ds* of the length element *d***s**.

• The magnitude of *d***B** is proportional to sin α, where α is the angle between the vectors *d***s** and **r**.

These observations are summarized in the mathematical expression known today as the **Biot–Savart law:**

(13)

where μo = 4π∙10-7 N/A2 (or T∙m/A, or H/m) is a constant called the **permeability of free space (or permeability of vacuum, or magnetic constant)**.

Notice that the field *d***B** in Equation (1) is the field created at a point by the current in only a small length element *d***s** of the conductor. To find the *total* magnetic field **B** created at some point by a current of finite size, we must sum up contributions from all current elements *I d***s** that make up the current. That is, we must evaluate **B** by integrating Equation (1)

(14)

where the integral is taken over the entire current distribution. This expression must be handled with special care because the integrand is a cross product and therefore a vector quantity.

Although the Biot–Savart law was discussed for a current-carrying wire, it is also valid for a current consisting of charges flowing through space such as the particle beam in an accelerator. In that case, *d***s** represents the length of a small segment of space in which the charges flow.

Interesting similarities and differences exist between Equation (13) for the magnetic field due to a current element and Equation for the electric field due to a point charge. The magnitude of the magnetic field varies as the inverse square of the distance from the source, as does the electric field due to a point charge.

a) The directions of the two fields are quite different, however. The electric field created by a point charge is radial, but the magnetic field created by a current element is perpendicular to both the length element *d***s** and the vector **r** as described by the cross product in Equation (13) and obey right-hand rule.

b) Another difference between electric and magnetic fields is related to the source of the field. An electric field is established by an isolated electric charge. The Biot–Savart law gives the magnetic field of an isolated current element at some point, but such an isolated current element cannot exist the way an isolated electric charge can. A current element *must* be part of an extended current distribution because a complete circuit is needed for charges to flow. Therefore, the Biot–Savart law (Eq. (13)) is only the first step in a calculation of a magnetic field; it must be followed by integration over the current distribution as in Equation (14).

1. **Application of the Biot-Savart-Laplace law to calculation of the magnetic field of current-carrying conductors of various forms.**

**a) Magnetic Field Surrounding a Thin, Straight Conductor**

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| Consider a thin, straight wire of finite length carrying a constant current *I* and placed along the *x* axis as shown in Figure. Determine the magnitude and direction of the magnetic field at point *P* due to this current.  We must find the field contribution from a small element of current and then integrate over the current distribution. Let’s start by considering a length element *d***s** located a distance *r* from *P.* The direction of the magnetic field at point *P* due to the current in this element is out of the page because *d***s** × **r** is out of the page. | Картинки по запросу Magnetic Field Surrounding a Thin, Straight Conductor |

In fact, because *all* the current elements *I d***s** lie in the plane of the page, they all produce a magnetic field directed out of the page at point *P.* Therefore, the direction of the magnetic field at point *P* is out of the page and we need only find the magnitude of the field.

Evaluate the magnitude of cross product in the Biot–Savart law: *|****ds× r****| = dx∙ r∙ sinθ*

From the geometry in Figure, express *r* and *dx* in terms of *θ*:

r = a/sin*θ; dx = rdθ/sinθ = adθ/sin2θ*

Substitute into Equation (1) we get for magnitude of *dB*:

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| Integrate this equation over all length elements on the wire, where the subtending angles range from 0 to π.  (3)  Field lines of magnetic induction of direct current-carrying conductor is a system of concentric circles. | Похожее изображение |

Figure also shows that the magnetic field line has no beginning and no end. Rather, it forms a closed loop. That is a major difference between magnetic field lines and electric field lines, which begin on positive charges and end on negative charges.

**b) Magnetic Field Due to a Curved Wire Segment**

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| Let calculate the magnetic field at point *O* for the current-carrying wire segment shown in Figure. The wire consists of two straight portions and a circular arc of radius *R*, which subtends an angle *θ*.  Each length element *d***s** along path *AC* is at the same distance *R* from *O*, and the current in each contributes a field element *d***B** directed into the page at *O.* Furthermore, at every point on *AC*, *d***s** is perpendicular to ***R***; hence, *|****ds× R****| = ds∙R* | Картинки по запросу Magnetic Field Due to a Curved Wire Segment |

Integrate this expression over the curved path *AC*, noting that *I* and *R* are constants:

From the geometry, note that *s = R∙ θ* and substitute:

For example in the centre of full circle magnetic field is equal (*θ= 2π*):

**The interaction of parallel currents.**

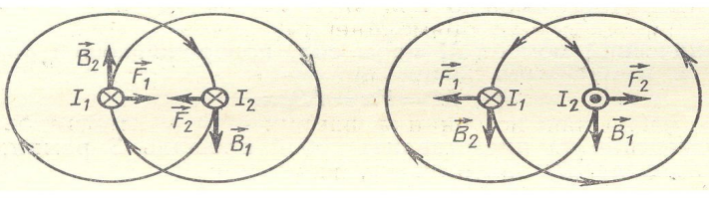
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| In our lecture 1, we described the magnetic force that acts on a current-carrying conductor placed in an external magnetic field. Because a current in a conductor sets up its own magnetic field, it is easy to understand that two current-carrying conductors exert magnetic forces on each other. One wire establishes the magnetic field and the other wire is modeled as a collection of particles in a magnetic field. Such forces between wires can be used as the basis for defining the ampere and the coulomb. | Картинки по запросу The Magnetic Force Between Two Parallel Conductors |

Consider two long, straight, parallel wires separated by a distance *a* and carrying currents *I*1 and *I*2 in the same direction as in Figure. Let’s determine the force exerted on one wire due to the magnetic field set up by the other wire. Wire 2, which carry a current *I*2 and is identified arbitrarily as the source wire, creates a magnetic field **B**2 at the location of wire 1, the test wire. The magnitude of this magnetic field is the same at all points on wire 1. The direction of **B**2 is perpendicular to wire 1 as shown in Figure. According to Equation

Because ***l*** is perpendicular to **B**2 in this situation, the magnitude of **F**1 is *F*1 = *I1lB2*. Because the magnitude of **B**2 is given by Equation (3)

(5)

Hence, parallel conductors carrying currents in the *same* direction *attract* each other, and parallel conductors carrying currents in *opposite* directions *repel* each other.



Because the magnitudes of the forces are the same on both wires, we denote the magnitude of the magnetic force between the wires as simply *FB*. We can rewrite this magnitude in terms of the force per unit length:

(6)

The force between two parallel wires is used to define the **ampere** as follows:

When the magnitude of the force per unit length between two long, parallel wires that carry identical currents and are separated by 1 m is 2 ∙10-7 N/m, the current in each wire is defined to be 1 A.

The SI unit of charge, the **coulomb,** is defined in terms of the ampere:

When a conductor carries a steady current of 1 A, the quantity of charge that flows through a cross section of the conductor in 1 s is 1 C.

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| The magnetic field produced by a current in a coil of wire gives us a hint as to what causes certain materials to exhibit strong magnetic properties. Earlier we found that a solenoid like the one shown in Figure has a north pole and a south pole. In general, *any* current loop has a magnetic field and therefore has a magnetic dipole moment, including the atomic-level current loops described in some models of the atom. | Похожее изображение |

**6. Magnetic media. Ferro-, Para- and Diamagnetic materials. Hysteresis**

In classical model of the atom electrons move in circular orbits around the much more massive nucleus. In this model, an orbiting electron constitutes a tiny current loop (because it is a moving charge), and the magnetic moment of the electron is associated with this orbital motion. Although this model has many deficiencies, some of its predictions are in good agreement with the correct theory, which is expressed in terms of quantum physics.

**Ferromagnetism**

A small number of crystalline substances exhibit strong magnetic effects called **ferromagnetism.** Some examples of ferromagnetic substances are iron, cobalt, nickel, gadolinium, and dysprosium. These substances contain permanent atomic magnetic moments that tend to align parallel to each other even in a weak external magnetic field. Once the moments are aligned, the substance remains magnetized after the external field is removed. This permanent alignment is due to a strong coupling between neighboring moments, a coupling that can be understood only in quantum-mechanical terms.

All ferromagnetic materials are made up of microscopic regions called **domains,** regions within which all magnetic moments are aligned. These domains have volumes of about 10-12 to 10-8 m3 and contain 1017 to 1021 atoms. The boundaries between the various domains having different orientations are called **domain walls.**

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| In an unmagnetized sample, the magnetic moments in the domains are randomly oriented so that the net magnetic moment is zero as in Figure.  When the sample is placed in an external magnetic field **B**, the size of those domains with magnetic moments aligned with the field grows, which results in a magnetized sample as in Figure. | Картинки по запросу an unmagnetized substance |

As the external field becomes very strong, the domains in which the magnetic moments are not aligned with the field become very small.

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| When the external field is removed, the sample may retain a net magnetization in the direction of the original field. At ordinary temperatures, thermal agitation is not sufficient to disrupt this preferred orientation of magnetic moments.  When the temperature of a ferromagnetic substance reaches or exceeds a critical temperature called the **Curie temperature,** the substance loses its residual magnetization. Below the Curie temperature, the magnetic moments are aligned and the substance is ferromagnetic. Above the Curie temperature, the thermal agitation is great enough to cause a random orientation of the moments and the substance becomes paramagnetic. Curie temperatures for several ferromagnetic substances are given in Table | Картинки по запросу Curie temperatures for several ferromagnetic substances table |

**Paramagnetism**

Paramagnetic substances have a weak magnetism resulting from the presence of atoms (or ions) that have permanent magnetic moments. These moments interact only weakly with one another and are randomly oriented in the absence of an external magnetic field. When a paramagnetic substance is placed in an external magnetic field, its atomic moments tend to line up with the field. This alignment process, however, must compete with thermal motion, which tends to randomize the magnetic moment orientations.

**Diamagnetism**

When an external magnetic field is applied to a diamagnetic substance, a weak magnetic moment is induced in the direction opposite the applied field, causing diamagnetic substances to be weakly repelled by a magnet. Although diamagnetism is present in all matter, its effects are much smaller than those of paramagnetism or ferromagnetism and are evident only when those other effects do not exist.

We can attain some understanding of diamagnetism by considering a classical model of two atomic electrons orbiting the nucleus in opposite directions but with the same speed. The electrons remain in their circular orbits because of the attractive electrostatic force exerted by the positively charged nucleus. Because the magnetic moments of the two electrons are equal in magnitude and opposite in direction, they cancel each other and the magnetic moment of the atom is zero. When an external magnetic field is applied, the electrons experience an additional magnetic force *q***v×B**. This added magnetic force combines with the electrostatic force to increase the orbital speed of the electron whose magnetic moment is antiparallel to the field and to decrease the speed of the electron whose magnetic moment is parallel to the field. As a result, the two magnetic moments of the electrons no longer cancel and the substance acquires a net magnetic moment that is opposite the applied field.

A superconductor is a substance in which the electrical resistance is zero below some critical temperature. Certain types of superconductors also exhibit perfect diamagnetism in the superconducting state. As a result, an applied magnetic field is expelled by the superconductor so that the field is zero in its interior. This phenomenon is known as the **Meissner effect.** If a permanent magnet is brought near a superconductor, the two objects repel each other. This repulsion is illustrated in Figure, which shows a small permanent magnet levitated above a superconductor maintained at 77 K.

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| https://upload.wikimedia.org/wikipedia/commons/thumb/b/b5/EfektMeisnera.svg/525px-EfektMeisnera.svg.png | Картинки по запросу floating a small permanent magnet above a superconductor |

**The magnetic field strength.**

The magnetic fields generated by currents and calculated from Ampere's Law or the Biot-Savart law are characterized by the magnetic field measured in Tesla. But when the generated fields pass through magnetic materials which themselves contribute internal magnetic fields, ambiguities can arise about what part of the field comes from the external currents and what comes from the material itself. It has been common practice to define another magnetic field quantity, usually called the "**magnetic field strength**" designated by H. It can be defined by the relationship

H = B/μ0 - M

and has the value of unambiguously designating the driving magnetic influence from external currents in a material, independent of the material's magnetic response. The quantity **M** in this equation is called the **magnetization** of the material.

The relationship for B can be written in the equivalent form

B = μ0(H + M)

Magnetization is related on magnetic field strength:

M = χmH

where χm - magnetic susceptibility of material.

H and M will have the same units, amperes/meter. To further distinguish B from H, B is sometimes called the magnetic flux density or the magnetic induction.

Another commonly used form for the relationship between B and H is

B = μ0H(1+ χm),

then

B = μ0 μ H

where

μ = 1 + χm or

Here Bo - magnetic field without materials (free space), B - magnetic field in magnetic material, μ0 being the magnetic permeability of vacuum and **μ** the relative magnetic permeability of the material. If the material does not respond to the external magnetic field by producing any magnetization, then μ = 1. The magnetic susceptibility specifies how much the relative permeability differs from one.

For paramagnetic and diamagnetic materials the relative permeability μ is very close to 1 and the magnetic susceptibility very close to zero. But for paramagnetic materials χm > 0 and μ >1, for diamagnetic materials χm < 0 and μ <1.

For ferromagnetic materials, these quantities may be very large μ >> 1 and equals several thousand.

For vacuum the formula is simple:

H = B0/μ0

The unit for the magnetic field strength H can be derived from its relationship to the magnetic field B, B=μo H. Since the unit of magnetic permeability μo is N/A2, then the unit for the magnetic field strength is:

T/(N/A2) = (N/Am)/(N/A2) = A/m

**Hysteresis**

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| Consider a toroid with an iron core that is initially unmagnetized and there is no current in the wire loops of toroid. Toroid looks like closed solenoid so practically all the lines of magnetic field *B* remain within the toroid (see Figure).  When the current *I* is slowly increased, and Bo (which is due only to *I*) increases linearly with *I*. | Похожее изображение |

The total field *B* also increases, but follows the curved line shown in Figure below which is a graph of total *B* vs *Bo*. Remind that total magnetic field *B* in an iron-core as a function of the external field *Bo* (*Bo* is caused by the current *I* in the coil). Initially, point **a**, the domains are randomly oriented. As *Bo* increases, the domains become more and more aligned until at point **b**, nearly all are aligned. The iron is said to be approaching **saturation**.

