Chapter 3

Current Electricity.

- "Electrostatics" deals with the study of forces, fields and potentials arising from static charges. In electrostatics, all charges whether free or bound (to the nucleus of an atom) were considered to be at rest.

- ~~Elect~~ "Current Electricity" deals with electrical/electronics circuits arising from moving charges. Charges in motion constitute an electric current.
  - In electric circuits this charge is often carried by moving electrons in a wire. It can also be carried by ions in an electrolyte, or both ions and electrons such as in an ionised gas (plasma)

- Examples of charges in motion → during lightening, electric charges flow from clouds to the earth thro' the atmosphere. The flow of charges in lightning is of short duration and not steady. In electric cells (batteries), flow of charges is steady and hence constitute a steady electric current. we shall discuss the steady current in this chapter.

- The flow of electric charges in a conductor constitutes an electric current in the conductor → Flow of charges in a conductor can be compared to the flow of water in a river. German physicist, George Simon Ohm considered electric current similar to heat flow in a conductor.

- The charged particles which constitute an electric current in solids, liquids or gases are known as current carriers.

→ **Solids:**

(a) In conductors (Cu, Silver, Al etc), free electrons constitute an electric current. Electrons in the outermost orbits of the atom (i.e. valence electrons) of conductors are ~~less~~ loosely bound to the atom. When external ~~fo~~ electric field is applied these electrons are set in motion (opposite in direction of the external electric field) and result in electric current.

Thus "Free electrons" are current carriers in Conductors

P.T.O.

(b) Insulators: All the electrons are tightly bound to their parent atoms. Hence, they do not have free electrons and hence practically no current carrier in an insulator (even under the influence of external electric field)

(c) Semi-conductors :→ Current Carriers → Free electrons & Holes. In SCs, Vacancy or deficiency of electron is known as positively charged "Holes". (Holes are not particles like electrons).

→ Liquids. Some liquids which allow electric current to pass thro' them and consequently dissociate into ions are called "electrolytes". eg. $CuSO_4$ solution, $AgNO_3$ soln, NaCl, H_2SO_4 etc. These electrolytes ~~dis~~associate into +ve and -ve ions (eg. Cu^{2+}, SO_4^{+}, Ag^+, NO_3^- ; Na^+, Cl^-). under the influence of external electric field, the +ve and -ve ions of the electrolyte move in definite directions to constitute electric current. Thus, +ve and -ve ions are the current carriers in the liquids.

→ Gases ▷ Generally, gases behave as insulators of electricity but they get ionized and become conductors at low pressure, when "high potential difference" is applied across them. Ionized gas contains +ve ions and electrons. These positive ions and electrons are the current carriers in gases.

Def^n^ of Electric current :

[Electric current is defined as the rate of flow of electric charges through a particular area of cross section of a conductor.]

OR

[Electric current is defined as the amount of electric charges flowing through any cross sectional area of a conductor per unit time.]

Imp def^n^ : use any one.

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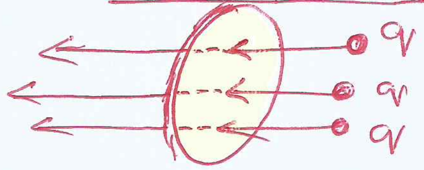
Any cross-section of a conductor



Let charge Q crosses through a cross-section of a conductor in time t, then electric current

$$I = \frac{\text{Total charge flowing } (Q)}{\text{Time taken } (t)} = \frac{Q}{t}$$

$$\therefore \boxed{I = \frac{Q}{t}}$$

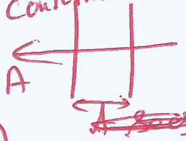
SI unit = "Ampere" (A)
If $Q = 1\,C$, $t = 1\,s$, then $I = 1\,C/s = 1\,A$.