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| Next, suppose current in the coil is reduced, so the field *Bo* decreases. If the current (and *Bo*) is reduced to zero, point **c** in Figure, the domains do *not* become completely random. Instead, some permanent magnetism remains in the iron core. If the current is increased in the opposite direction, enough domains can be turned around so the total *B* becomes zero at point **d**. As the reverse current is increased further, the iron approaches saturation in the opposite direction, point **e**. Finally, if the current is again reduced to zero (point ***f***) and then increased in the original direction, the total field follows the path **efgb**, again approaching saturation at point **b**. | Картинки по запросу hysteresis |

Notice that the field did not pass through the origin (point a) in this cycle. The fact that the curve does not retrace itself on the same path is called **hysteresis**. The curve **bcdefgb** is called a **hysteresis loop**. In such a cycle, much energy is transformed to thermal energy (friction) due to realigning of the domains. Note that at points **c** and **f**, the iron core is magnetized even though there is no current in the coils. These points correspond to a permanent magnet.

**Addition Figures**



**Fundamental of Physics Lecture 12. Magnetic flux. Electromagnetic Induction. Inductance**

1. **Magnetic flux. Gauss theorem for magnetic field.**

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| The flux associated with a magnetic field is defined in a manner similar to that used to define electric flux. Consider an element of area *dA* on an arbitrarily shaped surface as shown in Figure. If the magnetic field at this element is **B**, the magnetic flux through the element is , where *d***A** is a vector that is perpendicular to the surface and has a magnitude equal to the area *dA.*  Therefore, the total magnetic flux Ф*B* through the surface is | Картинки по запросу Gauss law for magnetic field |

(1)

Consider the special case of a plane of area *A* in a uniform field **B** that makes an angle *θ* with *d***A**. The magnetic flux through the plane in this case is:

*ФВ = В∙dА∙cosθ*

We found that the electric flux through a closed surface surrounding a net charge is proportional to that charge (Gauss’s law).

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| The situation is quite different for magnetic fields. Magnetic field lines do not begin or end at any point. For any closed surface such as the one outlined by the dashed line in Figure, the number of lines entering the surface equals the number leaving the surface; therefore, the net magnetic flux is zero. In contrast, for a closed surface surrounding some charges, the net electric flux is not zero.  **Gauss’s law in magnetism** states that  the net magnetic flux through any closed surface is always zero:  (2) | Картинки по запросу Gauss law for magnetic field |

1. **Ampere's Law. Net current.**

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| Oersted’s 1819 discovery about deflected compass needles demonstrates that a current-carrying conductor produces a magnetic field. In the Figure we see several compass needles are placed in a horizontal plane near a long, vertical wire. When no current is present in the wire, all the needles point in the same direction (that of the horizontal component of the Earth’s magnetic field) as expected. When the wire carries a strong, steady current, the needles all deflect in a direction tangent to the circle as in Figure. | Картинки по запросу 5. Application of the total current law to calculate the magnetic fields. |

Now let’s evaluate the product for a small length element *d***s** on the circular path defined by the compass needles and sum the products for all elements over the closed circular path.

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| Along this path, the vectors *d***s** and **B** are parallel at each point (see Figure), so **B∙***d***s =** *B ds*. Furthermore, the magnitude of **B** is constant on this circle. Therefore, the sum of the products *Bds* over the closed path, which is equivalent to the line integral of **B∙***d***s**, is | Похожее изображение |

Although this result was calculated for the special case of a circular path surrounding a wire of infinite length, it holds for a closed path of *any* shape (an *amperian loop*) surrounding a current that exists in an unbroken circuit. The general case, known as **Ampère’s law,** can be stated as follows:

The line integral of **B∙***d***s** around any closed path equals μo *I*, where *I* is the total steady current passing through any surface bounded by the closed path:

(3)

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| Ampere’s law describes the creation of magnetic fields by all continuous current configurations, but at our mathematical level it is useful only for calculating the magnetic field of current configurations having a high degree of symmetry. Its use is similar to that of Gauss’s law in calculating electric fields for highly symmetric charge distributions. | Картинки по запросу ampere's law |

**Application of the Ampere's current law to calculate the magnetic fields.**

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| A long, straight wire of radius *R* carries a steady current *I* that is uniformly distributed through the cross section of the wire (see Figure). Calculate the magnetic field at distance *r* from the center of the wire in the regions *r* ≥ *R* and *r* < *R.*  Note that the total current passing through the plane of the circle is *I* and apply Ampere’s law:  And we get:  (for regions *r* ≥ *R*) | Похожее изображение |
| Now consider the interior of the wire, where *r* < *R.* Here the current *I'* passing through the plane of circle 2 is less than the total current *I.*  *and*  Solve for B:  (for regions *r* < *R*) |  |

**The magnetic field of the solenoid.**

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| A **solenoid** is a long wire wound in the form of a helix. With this configuration, a reasonably uniform magnetic field can be produced in the space surrounded by the turns of wire—which we shall call the *interior* of the solenoid—when the solenoid carries a current. When the turns are closely spaced, each can be approximated as a circular loop; the net magnetic field is the vector sum of the fields resulting from all the turns. | Похожее изображение |

If the turns are closely spaced and the solenoid is of finite length, the external magnetic field lines are as shown in Figure. This field line distribution is similar to that surrounding a bar magnet. Hence, one end of the solenoid behaves like the North Pole of a magnet and the opposite end behaves like the South Pole. As the length of the solenoid increases, the interior field becomes more uniform and the exterior field becomes weaker. An *ideal solenoid* is approached when the turns are closely spaced and the length is much greater than the radius of the turns.

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| We can use Ampere’s law to obtain a quantitative expression for the interior magnetic field in an ideal solenoid. Because the solenoid is ideal, **B** in the interior space is uniform and parallel to the axis and the magnetic field lines in the exterior space form circles around the solenoid. The planes of these circles are perpendicular to the page. Consider the rectangular path of length *l*, and width *w* shown in Figure.  Let’s apply Ampere’s law to this path by evaluating the integral of **B∙***d***s** over each side of the rectangle. The contribution alongside 3 is zero because the external magnetic field of a long (infinite) solenoid approaches zero in this region (it follows from Gauss' law). The contributions from sides 2 and 4 are both zero, again because **B** is perpendicular to *d***s** along these paths, both inside and outside the solenoid. Side 1 gives a contribution to the integral because along this path **B** is uniform and parallel to *d***s**. The integral over the closed rectangular path is therefore | Картинки по запросу ampere's law solenoid |

Ampere’s law applied to this path gives

(4)

where *n =* *N*/*l* is the number of turns per unit length.

Equation (4) is valid only for points near the center (that is, far from the ends) of a very long solenoid. As you might expect, the field near each end is smaller than the value given by Equation (10). As the length of a solenoid increases, the magnitude of the field at the end approaches half the magnitude at the center.

1. **Faraday’s Law of Induction. Motional emf. Lenz’s Law.**

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| Consider a magnetic flux through the closed loop. An emf is induced in a loop when the magnetic flux through the loop changes with time. In general, this emf is directly proportional to the time rate of change of the magnetic flux through the loop. This statement can be written mathematically as **Faraday’s law of induction:**  (5) | Картинки по запросу magnetic flux through the closed loop |

where ФВ- is the magnetic flux through the loop. If a coil consists of *N* loops with the same area and ФВ is the magnetic flux through one loop, an emf is induced in every loop. The loops are in series, so their emfs add; therefore, the total induced emf in the coil is given by

Suppose a loop enclosing an area *A* lies in a uniform magnetic field **B**. The magnetic flux through the loop is equal to ФВ= *BA* cos θ, where *θ* is the angle between the magnetic field and the normal to the loop; hence, the induced emf can be expressed as

From this expression, we see that an emf can be induced in the circuit in several ways (see figures):

• The magnitude of **B** can change with time.

• The area enclosed by the loop can change with time.

• The angle *θ* between **B** and the normal to the loop can change with time.

• Any combination of the above can occur.

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| Похожее изображение |  | Картинки по запросу electromagnetic induction |  | Картинки по запросу electromagnetic induction |

Let's us discus one interesting case of induced emf which can be explained as a case of changing of area of a loop. It is a case of **motional emf,** the emf induced in a conductor moving through a constant magnetic field.

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| The straight conductor of length *l* shown in Figure is moving through a uniform magnetic field directed into the page. For simplicity, let’s assume the conductor is moving in a direction perpendicular to the field with constant velocity under the influence of some external agent. From the magnetic version of the particle in a field model, the electrons in the conductor experience a force **F***B =* *q***v×B** that is directed along the length *l*, perpendicular to both **v** and **B**. | Похожее изображение |

Under the influence of this force, the electrons move to the lower end of the conductor and accumulate there, leaving a net positive charge at the upper end. As a result of this charge separation, an electric field **E** is produced inside the conductor. Therefore, the electrons are also described by the electric version of the particle in a field model. The charges accumulate at both ends until the downward magnetic force *qvB* on charges remaining in the conductor is balanced by the upward electric force *qE.* The electrons are then described by the particle in equilibrium model. The condition for equilibrium requires that the forces on the electrons balance:

*qE* = *qvB* or *E =* *vB*

The magnitude of the electric field produced in the conductor is related to the potential difference across the ends of the conductor according to the relationship Δ*V* = *El*. Therefore, for the equilibrium condition, Δ*V* = *El* = *Blv*

where the upper end of the conductor in Figure is at a higher electric potential than the lower end

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| A more interesting situation occurs when the moving conductor is part of a closed conducting path. This situation is particularly useful for illustrating how a changing magnetic flux causes an induced current in a closed circuit. Consider a circuit consisting of a conducting bar of length, sliding along two fixed, parallel conducting rails as shown in Figure (a). For simplicity, let’s assume the bar has zero resistance and the stationary part of the circuit has a resistance *R.* A uniform and constant magnetic field **B** is applied perpendicular to the plane of the circuit. | Похожее изображение |

As the bar is pulled to the right with a velocity **v** under the influence of an applied force **F**app, free charges in the bar are moving particles in a magnetic field that experience a magnetic force directed along the length of the bar. This force sets up an induced current because the charges are free to move in the closed conducting path. In this case, the rate of change of magnetic flux through the circuit and the corresponding induced motional emf across the moving bar are proportional to the change in area of the circuit.

Because the area enclosed by the circuit at any instant is *l∙x*, where *x* is the position of the bar, the magnetic flux through that area is

*ФB =* *B∙l∙x*

Using Faraday’s law and noting that *x* changes with time at a rate *dx*/*dt* = *v*, we find that the induced motional emf is

Because the resistance of the circuit is *R*, the magnitude of the induced current is

The equivalent circuit diagram for this example is shown in Figure (b).

Let’s examine the system using energy considerations. Because no battery is in the circuit, you might wonder about the origin of the induced current and the energy delivered to the resistor. We can understand the source of this current and energy by noting that the applied force does work on the conducting bar. The change in energy in the system during some time interval must be equal to the transfer of energy into the system by work. Using last Equation and *F*app = *FB =* *IlB*, the power delivered by the applied force is

we see that this power input is equal to the rate at which energy is delivered to the resistor, consistent with the principle of conservation of energy.

Faraday’s law (Eq. (1)) indicates that the induced emf and the change in flux have opposite algebraic signs. This feature has a very real physical interpretation that has come to be known as **Lenz’s law:**

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| The induced current in a loop is in the direction that creates a magnetic field that opposes the change in magnetic flux through the area enclosed by the loop. |

That is, the induced current tends to keep the original magnetic flux through the loop from changing. This law is a consequence of the law of conservation of energy.

1. **Induced emf and Induced Electric Fields. Eddy Currents.**

We have seen that a changing magnetic flux induces an emf and a current in a conducting loop. In our study of electricity, we related a current to an electric field that applies electric forces on charged particles. In the same way, we can relate an induced current in a conducting loop to an electric field by claiming that an electric field is created in the conductor as a result of the changing magnetic flux.

We also noted in our study of electricity that the existence of an electric field is independent of the presence of any test charges. This independence suggests that even in the absence of a conducting loop, a *changing magnetic field* generates an electric field in empty space.

This induced electric field is *nonconservative,* unlike the electrostatic field produced by stationary charges.

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| To illustrate this point, consider a conducting loop of radius *r* situated in a uniform magnetic field that is perpendicular to the plane of the loop as in Figure. If the magnetic field changes with time, an emf ℰ = -*dФB*/*dt* is, according to Faraday’s law, induced in the loop. The induction of a current in the loop implies the presence of an induced electric field **E**, which must be tangent to the loop because that is the direction in which the charges in the wire move in response to the electric force. The work done by the electric field in moving a charge *q* once around the loop is equal to *q*ℰ. | Картинки по запросу A conducting loop of radius r in a uniform magnetic field |
| Because the electric force acting on the charge is *q***E** , the work done by the electric field in moving the charge once around the loop is *qE*(2π*r*), where 2π*r* is the circumference of the loop. These two expressions for the work done must be equal; therefore,  *q*ℰ = *qE*(2π*r*), | Картинки по запросу вихревое электрическое поле |

Using this result along with Equation ℰ = -*dФB*/*dt* and that Ф*B =* *BA* = *Bπr*2 for a circular loop, the induced electric field can be expressed as

If the time variation of the magnetic field is specified, the induced electric field can be calculated from this Equation.

The emf for any closed path can be expressed as the line integral of **E∙***d***s** over that path:

(In more general cases, *E* may not be constant and the path may not be a circle.)

Hence, the induced electric field **E** in last Equation that is generated by a changing magnetic field is a nonconservative field (work done on a closed path is not zero). This field **E** isanotherkind of electric field because a work done by electrostatic electric field over closed path is equal zero.

As we have seen, an emf and a current are induced in a circuit by a changing magnetic flux. In the same manner, circulating currents called **eddy currents** are induced in bulk pieces of metal moving through a magnetic field.

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| This phenomenon can be demonstrated by allowing a flat copper or aluminum plate attached at the end of a rigid bar to swing back and forth through a magnetic field (see Figure). As the plate enters the field, the changing magnetic flux induces an emf in the plate, which in turn causes the free electrons in the plate to move, producing the swirling ***eddy currents***. According to Lenz’s law, the direction of the eddy currents is such that they create magnetic fields that oppose the change that causes the currents. For this reason, the eddy currents must produce effective magnetic poles on the plate, which are repelled by the poles of the magnet; this situation gives rise to a repulsive force that opposes the motion of the plate. | Похожее изображение |

(If the opposite were true, the plate would accelerate and its energy would increase after each swing, in violation of the law of conservation of energy.)

As indicated in Figure, with **B** directed into the page, the induced eddy current is counterclockwise as the swinging plate enters the field at position 1 because the flux due to the external magnetic field into the page through the plate is increasing. Hence, by Lenz’s law, the induced current must provide its own magnetic field out of the page. The opposite is true as the plate leaves the field at position 2, where the current is clockwise. Because the induced eddy current always produces a magnetic retarding force **F***B* when the plate enters or leaves the field, the swinging plate eventually comes to rest.

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| If slots are cut in the plate as shown in Figure, the eddy currents and the corresponding retarding force are greatly reduced. We can understand this reduction in force by realizing that the cuts in the plate prevent the formation of any large current loops.  The braking systems on many subway and rapid-transit cars make use of electromagnetic induction and eddy currents. An electromagnet attached to the train is positioned near the steel rails. (An electromagnet is essentially a solenoid with an iron core.) The braking action occurs when a large current is passed through the electromagnet. | Картинки по запросу Formation of eddy currents in a conducting plate |

The relative motion of the magnet and rails induces eddy currents in the rails, and the direction of these currents produces a drag force on the moving train. Because the eddy currents decrease steadily in magnitude as the train slows down, the braking effect is quite smooth. As a safety measure, some power tools use eddy currents to stop rapidly spinning blades once the device is turned off.

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| Eddy currents are often undesirable because they represent a transformation of mechanical energy to internal energy. To reduce this energy loss, conducting parts are often laminated; that is, they are built up in thin layers separated by a nonconducting material such as lacquer or a metal oxide. This layered structure prevents large current loops and effectively confines the currents to small loops in individual layers. Such a laminated structure is used in transformer cores and motors to minimize eddy currents and thereby increase the efficiency of these devices. | Похожее изображение |

1. **Self-Induction and Inductance.**

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| Consider a circuit consisting of a switch, a resistor, and a source of emf as shown in Figure. The circuit diagram is represented in perspective to show the orientations of some of the magnetic field lines due to the current in the circuit. When the switch is thrown to its closed position, the current does not immediately jump from zero to its maximum value ℰ/*R.* Faraday’s law of electromagnetic induction Eq. (1) can be used to describe this effect as follows. | Картинки по запросу Self-induction in a simple circuit. |

As the current increases with time, the magnetic field lines surrounding the wires pass through the loop represented by the circuit itself. This magnetic field passing through the loop causes a magnetic flux through the loop. This increasing flux creates an induced emf in the circuit. The direction of the induced emf is such that it would cause an induced current in the loop (if the loop did not already carry a current), which would establish a magnetic field opposing the change in the original magnetic field. Therefore, the direction of the induced emf is opposite the direction of the emf of the battery, which results in a gradual rather than instantaneous increase in the current to its final equilibrium value. Because of the direction of the induced emf, it is also called a *back emf,* similar to that in a motors. This effect is called **self-induction** because the changing flux through the circuit and the resultant induced emf arise from the circuit itself. The emf ℰ*L* set up in this case is called a **self-induced emf.**

To obtain a quantitative description of self-induction, recall from Faraday’s law that the induced emf is equal to the negative of the time rate of change of the magnetic flux. The magnetic flux is proportional to the magnetic field, which in turn is proportional to the current in the circuit. Therefore, a self-induced emf is always proportional to the time rate of change of the current. For any loop of wire, we can write this proportionality as

(6)

where *L* is a proportionality constant—called the **inductance** of the loop—that depends on the geometry of the loop and other physical characteristics.

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| If we consider a closely spaced coil of *N* turns (a toroid or an ideal solenoid) carrying a current *i* and containing *N* turns, Faraday’s law tells us that ℰ*L* = -*N d*Ф*B*/*dt.* Combining this expression with Equation (5) gives  (7)  where it is assumed the same magnetic flux passes through each turn and *L* is the inductance of the entire coil.  From Equation (6), we can also write the inductance as the ratio  (8) | Картинки по запросу solenoid and toroid |

Recall that resistance is a measure of the opposition to current as given by Equation (Ohm's law) *R =* Δ*V*/*I*; in comparison with this, Equation (4) shows us that inductance is a measure of the opposition to a *change* in current.

The SI unit of inductance is the **henry** (H), which as we can see from Equation (8) is 1 volt-second per ampere: 1 H = 1 V∙s/A.

The inductance of a coil depends on its geometry. This dependence is analogous to the capacitance of a capacitor depending on the geometry of its plates as we found in course of Physics 1 and the resistance of a resistor depending on the length and area of the conducting material. Inductance calculations can be quite difficult to perform for complicated geometries, but the examples below involve simple situations for which inductances are easily evaluated.

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| Consider a uniformly wound solenoid having *N* turns and length *l*. Assume *l* is much longer than the radius of the windings and the core of the solenoid is air. Find the inductance of the solenoid.  Find the magnetic flux through each turn of area *A* in the solenoid, using the expression for the magnetic field: | Картинки по запросу solenoid |

Substitute this expression into Equation (7):

(9)

1. **Energy of a Magnetic Field.**

The energy stored in the inductor at any time, we can write as

(10)

We can also determine the energy density of a magnetic field. For simplicity, consider a solenoid whose inductance is given by Equation (9):

where V is the volume of solenoid.

The magnetic field of a solenoid is:

Combine these equations with equation (10):

The magnetic energy density, or the energy stored per unit volume in the magnetic field of the inductor, is

(11)

Equation (11) is similar in form to Equation for the energy per unit volume stored in an electric field,

In both cases, the energy density is proportional to the square of the field magnitude.

**Fundamental of Physics Lecture 13.** **Wave optics.**

1. **Nature of the light. Huygen’s principle.**

Before the beginning of the 19th century, light was considered to be a stream of particles that either was emitted by the object being viewed or emanated from the eyes of the viewer. Newton, the chief architect of the particle model of light, held that particles were emitted from a light source and that these particles stimulated the sense of sight upon entering the eye. Using this idea, he was able to explain reflection and refraction.

Most scientists accepted Newton’s particle model. During Newton’s lifetime, however, another model was proposed, one that argued that light might be some sort of wave motion. In 1678, Dutch physicist and astronomer Christian Huygens showed that a wave model of light could also explain reflection and refraction.

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| All points on a given wave front are taken as point sources for the production of spherical secondary waves, called wavelets, that propagate outward through a medium with speeds characteristic of waves in that medium. After some time interval has passed, the new position of the wave front is the surface tangent to the wavelets. |  |

In 1801, Thomas Young (1773–1829) provided the first clear experimental demonstration of the wave nature of light. Young showed that under appropriate conditions light rays interfere with one another according to the waves in interference model, just like mechanical waves. Such behavior could not be explained at that time by a particle model because there was no conceivable way in which two or more particles could come together and cancel one another. Additional developments during the 19th century led to the general acceptance of the wave model of light, the most important resulting from the work of Maxwell, who in 1873 asserted that light was a form of high-frequency electromagnetic wave. As discussed, Hertz provided experimental confirmation of Maxwell’s theory in 1887 by producing and detecting electromagnetic waves.

Although the wave model and the classical theory of electricity and magnetism were able to explain most known properties of light, they could not explain some subsequent experiments. The most striking phenomenon is the photoelectric effect, also discovered by Hertz: when light strikes a metal surface, electrons are sometimes ejected from the surface. As one example of the difficulties that arose, experiments showed that the kinetic energy of an ejected electron is independent of the light intensity. This finding contradicted the wave model, which held that a more intense beam of light should add more energy to the electron. Einstein proposed an explanation of the photoelectric effect in 1905 using a model based on the concept of quantization developed by Max Planck (1858–1947) in 1900.

The quantization model assumes the energy of a light wave is present in particles called *photons;* hence, the energy is said to be quantized. According to Einstein’s theory, the energy of a photon is proportional to the frequency of the electromagnetic wave:

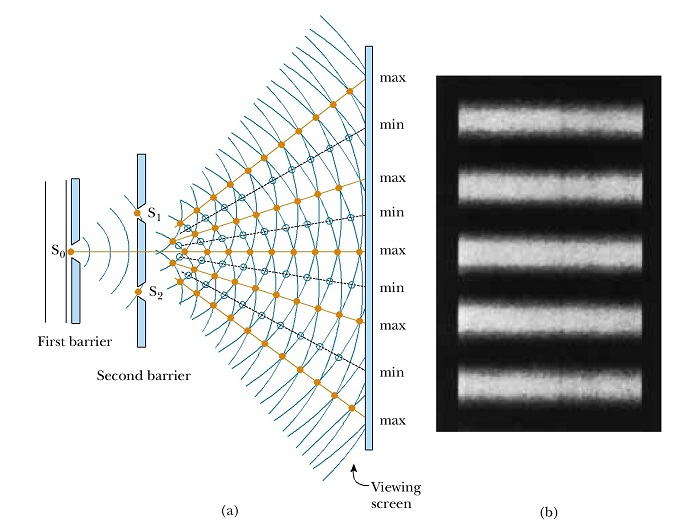
*E* = *hf*

where the constant of proportionality *h* = 6.63∙10-34 J∙s is called *Planck’s constant.* We study this theory later.

In view of these developments, light must be regarded as having a dual nature. Light exhibits the characteristics of a wave in some situations and the characteristics of a particle in other situations. Light is light, to be sure. The question “Is light a wave or a particle?” is inappropriate, however. Sometimes light acts like a wave, and other times it acts like a particle.

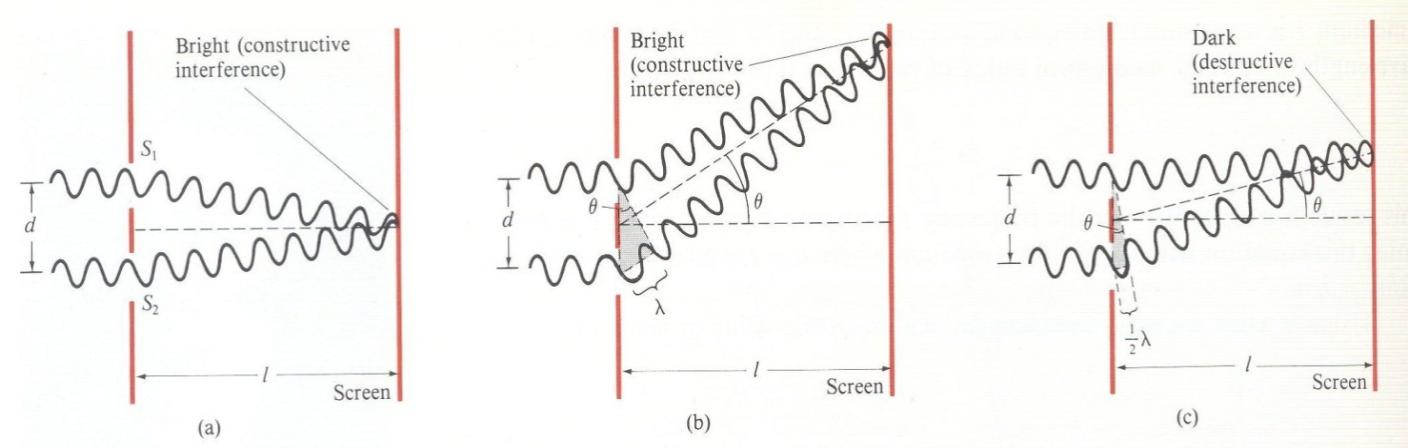
1. **Interference. Coherent sources. Two-source interference. Interference condition.**

Interference in light waves from two sources was first demonstrated by Thomas Young in 1801. A schematic diagram of the apparatus Young used is shown in Figure.



Plane light waves arrive at a barrier that contains two slits S1 and S2. The light from S1 and S2 produces on a viewing screen a visible pattern of bright and dark parallel bands called **fringes** (Fig. b). When the light from S1 and that from S2 both arrive at a point on the screen such that constructive interference occurs at that location, a bright fringe appears. When the light from the two slits combines destructively at any location on the screen, a dark fringe results.

Next Figure shows some of the ways in which two waves can combine at the screen.



In Figure a, the two waves, which leave the two slits in phase, strike the screen at the central point. Because both waves travel the same distance, they arrive at point in phase. As a result, constructive interference occurs at this location and a bright fringe is observed. In Figure b, the two waves also start in phase, but here the lower wave has to travel one wavelength farther than the upper wave to reach the point. Because the lower wave falls behind the upper one by exactly one wavelength, they still arrive in phase at *P* and a another bright fringe appears at this location. At point in Figure c, however, the lower wave has fallen half a wavelength behind the upper wave and a crest of the upper wave overlaps a trough of the lower wave, giving rise to destructive interference at this point*.* A dark fringe is therefore observed at this location.

If two lightbulbs are placed side by side so that light from both bulbs combines, no interference effects are observed because the light waves from one bulb are emitted independently of those from the other bulb. The emissions from the two lightbulbs do not maintain a constant phase relationship with each other over time.

Light waves from an ordinary source such as a lightbulb undergo random phase changes in time intervals of less than a nanosecond. Therefore, the conditions for constructive interference, destructive interference, or some intermediate state are maintained only for such short time intervals. Because the eye cannot follow such rapid changes, no interference effects are observed. Such light sources are said to be **incoherent.** To observe interference of waves from two sources, the following conditions must be met:

• The sources must be **coherent;** that is, they must maintain a constant phase with respect to each other.

• The sources should be **monochromatic;** that is, they should be of a single wavelength.

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| Let’s look in more detail at the two-dimensional nature of Young’s experiment with the help of Figure. The viewing screen is located a perpendicular distance *L* from the barrier containing two slits, S1 and S2. These slits are separated by a distance *d*, and the source is monochromatic. To reach any arbitrary point *P* in the upper half of the screen, a wave from the lower slit must travel farther than a wave from the upper slit. The extra distance traveled from the lower slit is the **path difference** δ (Greek letter delta). If we assume the rays labeled *r*1 and *r*2 are parallel, which is approximately true if *L* is much greater than *d*, then δ is given by | Картинки по запросу young’s double-slit experiment |

δ = *r*2 - *r*1 = *d* sin θ

The value of δ determines whether the two waves are in phase when they arrive at point *P.* If δ is either zero or some integer multiple of the wavelength, the two waves are in phase at point *P* and constructive interference results. Therefore, the condition for bright fringes, or **constructive interference,** at point *P* is

*d sin θbright = m λ* *m* = 0, ± 1, ± 2, ±3, ...

The number *m* is called the **order number.** For constructive interference, the order number is the same as the number of wavelengths that represents the path difference between the waves from the two slits. The central bright fringe at θbright = 0 is called the *zeroth-order maximum.* The first maximum on either side, where *m =* ±1, is called the *first-order maximum,* and so forth.

When δ is an odd multiple of λ/2, the two waves arriving at point *P* are 180° out of phase and give rise to destructive interference. Therefore, the condition for dark fringes, or **destructive interference,** at point *P* is

*d sin θdark = (m+1/2) λ* *m* = 0, ± 1, ± 2, ±3, ...

These equations provide the *angular* positions of the fringes. It is also useful to obtain expressions for the *linear* positions measured along the screen from *O* to *P.*

From the triangle *OPQ* in Figure, we see that

*tan θ = y/L*

Using this result, the linear positions of bright and dark fringes are given by

*ybright =L∙tan θbright*

*ydark =L∙tan θdark*

When the angles to the fringes are small, the positions of the fringes are linear near the center of the pattern. That can be verified by noting that for small angles, tan θ ≈ sin θ, so Equations give the positions of the bright fringes as *y*bright = *L* sin θbright and dark fringes *y*dark = *L* sin θdark. Incorporating these Equations give

(small angles)

(small angles)

This result shows that *y*bright and *y*dark are linear in the order number *m*, so the fringes are equally spaced for small angles. As demonstrated, Young’s double-slit experiment provides a method for measuring the wavelength of light.

1. **Observation methods for interference.**

**Lloyd's mirror**

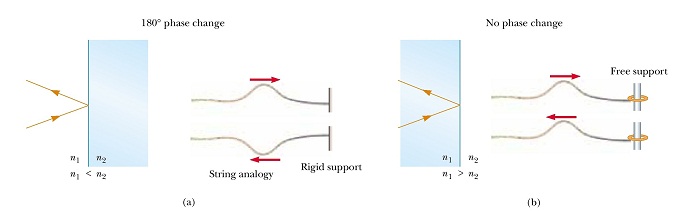
Young’s method for producing two coherent light sources involves illuminating a pair of slits with a single source. Another simple, yet ingenious, arrangement for producing an interference pattern with a single light source is known as *Lloyd’s mirror* (see Figure).

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| A point light source S is placed close to a mirror, and a viewing screen is positioned some distance away and perpendicular to the mirror. Light waves can reach point *P* on the screen either directly from S to *P* or by the path involving reflection from the mirror. The reflected ray can be treated as a ray originating from a virtual source S'. As a result, we can think of this arrangement as a doubleslit source where the distance *d* between sources S and S' in Figure is analogous to length *d* in doubleslit. | Картинки по запросу Lloyd’s mirror |

Hence, at observation points far from the source (*L* >> *d*), we expect waves from S and S' to form an interference pattern exactly like the one formed by two real coherent sources. An interference pattern is indeed observed. The positions of the dark and bright fringes, however, are reversed relative to the pattern created by two real coherent sources (Young’s experiment). Such a reversal can only occur if the coherent sources S and S' differ in phase by 180°.

To illustrate further, consider point *P*', the point where the mirror intersects the screen. This point is equidistant from sources S and S'. If path difference alone were responsible for the phase difference, we would see a bright fringe at *P'* (because the path difference is zero for this point), corresponding to the central bright fringe of the two-slit interference pattern. Instead, a dark fringe is observed at *P'*. We therefore conclude that a 180° phase change must be produced by reflection from the mirror. In general, an electromagnetic wave undergoes a phase change of 180° upon reflection from a medium that has a higher index of refraction than the one in which the wave is traveling.

It is useful to draw an analogy between reflected light waves and the reflections of a transverse pulse on a stretched string (See course Physics 1). The reflected pulse on a string undergoes a phase change of 180° when reflected from the boundary of a denser string or a rigid support, but no phase change occurs when the pulse is reflected from the boundary of a less dense string or a freely-supported end. Similarly, an electromagnetic wave undergoes a 180° phase change when reflected from a boundary leading to an ***optically denser*** medium (defined as a medium with a higher index of refraction **n**), but no phase change occurs when the wave is reflected from a boundary leading to a ***less dense*** medium. These rules, summarized in Figure bellow, can be deduced from Maxwell’s equations, but the treatment is beyond our course.



**Plane-parallel film**

Interference effects are commonly observed in thin films, such as thin layers of oil on water or the thin surface of a soap bubble. The varied colors observed when white light is incident on such films result from the interference of waves reflected from the two surfaces of the film.

Consider a film of uniform thickness *t* and index of refraction *n*. The wavelength of light λ*n* in the film is λ*n =λ/n* where λ is the wavelength of the light in free space and *n* is the index of refraction of the film material.

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| Let’s assume light rays traveling in air are nearly normal to the two surfaces of the film as shown in Figure. Reflected ray 1, which is reflected from the upper surface (*A*) in Figure, undergoes a phase change of 180° with respect to the incident wave. Reflected ray 2, which is reflected from the lower film surface (*B*), undergoes no phase change because it is reflected from a medium (air) that has a lower index of refraction.  Therefore, ray 1 is 180° out of phase with ray 2, which is equivalent to a path difference of λ*n*/2. We must also consider, however, that ray 2 travels an extra distance 2*t* before the waves recombine in the air above surface *A.* (Remember that we are considering light rays that are close to normal to the surface. If the rays are not close to normal, the path difference is larger than 2*t.*) | Похожее изображение |

If 2*t* = λ*n*/2, rays 1 and 2 recombine in phase and the result is constructive interference. In general, the condition for *constructive* interference in thin films is

2*t* = (*m +* 1/2) λ*n m* = 0, 1, 2,...

This condition takes into account two factors: (1) the difference in path length for the two rays (the term *m* λ*n*) and (2) the 180° phase change upon reflection (the term 1/2 λ*n*). Because λ*n* = λ/*n*, we can rewrite Equation for constructive interference as

2n*t* = (*m +* 1/2) λ *m* = 0, 1, 2, ...

If the extra distance 2*t* traveled by ray 2 corresponds to a multiple of λ*n*, the two waves combine out of phase and the result is destructive interference. The general equation for *destructive* interference in thin films is

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| 2*nt* = *mλ* *m* = 0, 1, 2, ...  The foregoing conditions for constructive and destructive interference are valid when the medium above the top surface of the film is the same as the medium below the bottom surface or, if there are different media above and below the film, the index of refraction of both is less than *n.*  If the film is placed between two different media, one with *n* < *n*film and the other with *n* > *n*film (see Figure), the conditions for constructive and destructive interference are reversed. | Похожее изображение |

In that case, either there is a phase change of 180° for both ray 1 reflecting from surface *A* and ray 2 reflecting from surface *B* or there is no phase change for either ray; hence, the net change in relative phase due to the reflections is zero.

**Newton’s Rings**

Another method for observing interference in light waves is to place a plano-convex lens on top of a flat glass surface as shown in Figure a.

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| With this arrangement, the air film between the glass surfaces varies in thickness from zero at the point of contact to some nonzero value at point *P.* If the radius of curvature *R* of the lens is much greater than the distance *r* and the system is viewed from above, a pattern of light and dark rings is observed as shown in Figure b. These circular fringes, discovered by Newton, are called **Newton’s rings.** | Картинки по запросу The combination of rays reflected from the flat plate and the curved lens surface |

The interference effect is due to the combination of ray 1, reflected from the flat plate, with ray 2, reflected from the curved surface of the lens. Ray 1 undergoes a phase change of 180° upon reflection (because it is reflected from a medium of higher index of refraction), whereas ray 2 undergoes no phase change (because it is reflected from a medium of lower index of refraction). Hence, the conditions for constructive and destructive interference are given by Equations above, respectively, with *n* = 1 because the film is air. Because there is no path difference and the total phase change is due only to the 180° phase change upon reflection, the contact point at *O* is dark as seen in Figure b.

Using the geometry shown in Figure a, we can obtain expressions for the radii of the bright and dark bands in terms of the radius of curvature *R* and wavelength l. For example, the dark rings have radii given by the expression

We can obtain the wavelength of the light causing the interference pattern by measuring the radii of the rings, provided *R* is known. Conversely, we can use a known wavelength to obtain *R.*

One important use of Newton’s rings is in the testing of optical lenses. A circular pattern like that pictured in Figure ***a*** is obtained only when the lens is ground to a perfectly symmetric curvature. Variations from such symmetry produce a pattern with fringes that vary from a smooth, circular shape. These variations indicate how the lens must be reground and repolished to remove imperfections.

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| Картинки по запросу newton's rings  (a) | Похожее изображение  (b) | Похожее изображение  (c) |

1. **Fresnel's principle. Fresnel and Fraunhofer diffraction. Diffraction on a single slit.**

We discussed before in Young's double slit experiment, that light of wavelength comparable to or larger than the width of a slit spreads out in all forward directions upon passing through the slit. This phenomenon is called *diffraction.* When light passes through a narrow slit, it spreads beyond the narrow path defined by the slit into regions that would be in shadow if light traveled in straight lines. Other waves, such as sound waves and water waves also have this property of spreading when passing through apertures or by sharp edges.

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| Картинки по запросу diffraction | Картинки по запросу Light from a small source passes by the edge |

You might expect that the light passing through a small opening would simply result in a broad region of light on a screen due to the spreading of the light as it passes through the opening. We find something more interesting, however.

A **diffraction pattern** consisting of light and dark areas is observed, somewhat similar to the interference patterns discussed earlier. For example, when a narrow slit is placed between a distant light source (or a laser beam) and a screen, the light produces a diffraction pattern like that shown in Figure. The pattern consists of a broad, intense central band (called the **central maximum**) flanked by a series of narrower, less intense additional bands (called **side maxima** or **secondary maxima**) and a series of intervening dark bands (or **minima**).

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| Картинки по запросу diffraction pattern  Diffraction by the slit | Картинки по запросу diffraction pattern  Diffraction by the aperture | Картинки по запросу diffraction pattern by the edge  Diffraction by the edge |

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| Figure on the right shows diffraction pattern associated with the shadow of a coin. A bright spot occurs at the center, and circular fringes extend outward from the shadow’s edge. We can explain the central bright spot by using the wave theory of light, which predicts constructive interference at this point. From the viewpoint of ray optics (in which light is viewed as rays traveling in straight lines), we expect the center of the shadow to be dark because that part of the viewing screen is completely shielded by the coin. | Картинки по запросу Light from a small source passes by the edge |

Shortly before the central bright spot was first observed, one of the supporters of ray (corpuscular) optics, Simeon Poisson, argued that if Augustin Fresnel’s wave theory of light were valid, a central bright spot should be observed in the shadow of a circular object illuminated by a point source of light. To Poisson’s astonishment, the spot was observed by Dominique Arago shortly thereafter. Therefore, Poisson’s prediction reinforced the wave theory rather than disproving it.

The **Huygens–Fresnel principle** (named after [Dutch](https://en.wikipedia.org/wiki/Netherlands" \o "Netherlands) [physicist](https://en.wikipedia.org/wiki/Physicist" \o "Physicist) [Christiaan Huygens](https://en.wikipedia.org/wiki/Christiaan_Huygens" \o "Christiaan Huygens) and [French](https://en.wikipedia.org/wiki/France" \o "France) physicist [Augustin-Jean Fresnel](https://en.wikipedia.org/wiki/Augustin-Jean_Fresnel" \o "Augustin-Jean Fresnel)) is a method of analysis applied to problems of [wave propagation](https://en.wikipedia.org/wiki/Wave_propagation" \o "Wave propagation) both in the far-field limit and in near-field diffraction.

Recall that in 1678, Huygens proposed that every point which a luminous disturbance reaches becomes a source of a spherical wave; the sum of these secondary waves determines the form of the wave at any subsequent time. He assumed that the secondary waves travelled only in the "forward" direction and it is not explained in the theory why this is the case. He was able to provide a qualitative explanation of linear and spherical wave propagation, and to derive the laws of reflection and refraction using this principle, but could not explain the deviations from rectilinear propagation that occur when light encounters edges, apertures and screens, commonly known as diffraction effects.

In 1816, Fresnelshowed that Huygens' Principle, together with his own principle of interference could explain both the rectilinear propagation of light and also diffraction effects. To obtain agreement with experimental results, he had to include additional arbitrary assumptions about the phase and amplitude of the secondary waves, and also an obliquity factor. These assumptions have no obvious physical foundation but led to predictions that agreed with many experimental observations, including the Arago spot.

A zone plate is a diffractive optic that consists of several radially symmetric rings called *zones*. Zones alternate between opaque and transparent, and are spaced so that light transmitted by the transparent zones constructively interferes at the desired focus.

To begin, consider a source point in the plane of the zone plate located a distance r from the center of the zone plate.

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| The distance *l* between the source point and the focus is called the *optical path length*, and is given by:  The goal is to locate source points that constructively interfere at the focus. This is accomplished by requiring that optical path lengths *l* differ by no more than λ/2 from the optical pathlength of the on-axis source *f*  *l - f < λ/2*  Source points satisfying this criterion define the *1st zone*  As source points move further away from the center of the zone plate, the quantity (*l*−f) will increase beyond λ/2. These sources with optical pathlengths satisfying  λ/2 < *l - f < λ* | Похожее изображение |

define the *2nd zone*, and will *destructively* interfere with the sources in the 1st zone.

By continuing in this manner, the definition of the *nth zone* can be generalized to be the collection of source points with optical pathlengths satisfying

Source points from odd zones (n=1,3,5,...) will *constructively* interfere with the 1st zone, whereas source points from even zones (n=2,4,6,...) will *destructively* interfere with the 1st zone. To maximize constructive interference, the zone plate is constructed by blocking the even numbered zones with an appropriate absorber and letting the odd zones pass through.

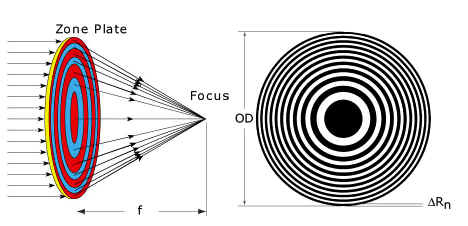
Number of open zones is

n = rn2/(λ∙f)

where rn - radius of aperture or obstacle

λ - wavelength

f - distance to the point of observation.



The **Fresnel number** (*F*), named after the physicist Augustin Fresnel  is a dimensionless number occurring in optics, in scalar diffraction theory.

where: {\displaystyle a\!}*a* is the characteristic size (e.g. radius) of the aperture or obstacle

*{\displaystyle L\!}L* is the distance of the screen from the aperture

{\displaystyle \lambda \!}λ is the incident wavelength.

*Fresnel diffraction or near-field diffraction* is a process of diffraction that occurs when a wave passes through an aperture and diffracts in the near field, causing any diffraction pattern observed to differ in size and shape, depending on the distance between the aperture and the projection. It occurs due to the short distance in which the diffracted waves propagate, which results in a Fresnel number greater than 1 (F>1).

When the distance is increased (the distance to the aperture is much bigger than the aperture size), outgoing diffracted waves become planar and *Fraunhofer or far-field diffraction occurs*. This propagation regime verifies F{\displaystyle \ F\ll 1}FF << 1.

If case F >> 1 no diffraction observed.

**Diffraction Patterns from Narrow Slits.** Let’s consider a common situation, that of light passing through a narrow opening modeled as a slit and projected onto a screen. To simplify our analysis, we assume the observing screen is far from the slit and the rays reaching the screen are approximately parallel. (This situation can also be achieved experimentally by using a converging lens to focus the parallel rays on a nearby screen.) In this model, the pattern on the screen is called a **Fraunhofer diffraction pattern.** If the screen is brought close to the slit (and no lens is used), the pattern is a *Fresnel* diffraction pattern. (In this course we will discourse only Fraunhofer diffraction.)

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| Until now, we have assumed slits are point sources of light. In this section, we abandon that assumption and see how the finite width of slits is the basis for understanding Fraunhofer diffraction. We can explain some important features of this phenomenon by examining waves coming from various portions of the slit as shown in Figure. According to Huygens’s principle, each portion of the slit acts as a source of light waves. Hence, light from one portion of the slit can interfere with light from another portion, and the resultant light intensity on a viewing screen depends on the direction θ. Based on this analysis, we recognize that a diffraction pattern is actually an interference pattern in which the different sources of light are different portions of the single slit! | Картинки по запросу Paths of light rays that encounter a narrow slit |

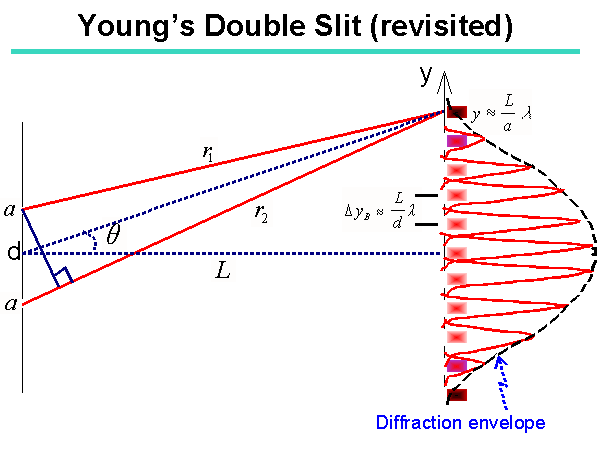
Therefore, the diffraction patterns we discuss in this chapter are applications of the waves in interference analysis model. To analyze the diffraction pattern, let’s divide the slit into two halves as shown in Figure. Keeping in mind that all the waves are in phase as they leave the slit, consider rays 1 and 3. As these two rays travel toward a viewing screen far to the right of the figure, ray 1 travels farther than ray 3 by an amount equal to the path difference (*a*/2) sin θ, where *a* is the width of the slit. Similarly, the path difference between rays 2 and 4 is also (*a*/2) sin θ, as is that between rays 3 and 5. If this path difference is exactly half a wavelength (corresponding to a phase difference of 180°), the pairs of waves cancel each other and destructive interference results. This cancellation occurs for any two rays that originate at points separated by half the slit width because the phase difference between two such points is 180°. Therefore, waves from the upper half of the slit interfere destructively with waves from the lower half when

or, if we consider waves at angle θ both above the dashed line in Figure and below,

Therefore, the general condition for destructive interference is

*m* = ± 1, ± 2, ±3, ...

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| This equation gives the values of θdark for which the diffraction pattern has zero light intensity, that is, when a dark fringe is formed. It tells us nothing, however, about the variation in light intensity along the screen.  The general features of the intensity distribution are shown in Figure. A broad, central bright fringe is observed; this fringe is flanked by much weaker bright fringes alternating with dark fringes. The various dark fringes occur at the values of θdark that satisfy Equation. Each bright-fringe peak lies approximately halfway between its bordering dark-fringe minima. Notice that the central bright maximum is twice as wide as the secondary maxima. There is no central dark fringe, represented by the absence of *m* = 0 in Equation. | Картинки по запросу single slit diffraction pattern |



**Fundamentals of Physics Lecture 14. Polarization of Light. Absorption of light. Dispersion. Thermal radiation.**

1. **Polarized and unpolarized light. Malus’s law.**

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| In Lecture 6, we described the transverse nature of light and all other electromagnetic waves. Polarization, discussed in this section, is firm evidence of this transverse nature.  An ordinary beam of light consists of a large number of waves emitted by the atoms of the light source. Each atom produces a wave having some particular orientation of the electric field vector **E**, corresponding to the direction of atomic vibration. The *direction of polarization* of each individual wave is defined to be the direction in which the electric field is vibrating. In Figure, this direction happens to lie along the *y* axis. |  | |
| All individual electromagnetic waves traveling in the ***z***direction have an **E** vector parallel to the ***xy***plane, but this vector could be at any possible angle with respect to the *y* axis. Because all directions of vibration from a wave source are possible, the resultant electromagnetic wave is a superposition of waves vibrating in many different directions. The result is an **unpolarized** light beam, represented in Figure a. The direction of wave propagation in this figure is perpendicular to the page. The arrows show a few possible directions of the electric field vectors for the individual waves making up the resultant beam. At any given point and at some instant of time, all these individual electric field vectors add to give one resultant electric field vector. | | Картинки по запросу unpolarized light beam |

As noted in Lecture 6, a wave is said to be **linearly polarized** if the resultant electric field **E** vibrates in the same direction *at all times* at a particular point as shown in Figure b. (Sometimes, such a wave is described as *plane-polarized,* or simply *polarized.*) The plane formed by **E** and the direction of propagation is called the *plane of polarization* of the wave. If the wave on the first Figure represents the resultant of all individual waves, the plane of polarization is the ***yz***plane.

A linearly polarized beam can be obtained from an unpolarized beam by removing all waves from the beam except those whose electric field vectors oscillate in a single plane. We now discuss four processes for producing polarized light from unpolarized light.

The most common technique for producing polarized light is to use a material that transmits waves whose electric fields vibrate in a plane parallel to a certain direction and that absorbs waves whose electric fields vibrate in all other directions.

In 1938, E. H. Land (1909–1991) discovered a material, which he called *Polaroid,* that polarizes light through selective absorption. This material is fabricated in thin sheets of long-chain hydrocarbons. The sheets are stretched during manufacture so that the long-chain molecules align. After a sheet is dipped into a solution containing iodine, the molecules become good electrical conductors. Conduction takes place primarily along the hydrocarbon chains because electrons can move easily only along the chains. If light whose electric field vector is parallel to the chains is incident on the material, the electric field accelerates electrons along the chains and energy is absorbed from the radiation. Therefore, the light does not pass through the material. Light whose electric field vector is perpendicular to the chains passes through the material because electrons cannot move from one molecule to the next. As a result, when unpolarized light is incident on the material, the exiting light is polarized perpendicular to the molecular chains.

It is common to refer to the direction perpendicular to the molecular chains as the *transmission axis.* In an ideal polarizer, all light with **E** parallel to the transmission axis is transmitted and all light with **E** perpendicular to the transmission axis is absorbed.

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| Figure represents an unpolarized light beam incident on a first polarizing sheet, called the *polarizer.* Because the transmission axis is oriented vertically in the figure, the light transmitted through this sheet is polarized vertically. A second polarizing sheet, called the *analyzer,* intercepts the beam. In Figure, the analyzer transmission axis is set at an angle u to the polarizer axis. | Картинки по запросу unpolarized light beam |

We call the electric field vector of the first transmitted beam **E**o. The component of **Eo** perpendicular to the analyzer axis is completely absorbed. The component of **Eo** parallel to the analyzer axis, which is transmitted through the analyzer, is *Eo cos θ.* Because the intensity of the transmitted beam varies as the square of its magnitude, we conclude that the intensity *I* of the (polarized) beam transmitted through the analyzer varies as

*I* = *I*max cos2*θ*

where *I*max is the intensity of the polarized beam incident on the analyzer. This expression, known as **Malus’s law,** applies to any two polarizing materials whose transmission axes are at an angle u to each other. This expression shows that the intensity of the transmitted beam is maximum when the transmission axes are parallel *(θ = 0 or 180°)* and is zero (complete absorption by the analyzer) when the transmission axes are perpendicular to each other.

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| This variation in transmitted intensity through a pair of polarizing sheets is illustrated in Figure. Because the average value of cos2 θ is 1/2 , the intensity of initially unpolarized light is reduced by a factor of one-half as the light passes through a single ideal polarizer. | Картинки по запросу The intensity of light transmitted through two polarizers depends on the relative orientation of their transmission axes. |

The degree of polarization is the expression:



For plane-polarized light *Imin* = 0 and *P* = 1; For natural light I*max* = I*min* and *P* = 0.

1. **Polarization by reflection and refraction. Brewster’s law.**

When an unpolarized light beam is reflected from a surface, the polarization of the reflected light depends on the angle of incidence. If the angle of incidence is 0°, the reflected beam is unpolarized. For other angles of incidence, the reflected light is polarized to some extent, and for one particular angle of incidence, the reflected light is completely polarized. Let’s now investigate reflection at that special angle.

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| Suppose an unpolarized light beam is incident on a surface as in Figure. Each individual electric field vector can be resolved into two components: one parallel to the surface (and perpendicular to the page in Figure, represented by the dots) and the other (represented by the orange arrows) perpendicular both to the first component and to the direction of propagation. Therefore, the polarization of the entire beam can be described by two electric field components in these directions. | Картинки по запросу Figure 38.28 (a) When unpolarized light is incident on a reflecting surface, the reflected and refracted beams are partially polarized. |

It is found that the parallel component represented by the dots reflects more strongly than the other component represented by the arrows, resulting in a ***partially polarized reflected*** beam. Furthermore, the refracted beam is also partially polarized.

Now suppose the angle of incidence θ1 is varied until the angle between the reflected and refracted beams is 90° (see Figure b above). At this particular angle of incidence, the reflected beam is completely polarized (with its electric field vector parallel to the surface) and the refracted beam is still only partially polarized. The angle of incidence at which this polarization occurs is called the **polarizing angle** θ*p*.

We can obtain an expression relating the polarizing angle to the index of refraction of the reflecting substance by using Figure b. From this figure, we see that θ*p* + 90° + θ2 = 180°; therefore, θ2 = 90° - θ*p*. Using Snell’s law of refraction gives

Because sin θ2 = sin (90° - θ*p*) = cos θ*p*, we can write this expression as *n*2/*n*1 =sin θ*p* /cos θ*p* , which means that

This expression is called **Brewster’s law,** and the polarizing angle θ*p* is sometimes called **Brewster’s angle,** after its discoverer, David Brewster (1781–1868). Because *n* varies with wavelength for a given substance, Brewster’s angle is also a function of wavelength.

We can understand polarization by reflection by imagining that the electric field in the incident light sets electrons at the surface of the material in Figure 38.28b into oscillation. The component directions of oscillation are (1) parallel to the arrows shown on the refracted beam of light and therefore parallel to the reflected beam and (2) perpendicular to the page. The oscillating electrons act as dipole antennas radiating light with a polarization parallel to the direction of oscillation. Consult Figure 34.12, which shows the pattern of radiation from a dipole antenna. Notice that there is no radiation at an angle of u 5 0, that is, along the oscillation direction of the antenna. Therefore, for the oscillations in direction 1, there is no radiation in the direction along the reflected ray. For oscillations in direction 2, the electrons radiate light with a polarization perpendicular to the page. Therefore, the light reflected from the surface at this angle is completely polarized parallel to the surface.

Polarization by reflection is a common phenomenon. Sunlight reflected from water, glass, and snow is partially polarized. If the surface is horizontal, the electric field vector of the reflected light has a strong horizontal component. Sunglasses made of polarizing material reduce the glare of reflected light. The transmission axes of such lenses are oriented vertically so that they absorb the strong horizontal component of the reflected light. If you rotate sunglasses through 90°, they are not as effective at blocking the glare from shiny horizontal surfaces.

1. **Light absorption** (attenuation of light)

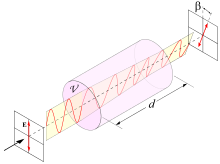
If we use the symbol alpha to denote the absorption coefficient where alpha is the fraction of photons absorbed per unit thickness, then changing of light intensity because of absorption can be written:

or in standard differential notation as:

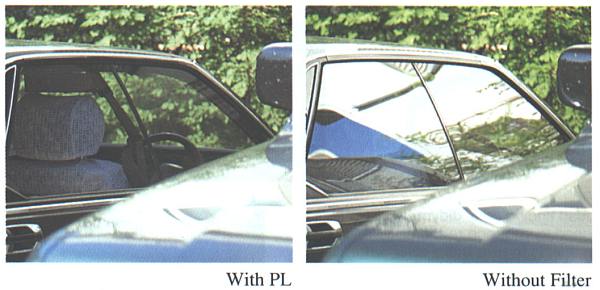
This equation can be integrated from the surface at X=0 to a depth x, and leads to the relation that the intensity I(x) at depth x is given by

where I0 is the light intensity at x=0, I0=I(x=0). This Equation expresses the so-called Beer-Lambert law or Bouguer law for transparent materials.

The reciprocal to absorption coefficient is equal to a distance, when the light intensity decreases by a factor e (the value of e=2.718).







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| Картинки по запросу Polarization by Reflection | Картинки по запросу Polarization by Reflection |

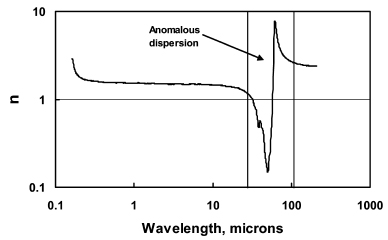
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1. **Dispersion phenomena. The electron theory of light dispersion** **and relation of dispersion with absorption.**

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| The phenomenon of **dispersion** is that the refractive index depends on the wavelength.  **n = f(λ)**  **The reason of dispersion** is that the refractive index depends on the phase velocity of a wave n = c/v and velocity depends on wavelength (or frequency).  **v= f'(λ)** | **C:\Xazar\XAZAR Physics\Course Physics 2\photo3.jpg** |

Media having this common property may be termed *dispersive media*. One important and familiar consequence of dispersion is the change in the angle of refraction of different colors of light, as seen in the spectrum produced by a dispersive prism and in chromatic aberration of lenses. Chromatic dispersion can be a problem in optical equipment like cameras, microscopes and telescopes. Since a lens is similar to a prism, it will disperse the light into a spectrum. This can be exaggerated when there are several lenses in the system. But you don't want a blurry image where the system focuses different colors of light at different spots. Such blurring is called chromatic aberration.

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| Dispersion of light is called **normal** if the refractive index decreases with increasing wavelength (with decreasing frequency). | http://www.bog5.in.ua/lection/wave_optics_lect/image_wave/clip_image093.jpg |
| In case  dispersion of light is called **anomalous**.  Normal dispersion of light seen in the distance from their own absorption lines, anomalous - within the lines or absorption lines. | http://www.bog5.in.ua/lection/wave_optics_lect/image_wave/clip_image093.jpg |



Macroscopic Maxwell's theory can not explain the dispersion of light. From Maxwell's theory that

(here we assume μ = 1)

For example for water, ε = 81, therefore, , but in fact nw = 1.33. Such a contradiction between Maxwell's theory and experiment is due to the fact, that we can correctly apply the ε = 81 only in case of static field (frequency ω = 0). In case of alternating electric field:

ε(ω) < ε(0), thus *n(ω) < n(0)*.

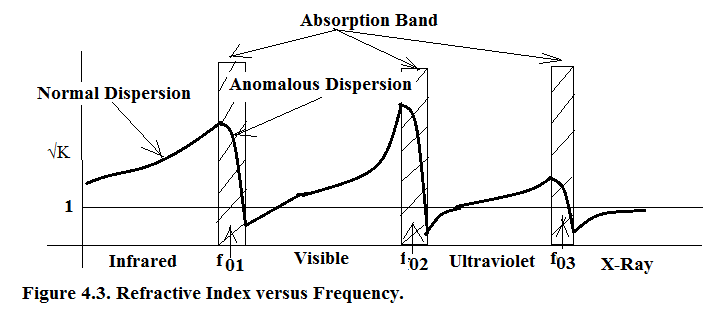
The phenomenon of dispersion can be explained by considering the interaction of light waves with matter. According to the classical theory, electrons in atoms vibrate under the influence of the quasi-elastic force. Light wave incident on a dielectric causes the electrons in an atom of the dielectric to make the forced oscillations with a frequency equal to the frequency of the driving force. But rapidly moving electrons radiate electromagnetic waves. The secondary waves (wavelets) emitted by electrons of the atoms of matter, have the same frequency as the incident wave. The initial phase may vary. These secondary waves interfere with the incident wave and the material covered in the resultant wave whose direction coincides with the direction of the incident wave, the rate of which depends on the frequency. (In vacuum speed of all frequencies is equal to the light speed in free space.) Therefore, the refractive index n depends on the frequency ω.

We will not here discuss this theory and adduce only a resulting formula:

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| where *n*0 - the number of atoms per unit volume,  e - charge of electron  m - mass of electron  ω - light frequency  ωio - natural frequencies of oscillations of electrons in atom | http://www.bog5.in.ua/lection/wave_optics_lect/image_wave/clip_image056_0000.jpg |

The last formula shows that n is dependent on the frequency of the incident light, as well as ε. If ω0 ≠ ω, then n behave as a normal dispersion, if ωo = ω, then n has a discontinuity of the 2-nd kind.

If we consider the damping of electron's oscillations (β ≠ 0), then we get a formula which gives a good agreement with the experimental curve.



The anomalous dispersion is explained by the absorption of light in matter. The deviation from normal dispersion is observed near the natural frequencies of electron oscillations in the atoms of the medium.

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| Картинки по запросу dispersion | Похожее изображение |

**Fundamental of Physics Lecture 15. Light quantum properties. Classical and Quantum mechanics.**

1. **Photoelectric effect of light.**

Blackbody radiation was the first phenomenon to be explained with a quantum model. In the latter part of the 19th century, at the same time that data were taken on thermal radiation, experiments showed that light incident on certain metallic surfaces causes electrons to be emitted from those surfaces. This phenomenon is known as the **photoelectric effect,** and the emitted electrons are called **photoelectrons.**

Several features of the photoelectric effect are listed below. For each feature, we compare the predictions made by a classical approach, using the wave model for light, with the experimental results.

**1.** Dependence of photoelectron kinetic energy on light intensity

*Classical prediction:* Electrons should absorb energy continuously from the electromagnetic waves. As the light intensity incident on a metal is increased, energy should be transferred into the metal at a higher rate and the electrons should be ejected with more kinetic energy.

*Experimental result:* The maximum kinetic energy of photoelectrons is *independent* of light intensity as shown in Figure before with both curves falling to zero at the *same* negative voltage. (According to Equation *K*max = *e* Δ*Vs*, the maximum kinetic energy is proportional to the stopping potential.)

**2.** Time interval between incidence of light and ejection of photoelectrons.

*Classical prediction:* At low light intensities, a measurable time interval should pass between the instant the light is turned on and the time an electron is ejected from the metal. This time interval is required for the electron to absorb the incident radiation before it acquires enough energy to escape from the metal.

*Experimental result:* Electrons are emitted from the surface of the metal almost *instantaneously* (less than 10-9 s after the surface is illuminated), even at very low light intensities.

**3.** Dependence of ejection of electrons on light frequency

*Classical prediction:* Electrons should be ejected from the metal at any incident light frequency, as long as the light intensity is high enough, because energy is transferred to the metal regardless of the incident light frequency.

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| *Experimental result:* No electrons are emitted if the incident light frequency falls below some **cutoff frequency** *fc*, whose value is characteristic of the material being illuminated. No electrons are ejected below this cutoff frequency *regardless* of the light intensity. | Похожее изображение |

**4.** Dependence of photoelectron kinetic energy on light frequency

*Classical prediction:* There should be *no* relationship between the frequency of the light and the electron kinetic energy. The kinetic energy should be related to the intensity of the light.

*Experimental result:* The maximum kinetic energy of the photoelectrons increases with increasing light frequency.

A successful explanation of the photoelectric effect was given by Einstein in 1905. Einstein's formula for photoelectric effect:

*hf* = *ϕ + K* max (1)

where *hf* - photon's energy; *ϕ -* work function (the work function represents the minimum energy with which an electron is bound in the metal); *K* max - kinetic energy of extracted photoelectron

With Einstein’s structural model, one can explain the observed features of the photoelectric effect that cannot be understood using classical concepts:

**1.** Dependence of photoelectron kinetic energy on light intensity.

Equation (1) shows that *K*max is independent of the light intensity. The maximum kinetic energy of any one electron, which equals *hf* - ϕ, depends only on the light frequency and the work function. If the light intensity is doubled, the number of photons arriving per unit time is doubled, which doubles the rate at which photoelectrons are emitted. The maximum kinetic energy of any one photoelectron, however, is unchanged.

**2.** Time interval between incidence of light and ejection of photoelectrons.

Near-instantaneous emission of electrons is consistent with the photon model of light. The incident energy appears in small packets, and there is a one-to-one interaction between photons and electrons. If the incident light has very low intensity, there are very few photons arriving per unit time interval; each photon, however, can have sufficient energy to eject an electron immediately.

**3.** Dependence of ejection of electrons on light frequency.

Because the photon must have energy greater than the work function ϕ to eject an electron, the photoelectric effect cannot be observed below a certain cutoff frequency. If the energy of an incoming photon does not satisfy this requirement, an electron cannot be ejected from the surface, even though many photons per unit time are incident on the metal in a very intense light beam.

**4.** Dependence of photoelectron kinetic energy on light frequency.

A photon of higher frequency carries more energy and therefore ejects a photoelectron with more kinetic energy than does a photon of lower frequency.

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| Einstein’s model predicts a linear relationship (1) between the maximum electron kinetic energy *K*max and the light frequency *f.* Experimental observation of a linear relationship between *K*max and *f* would be a final confirmation of Einstein’s theory. Indeed, such a linear relationship was observed experimentally within a few years of Einstein’s theory and is sketched in Figure.  The slope of the lines in such a plot is Planck’s constant *h.* The intercept on the horizontal axis gives the cutoff frequency below which no photoelectrons are emitted. The cutoff frequency is related to the work function through the relationship *fc =* ϕ/*h.* The cutoff frequency corresponds to a **cutoff wavelength** λ*c*, where | Похожее изображение |

(2)

and *c* is the speed of light. Wavelengths greater than λ*c* incident on a material having a work function ϕ do not result in the emission of photoelectrons.

The photoelectric effect considered above is an external photoelectric effect. In semiconductors it is possible to observe an internal photoelectric effect. With an internal photoelectric effect, the energy of the absorbed quantum of light is expended to break the covalent bond and form an additional electron-hole pair. The formation of additional electron-hole pairs leads to an increase in the conductivity of the semiconductor. The internal photoelectric effect is used in charge-coupled devices (CCD), semiconductor photo-detectors andphotovoltaic solar cells.

1. **Compton effect.**

Prior to 1922, Compton and his coworkers had accumulated evidence showing that the classical wave theory of light failed to explain the scattering of x-rays from electrons. According to classical theory, electromagnetic waves of frequency *f* incident on electrons should have two effects: (1) radiation pressure should cause the electrons to accelerate in the direction of propagation of the waves, and (2) the oscillating electric field of the incident radiation should set the electrons into oscillation at the apparent frequency *f* ', where *f* ' is the frequency in the frame of the moving electrons. This apparent frequency is different from the frequency *f* of the incident radiation because of the Doppler effect. Each electron first absorbs radiation as a moving particle and then reradiates as a moving particle, thereby exhibiting two Doppler shifts in the frequency of radiation.

Contrary to this prediction of classical wave theory of light, Compton’s experiments showed that at a given angle only *one* frequency of radiation is observed. Compton and his coworkers explained these experiments by treating photons not as waves but rather as point-like particles having energy *hf* and momentum *hf/c* and by assuming the energy and momentum of the isolated system of the colliding photon–electron pair are conserved. Compton adopted a particle model for something that was well known as a wave, and today this scattering phenomenon is known as the **Compton effect.**

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| Figure shows the quantum picture of the collision between an individual x-ray photon of frequency *f*o and an electron. In the quantum model, the electron is scattered through an angle ϕ with respect to this direction as in a billiard-ball type of collision. (The symbol ϕ used here is an angle and is not to be confused with the work function, which was discussed in the preceding section.) The incident beam consisted of monochromatic x-rays of wavelength λo = 0.071 nm. | Картинки по запросу The quantum model for x-ray scattering from an electron |
| The experimental intensity- versus-wavelength plots observed by Compton for four scattering angles (corresponding to θ in Figure) are shown in the next Figure. The graphs for the three nonzero angles show two peaks, one at λo and one at λ' > λo. The shifted peak at λ' is caused by the scattering of x-rays from free electrons, which was predicted by Compton to depend on scattering angle as  where *me* is the mass of the electron. This expression is known as the **Compton shift equation** and correctly describes the positions of the peaks in Figure. | Картинки по запросу Scattered x-ray intensity versus wavelength for Compton scattering at u 5 0°, 45°, 90°, and 135°. |

1. **The laws of blackbody radiation. Kirchhoff's law.**

An object at any temperature emits electromagnetic waves in the form of **thermal radiation** from its surface. The characteristics of this radiation depend on the temperature and properties of the object’s surface. Careful study shows that the radiation consists of a continuous distribution of wavelengths from all portions of the electromagnetic spectrum. If the object is at room temperature, the wavelengths of thermal radiation are mainly in the infrared region and hence the radiation is not detected by the human eye. As the surface temperature of the object increases, the object eventually begins to glow visibly red, like the coils of a toaster. At sufficiently high temperatures, the glowing object appears white, as in the hot tungsten filament of an incandescent lightbulb.

From a classical viewpoint, thermal radiation originates from accelerated charged particles in the atoms near the surface of the object; those charged particles emit radiation much as small antennas do. The thermally agitated particles can have a distribution of energies, which accounts for the continuous spectrum of radiation emitted by the object. By the end of the 19th century, however, it became apparent that the classical theory of thermal radiation was inadequate. The basic problem was in understanding the observed distribution of wavelengths in the radiation emitted by a black body.

The value of emissivity *(e)* of bodycan vary between zero and unity depending on the properties of the surface of the object. The emissivity is equal to the **absorptivity,** which is the fraction of the incoming radiation that the surface absorbs. A mirror has very low absorptivity because it reflects almost all incident light. Therefore, a mirror surface also has a very low emissivity (e ≈ 0). At the other extreme, a black surface has high absorptivity and high emissivity. An **ideal absorber** is defined as an object that absorbs the entire energy incident on it, and for such an object, *e* = 1. An object for which *e* = 1 is often referred to as a **black body.**

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| The spaces between lumps of hot charcoal (see Figure) emit light that is very much like blackbody radiation.  As defined, a **black body** is an ideal system that absorbs all radiation incidents on it. The electromagnetic radiation emitted by the black body is called **blackbody radiation.** | Картинки по запросу The spaces between lumps of hot charcoal |
| A good approximation of a black body is a small hole leading to the inside of a hollow object as shown in Figure. Any radiation incident on the hole from outside the cavity enters the hole and is reflected a number of times on the interior walls of the cavity; hence, the hole acts as a perfect absorber.  The nature of the radiation leaving the cavity through the hole depends only on the temperature of the cavity walls and not on the material of which the walls are made. | Картинки по запросу black body |

The radiation emitted by oscillators in the cavity walls in Figure experiences boundary conditions and can be analyzed using the waves under boundary conditions analysis model. As the radiation reflects from the cavity’s walls, standing electromagnetic waves are established within the three-dimensional interior of the cavity.

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| Many standing-wave modes are possible, and the distribution of the energy in the cavity among these modes determines the wavelength distribution of the radiation leaving the cavity through the hole.  The wavelength distribution of radiation from cavities was studied experimentally in the late 19th century. Figure shows how the intensity of blackbody radiation varies with temperature and wavelength. The following two consistent experimental findings were seen as especially significant: (Stephen - Boltzmann Law and Wien's displacement law) | Картинки по запросу black body radiation |

**Kirchhoff's law.**

Quantitative characteristic of thermal radiation is the spectral density of body emissivity *Rf,T* (radiation ability) - the radiated energy from unit surface area per unit frequency range:

 (1)

where *dWf,T* - the energy of the electromagnetic radiation emitted per unit time from an area *dA* of the body surface at temperature *T* in the frequency range from *f* to (*f* + *df).*

The ability of body to absorb the radiation incident upon them is characterized by spectral absorptivity (absorbing ability) *Af,T*:

 (2),

showing absorbed part of the electromagnetic wave energy incident per unit body surface area at frequency region of *f* up to (*f* + *df)* by the body. Here *dW* - incident energy range from *f* up to (*f* + *df)* and *d(W)absor* - absorbed energy at the same region of frequencies.

The body with ability to absorb entirely all incident radiation at all temperatures and any frequency, called a perfect blackbody. Consequently, the absorptivity of a perfect blackbody for all frequencies and temperatures are identically equal to unit.

Based on the thermodynamics and analyzing equilibrium radiation conditions in an isolated system of bodies Kirchhoff found that the ratio of the emissivity to absorptivity do not depend on the nature of the body, it is the same universal function of frequency and temperature for all bodies and is equal to the emissivity of the perfect blackbody *Ef,T*,

 (3)

The energy flow emitted by the unit surface of the blackbody in all directions (within a solid angle 2π), called integral emissivity of the blackbody *RT*.

 (4)

1. **Stephen - Boltzmann Law. Wien's displacement law.**

*The total power of the emitted radiation increases with temperature. Stefan’s law:*

*P =* σ*AeT*4

where *P* is the power in watts radiated at all wavelengths from the surface of an object, *P = ART*

σ = 5.670∙10-8 W/m2∙K4 is the Stefan–Boltzmann constant,

*A* is the surface area of the object in square meters,

*e* is the integral emissivity coefficient of the surface,

*T* is the surface temperature in kelvins.

For a black body the emissivity coefficient is *e* = 1 exactly. For other bodies *0 < e < 1*

As an object radiates energy at a rate given by Stefan's law, it also absorbs electromagnetic radiation from the surroundings, which consist of other objects that radiate energy. If the latter process did not occur, an object would eventually radiate all its energy and its temperature would reach absolute zero. If an object is at a temperature *T* and its surroundings are at an average temperature *T*о, the net rate of energy gained or lost by the object as a result of radiation is

*P*net = σ*Ae*(*T*4 - *T*o4)

When an object is in equilibrium with its surroundings, it radiates and absorbs energy at the same rate and its temperature remains constant. When an object is hotter than its surroundings, it radiates more energy than it absorbs and its temperature decreases.

**The peak of the wavelength distribution shifts to shorter wavelengths as the temperature increases.** This behavior is described by the following relationship, called **Wien’s displacement law:**

λmax *T* = 2.898∙10-3 m∙K

where λmax is the wavelength at which the curve peaks and *T* is the absolute temperature of the surface of the object emitting the radiation.

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| The wavelength at the curve’s peak is inversely proportional to the absolute temperature; that is, as the temperature increases, the peak is “displaced” to shorter wavelengths (see Figure).  Wien’s displacement law is consistent with the behavior of the object mentioned at the beginning of this section. At room temperature, the object does not appear to glow because the peak is in the infrared region of the electromagnetic spectrum. | Картинки по запросу black body radiation |

At higher temperatures, it glows red because the peak is in the near infrared with some radiation at the red end of the visible spectrum, and at still higher temperatures, it glows white because the peak is in the visible so that all colors are emitted.

1. **Planck's theory.**

A successful theory for blackbody radiation must predict the shape of the curves in Figure before, the temperature dependence expressed in Stefan’s law, and the shift of the peak with temperature described by Wien’s displacement law. One of the attempts was done by Rayleigh and Jeans, but all early attempts used classical ideas to explain the shapes of the curves in Figure and were failed.

In 1900, Max Planck developed a theory of blackbody radiation that leads to an equation for *I*(λ,*T*) that is in complete agreement with experimental results at all wavelengths. In discussing this theory, we use the outline of properties of structural models:

**1.** *Physical components:*

Planck assumed the cavity radiation came from atomic oscillators in the cavity walls.

**2.** *Behavior of the components:*

(a) The energy of an oscillator can have only certain *discrete* values *En*:

*En =* *nhf*

where *n* is a positive integer called a **quantum number,** *f* is the oscillator’s frequency, and *h* is a parameter Planck introduced that is now called **Planck’s constant.** Because the energy of each oscillator can have only discrete values given by Equation above, we say the energy is **quantized.** Each discrete energy value corresponds to a different **quantum state,** represented by the quantum number *n.* When the oscillator is in the *n* = 1 quantum state, its energy is *hf* ; when it is in the *n* = 2 quantum state, its energy is 2*hf* ; and so on.

(b) The oscillators emit or absorb energy when making a transition from one quantum state to another. The entire energy difference between the initial and final states in the transition is emitted or absorbed as a single quantum of radiation. If the transition is from one state to a lower adjacent state—say, from the *n* = 3 state to the *n* = 2 state—Equation for *En* shows that the amount of energy emitted by the oscillator and carried by the quantum of radiation is *E* = *hf*

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| According to property 2(b), an oscillator emits or absorbs energy only when it changes quantum states. If it remains in one quantum state, no energy is absorbed or emitted. Figure is an **energy-level diagram** showing the quantized energy levels and allowed transitions proposed by Planck. This important semigraphical representation is used often in quantum physics. The vertical axis is linear in energy, and the allowed energy levels are represented as horizontal lines. The quantized system can have only the energies represented by the horizontal lines.  The key point in Planck’s theory is the radical assumption of quantized energy states. | Картинки по запросу energy-level diagram in Planck theory |

This development—a clear deviation from classical physics—marked the birth of the quantum theory.In the Rayleigh–Jeans model, the average energy associated with a particular wavelength of standing waves in the cavity is the same for all wavelengths and is equal to *k*B*T.* Planck used the same classical ideas as in the Rayleigh–Jeans model to arrive at the energy density as a product of constants and the average energy for a given wavelength, but the average energy is not given by the equipartition theorem. A wave’s average energy is the average energy difference between levels of the oscillator, *weighted according to the probability of the wave being emitted.* This weighting is based on the occupation of higher-energy states as described by the Boltzmann distribution law. According to this law, the probability of a state being occupied is proportional to the factor , where *E* is the energy of the state.

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| At low frequencies (long wavelengths), according to property 2(a), the energy levels are close together as on the right in Figure, and many of the energy states are excited because the Boltzmann factor is relatively large for these states. Therefore, there are many contributions to the outgoing radiation, although each contribution has very low energy. Now, consider high-frequency radiation, that is, radiation with short wavelength. To obtain this radiation, the allowed energies are very far apart as on the left in Figure. | Картинки по запросу black body radiation |

The probability of thermal agitation exciting these high energy levels is small because of the small value of the Boltzmann factor for large values of *E.* At high frequencies, the low probability of excitation results in very little contribution to the total energy, even though each quantum is of large energy. This low probability “turns the curve over” and brings it down to zero again at short wavelengths.

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| Using this approach, Planck generated a theoretical expression for the wavelength distribution that agreed remarkably well with the experimental curves in Figure: | Похожее изображение |

This function includes the parameter *h*, which Planck adjusted so that his curve matched the experimental data at all wavelengths. The value of this parameter is found to be independent of the material of which the black body is made and independent of the temperature; it is a fundamental constant of nature. The value of *h*, Planck’s constant is *h* = 6.626∙10-34 J∙s

At long wavelengths, Planck's Equation reduces to the Rayleigh–Jeans expression, and at short wavelengths, it predicts an exponential decrease in *I*(λ,*T*) with decreasing wavelength, in agreement with experimental results.

When Planck presented his theory, most scientists (including Planck!) did not consider the quantum concept to be realistic. They believed it was a mathematical trick that happened to predict the correct results. Hence, Planck and others continued to search for a more “rational” explanation of blackbody radiation. Subsequent developments, however, showed that a theory based on the quantum concept (rather than on classical concepts) had to be used to explain not only blackbody radiation but also a number of other phenomena at the atomic level.

In 1905, Einstein rederived Planck’s results by assuming the oscillations of the electromagnetic field were themselves quantized. In other words, he proposed that quantization is a fundamental property of light and other electromagnetic radiation, which led to the concept of photons. Critical to the success of the quantum or photon theory was the relation between energy and frequency, which classical theory completely failed to predict.

You may have had your body temperature measured at the doctor’s office by an *ear thermometer,* which can read your temperature very quickly. In a fraction of a second, this type of thermometer measures the amount of infrared radiation emitted by the eardrum. It then converts the amount of radiation into a temperature reading. This thermometer is very sensitive because temperature is raised to the fourth power in Stefan’s law.

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| Похожее изображение | Картинки по запросу In Planck’s model, the average energy associated with a given wavelength is the product of the energy of a transition and a factor related to the probability of the transition occurring. |

1. **The Bohr’s model.**

Bohr combined ideas from Planck’s original quantum theory, Einstein’s concept of the photon, Rutherford’s planetary model of the atom, and Newtonian mechanics to arrive at a semiclassical structural model based on some revolutionary ideas. The structural model of the Bohr theory as it applies to the hydrogen atom has the following properties:

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| 1. The electron moves in circular orbits around the proton under the influence of the electric force of attraction as shown in Figure    1. Only certain electron orbits are stable. When in one of these **stationary states,** as Bohr called them, the electron does not emit energy in the form of radiation, even though it is accelerating. Hence, the total energy of the atom remains constant and classical mechanics can be used to describe the electron’s motion. | Похожее изображение |

Bohr’s model claims that the centripetally accelerated electron does not continuously emit radiation, losing energy and eventually spiraling into the nucleus, as predicted by classical physics in the form of Rutherford’s planetary model.

* 1. The atom emits radiation when the electron makes a transition from a more energetic initial stationary state to a lower-energy stationary state. This transition cannot be visualized or treated classically. In particular, the frequency *f* of the photon emitted in the transition is related to the change in the atom’s energy and is not equal to the frequency of the electron’s orbital motion*.* The frequency of the emitted radiation is found from the energy-conservation expression

*Ei* - *Ef* = *hf ,* (1)

where *Ei* is the energy of the initial state, *Ef* is the energy of the final state, and *Ei >* *Ef* . In addition, energy of an incident photon can be absorbed by the atom, but only if the photon has an energy that exactly matches the difference in energy between an allowed state of the atom and a higher-energy state. Upon absorption, the photon disappears and the atom makes a transition to the higher-energy state.

* 1. The size of an allowed electron orbit is determined by a condition imposed on the electron’s orbital angular momentum: the allowed orbits are those for which the electron’s orbital angular momentum about the nucleus is quantized and equal to an integral multiple of *ħ* = *h*/2π,

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| *mevr =* *nħ* (*n* = 1, 2, 3, ...) (2)  where *me* is the electron mass, *v* is the electron’s speed in its orbit, and *r* is the orbital radius.  The quantization of orbit radii leads to energy quantization.  (3)  where εo - permittivity of free space, and *a*o - **Bohr radius** *a*0, corresponds to *n =* 1 (first stationary orbit) | Картинки по запросу The first three Bohr orbits |
| The Figure of an energy-level diagram showing the energies of these discrete energy states and the corresponding quantum numbers *n.* The uppermost level corresponds to *n* = ∞ (or *r* = ∞) and *E* = 0.  Equations (1) and (3) can be used to calculate the frequency of the photon emitted when the electron makes a transition from an outer orbit to an inner orbit:  (4)  Because the quantity measured experimentally is wavelength, it is convenient to use λ *=c/f* to express Equation (4) in terms of wavelength:  Remarkably, this expression, which is purely theoretical, is *identical* to the general form of the empirical relationships discovered by Balmer and Rydberg: | Картинки по запросу An energy-level diagram for the hydrogen atom. |

provided the constant R= *e*2/8πεo*a*0*hc* is equal to the experimentally determined Rydberg constant (1.0973732∙107 m-1).

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| Franck and Hertz had designed a vacuum tube for studying energetic electrons that flew through a thin vapor of mercury atoms. They discovered that, when an electron collided with a mercury atom, it could lose only a specific quantity (4.9 eV) of its kinetic energy before flying away. These experimental results proved to be consistent with the Bohr model for atom. | Картинки по запросу 3. Franck and Hertz experiment |

1. **De Broglie waves. Electron diffraction.**

Some experiments can be explained either better or solely with the photon model, whereas others are explained either better or solely with the wave model. We must accept both models and admit that the true nature of light is not describable in terms of any single classical picture. The same light beam that can eject photoelectrons from a metal (meaning that the beam consists of photons) can also be diffracted by a grating (meaning that the beam is a wave). In other words, the particle model and the wave model of light complement each other. The exhibition of the corpuscular properties of electromagnetic radiation increases with increasing frequency ω

In the world around us, we are accustomed to regarding such things as baseballs solely as particles and other things such as sound waves solely as forms of wave motion. Every large-scale observation can be interpreted by considering either a wave explanation or a particle explanation, but in the world of photons and electrons, such distinctions are not as sharply drawn.

Even more disconcerting is that, under certain conditions, the things we unambiguously call “particles” exhibit wave characteristics. In his 1923 doctoral dissertation, Louis de Broglie postulated that because photons have both wave and particle characteristics, perhaps all forms of matter have both properties. This highly revolutionary idea had no experimental confirmation at the time. According to de Broglie, electrons, just like light, have a dual particle–wave nature.

If we consider a photon's mass to be equal *mph = E/c2* then, we found that the momentum of a photon can be expressed as:

This equation shows that the photon wavelength can be specified by its momentum: λ = *h/p.* De Broglie suggested that material particles of momentum *p* have a characteristic wavelength that is given by the *same expression* λ = *h/p.* Because the magnitude of the momentum of a particle of mass *m* and speed *u* is *p* = *mu*, the **de Broglie wavelength** of that particle is:

or (5)

There *ħ =h/2π* and *k = 2π/λ* - wave number. Furthermore, in analogy with photons, de Broglie postulated that particles obey the Plank relation *E* = *hf =ħω*, where *E* is the total energy of the particle. The frequency of a particle is then

or (6)

The dual nature of matter are apparent in Equations (5) and (6) because each contains both particle quantities (*p* and *E*) and wave quantities (λ and *f*).

The problem of understanding the dual nature of matter and radiation is conceptually difficult because the two models seem to contradict each other. This problem as it applies to light was discussed earlier. The **principle of complementarity** states that:

the wave and particle models of either matter or radiation complement each other.

De Broglie’s 1923 proposal that matter exhibits both wave and particle properties was regarded as pure speculation. If particles such as electrons had wave properties, under the correct conditions they should exhibit diffraction effects.

Only three years later, C. J. Davisson (1881–1958) and L. H. Germer (1896–1971) succeeded in observing electron diffraction and measuring the wavelength of electrons. The electron beam incident on the crystal of nickel (Ni). Scattered electrons are registered with movable galvanometer. In these experiments, crystal is played the role of a natural diffraction grating.

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| Похожее изображение |  |

This diffraction pattern is like a diffraction of X rays we have discussed at lecture 8 (**Bragg’s law)**. Condition for *constructive* interference (maxima in the reflected beam) is

2d sinθ = mλ m = 1, 2, 3, ...

Their important discovery provided the first experimental confirmation of the waves proposed by de Broglie.

**Fundamentals of Physics Lecture 16. Atomic Nuclear. Radioactivity**

1. **The composition of the atomic nucleus.**

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| All nuclei are composed of two types of particles: protons and neutrons. The only exception is the ordinary hydrogen nucleus, which is a single proton. We describe the atomic nucleus by the number of protons and neutrons it contains, using the following quantities:   * the atomic number *Z, which equals the number of protons in the nucleus* (sometimes called the *charge number)* * the neutron number *N, which equals the number of neutrons in the nucleus* * the mass number *A = Z + N, which equals the number of nucleons* (neutronsplus protons) in the nucleus |  |

A nuclide is a specific combination of atomic number and mass number that represents a nucleus. In representing nuclides, it is convenient to use the symbol *zAX* to convey the numbers of protons and neutrons, where X represents the chemical symbol of the element.

The proton carries a single positive charge *e, equal in magnitude to the charge -e* on the electron (*e =1.6∙10-19 C). The neutron is electrically neutral as its name* implies. Because the neutron has no charge, it was difficult to detect with early experimental apparatus and techniques. Today, neutrons are easily detected with devices such as plastic scintillators.

The **atomic mass unit u** is defined in such a way that the mass of one atom of the isotope 12C is exactly 12u, where 1 u is equal to 1.660 539∙10-27 kg. According to this definition, the proton and neutron each have a mass of approximately 1u.

It is often convenient to express the atomic mass unit in terms of its *rest-energy equivalent. For one atomic mass unit,*

*E=mc2 =(1.660 539∙10-27 kg)(2.997 92∙108 m/s)2 =931.494 MeV*

where we have used the conversion 1 eV = 1.6∙10-19 J.

***Models of nucleus***

In 1936, Bohr proposed treating nucleons like molecules in a drop of liquid. In this **liquid-drop model,** the nucleons interact strongly with one another and undergofrequent collisions as they jiggle around within the nucleus. This jiggling motion is analogous to the thermally agitated motion of molecules in a drop of liquid.

The **shell model** of the nucleus, also called the **independent-particle model,** was developed independently by two German scientists: Maria Goeppert**-**Mayer in 1949 and Hans Jensen (1907–1973) in 1950. In this model, each nucleon is assumed to exist in a shell, similar to an atomic shell for an electron. The nucleons exist in quantized energy states. The quantized states occupied by the nucleons can be described by a set of quantum numbers.

1. **Nuclear forces. The mass defect and the binding energy of the nucleus.**

You might expect that the very large repulsive Coulomb forces between the close packed protons in a nucleus should cause the nucleus to fly apart. Because that does not happen, there must be a counteracting attractive force. The **nuclear force** is a very short range about 2 fm (1 fm = 10-15 m - femtometer, which is sometimes called the **fermi**) attractive force that acts between all nuclear particles.

The nuclear force is independent of charge. In other words, the forces associated with the proton–proton, proton–neutron, and neutron–neutron interactions are the same.

Eventually, the repulsive Coulomb forces between protons cannot be compensated by the addition of more neutrons. This point occurs at *Z = 83, meaning that elements that contain more than 83 protons* do not have stable nuclei.

The total mass of a nucleus is less than the sum of the masses of its individual nucleons.

Δm = *Zmp + Nmn - Mnuc(zA*X) = *ZM(H) + Nmn - M(zA*X)

where *M(H) is the atomic mass of the neutral hydrogen atom, mn is the mass of the* neutron, *Mnuc(zA*X) - mass of isotope *zA*X, *M(zA*X) represents the atomic mass of an atom of the isotope *zA*X, and the masses are all in atomic mass units. The mass of the *Z electrons included in M(H)* cancels with the mass of the *Z electrons included in the term M(zA*X) within a small difference associated with the atomic binding energy of the electrons.

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| This difference in energy is called the **binding energy of** the nucleus and can be interpreted as the energy that must be added to a nucleus to break it apart into its components.  Conservation of energy and the Einstein mass–energy equivalence relationship show that the binding energy *Eb in MeV of any nucleus is*  *Eb = [ZM(H) + Nmn - M(zA*X)]∙931.494 MeV/u  A plot of binding energy per nucleon *Eb/A as a function of mass number A for* various stable nuclei is shown in Figure. Notice that the binding energy in Figure peaks in the vicinity of *A = 60.* The nucleus 2863Ni has the largest binding energy per nucleon of 8.794 5 MeV. | C:\ADNSU\binding.gif |

1. **Natural radioactivity. The law of radioactive decay.**

In 1896, Becquerel accidentally discovered that uranyl potassium sulfate crystals emit an invisible radiation that can darken a photographic plate even though the plate is covered to exclude light. This process of spontaneous emission of radiation by uranium was soon to be called **radioactivity.**

Additional experiments, including Rutherford’s famous work on alpha-particle scattering, suggested that radioactivity is the result of the *decay, or disintegration, of unstable nuclei.*

Three types of radioactive decay occur in radioactive substances: alpha (α) decay, in which the emitted particles are 4He nuclei; beta (β) decay, in which the emitted particles are either electrons or positrons; and gamma (γ) decay, in which the emitted particles are high-energy photons. A **positron** is a particle like the electron in all respects except that the positron has a charge of +*e.*

The decay process is probabilistic in nature and can be described with statistical calculations for a radioactive substance of macroscopic size containing a large number of radioactive nuclei. If *N is the* number of undecayed radioactive nuclei present at some instant, the rate of change of *N with time is*

*or*

where λ, called the **decay constant, is the probability of decay per nucleus per second.** The negative sign indicates that *dN/dt is negative, that is, N decreases in time.* Upon integration we get

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| The **decay rate *R*** (is often referred to as **activity** of a sample)*,*which is the number of decays per second | Похожее изображение |

where *Ro = λNo is the decay rate at t = 0*

The SI unit of activity is the **becquerel (Bq):**1 Bq = 1 decay/s

Another parameter useful in characterizing nuclear decay is the **half-life *T1/2:***

1. **Types of radioactivity. Mutual transformations of nucleons.**

Three types of radioactive decay occur in radioactive substances: alpha (α) decay, in which the emitted particles are 4He nuclei; beta (β) decay, in which the emitted particles are either electrons or positrons; and gamma (γ) decay, in which the emitted particles are high-energy photons. A **positron** is a particle like the electron in all respects except that the positron has a charge of +*e.*

**Displacement rules**

Alpha decay:

Beta minus decay (electron exit)

Beta plus decay (positron exit)

1. **Nuclear reactions.**

It is also possible to stimulate changes in the structure of nuclei by bombarding them with energetic particles. Such collisions, which change the identity of the target nuclei, are called **nuclear reactions.**

Consider a reaction in which a target nucleus X is bombarded by a particle a, resulting in a daughter nucleus Y and an outgoing particle b:

a + X →Y + b

Sometimes this reaction is written in the more compact form

X(a, b)Y

The **reaction energy *Q associated with a nuclear reaction i***s *the difference between the initial and final rest energies resulting from the reaction:*

*Q = (Ma + MX – MY - Mb)c2*

A reaction for which *Q is* positive, is called ***exothermic*.** A reaction for which *Q* is negative is called ***endothermic.***

1. **Nuclear fission.**

Nuclear fission is the process that occurs in present-day nuclear reactors and ultimately results in energy supplied to a community by electrical transmission.

* This process takes place under the effect of neutrons.
* Because of their charge neutrality, neutrons are not subject to Coulomb forces and therefore, neutrons can easily penetrate deep into an atom and collide with the nucleus.

A fast neutron (energy greater than approximately 1 MeV) traveling through matter without causing fission reaction, only undergoes many collisions with nuclei, giving up some of its kinetic energy in each collision. For fast neutrons in some materials, elastic collisions dominate. Materials for **slowing down** (or moderate) the originally energetic neutrons are called **moderators**. Moderator nuclei should be of low mass so that a large amount of kinetic energy is transferred to them when struck by neutrons. For this reason, materials that are abundant in hydrogen, such as paraffin and water, are good moderators for neutrons.

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| Eventually, most neutrons bombarding a moderator become **thermal neutrons,** which means they have given up so much of their energy that they are in thermal equilibrium with the moderator material.  *Ek avg = 3/2 kBT ≈ 3/2(*1.38∙10-23 J/K)(300 K) = 6.21∙10-21 J ≈ 0.04 eV  Once the neutrons have thermalized and the energy of a particular neutron is sufficiently low, there is a high probability the neutron will be captured by a nucleus, an event that is accompanied by the emission of a gamma ray. This neutron capture reaction can be written  Fission is initiated when a heavy nucleus captures a thermal neutron. | E:\My course in Physics 20.05.12\Chapter 28  Nucleus\Pictures\28.17.jpg |

After absorbing a neutron, nucleus (for example the uranium) had split into two nearly equal fragments **plus several neutrons**. On average, approximately 2.5 neutrons are released per event.



where X and Y fragments after fission. There are many combinations of X and Y that satisfy the requirements of conservation of energy and charge. The most probable products have mass numbers *A ≈ 95 and A ≈ 140*

The amount of energy released is 8.2 MeV - 7.2 MeV = 1 MeV per nucleon. Because there are a total of 235 nucleons in 235 92U, the energy released per fission event is approximately 235 MeV.

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| Released neutrons can trigger other nuclei to fission. Because more neutrons are produced by the event than are absorbed, there is the possibility of an ever-building chain reaction.  A nuclear reactor is a system designed to maintain what is called a **self-sustained chain reaction.** A useful parameter for describing the level of reactor operation is the **reproduction constant *K, defined as the average number of neutrons from* each fission event (generation) that cause another fission event.** A self-sustained and controlled chain reaction is achieved when *K =1.* | C:\Documents and Settings\sazakov\Desktop\28.19.jpg |

*When* in this condition, the reactor is said to be ***critical*.** When*K < 1****,*** the reactor is ***subcritical*** and the reaction dies out. When *K >1, the* reactoris***supercritical***andarunaway reaction occurs.

1. **Nuclear fusion.**

When two light nuclei combine to form a heavier nucleus, the process is called nuclear **fusion.** Because the mass of the final nucleus is less than the combined masses of the original nuclei, there is a loss of mass accompanied by a release of energy. For example:



Most of the energy production takes place in the Sun’s interior, where the temperature is approximately 1.5∙107 K. Because such high temperatures are required to drive these reactions, they are called **thermonuclear fusion reactions.** All the reactions in the proton–proton cycle **are exothermic.** An overview of the cycle is that four protons combine to generate an alpha particle, positrons, gamma rays, and neutrinos.