- If charge carrier is "electron":
  (1 electron charge $= 1.6 \times 10^{-19}$ C)
  $\Rightarrow$ 1 electron carries 1.6×10^{-19} C of charge)

- We know that in metals, the electric current is the flow of electrons $\Rightarrow$ 1 electron carries 1.6×10^{-19} C of charge.

IMP:
- Current is 1 A if 1 C charge flows through wire in 1 s.
- If charge carrier is "electron" whose charge = 1 electron = 1.6×10^{-19} C
- So, if 1 C of electron flows in 1 s (to give 1 A)

1 Coulomb charge (Q)



$\therefore$ Number of electrons flowing per second

In 1 sec $\longrightarrow$ (1 C) of electron flows
$= \left(\frac{1}{1.6 \times 10^{-19}}\right)$ electrons flows.

$\boxed{\text{In 1 sec} = 6.25 \times 10^{18}}$ electrons

1 Ampere $= 6.25 \times 10^{18}$ electrons per second.

For 2 Ampere current flow $= 2 \times (6.25 \times 10^{18})$ electrons will flow per sec.
For 3 ——"—— $= 3 \times (6.25 \times 10^{18})$ ——"——

In other words: If n electrons cross thro' a cross-sectional area of conductor in time t, then total charge passing thro' a cross-section of the conductor is given by $Q = ne$ $(e = 1.6 \times 10^{-19}\,C)$

$$\therefore \boxed{I = \frac{Q}{t} = \frac{ne}{t}} \longrightarrow \text{IMP}$$

This is for electrons

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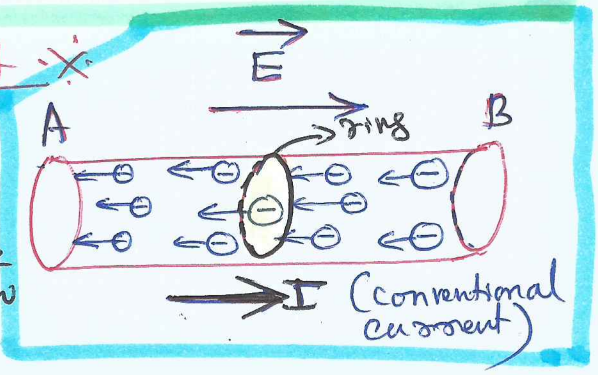
Tips: 1 ampere = 1 A = 6.25×10^{18} electrons / sec

This does not mean that in a wire carrying $I = 1A$, 6.25×10^{18} electrons travel per second from one end of the wire to the other. Instead it means that in second 6.25×10^{18} electrons enter at one end and an equal number of (other) electrons leave at the other end.

Concept of Electric current



To understand Concept of electric current, an example similar to flow of water in a river can be considered. The strength of the flow of water at any point of the river can be assessed by allowing the water to flow from a ring held ⊥r to flow of river at that point.

The amount of water ~~of the~~ flowing thro' the ring per second gives the idea regarding the water current.

- Let AB be the conductor. Consider any portion in AB of uniform cross-section placed under the influence of electric field ($\vec{E}$) applied in the direction from $A \to B$ (as shown in fig).
  - Now free electrons of the conductor will move from $B \to A$ resulting in current which is equal to the amount of charge flowing thro' the cross-section per unit time.
  - If the net charge ΔQ crosses the shaded cross-sectional area in a time Δt, then the ~~instaneous~~ "instantaneous current" across the conductor is given by

$$\boxed{I(t) \equiv \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt}} \quad \text{Instantaneous current.}$$

$$\boxed{I = \frac{Q}{t}} \longrightarrow \text{Steady current.}$$

The charge that passes thro' the given cross-section of the conductor in a time interval ~~a~~ from 0 to t is given by

$$Q = \int dQ = \int_0^t I(t)\, dt \quad ; \text{ where } I \text{ varies with time.}$$

Tips:
- The current in human nerve $\simeq$ μA
- Average current during lightning $\simeq$ tens of thousands of ampere.
- passage of electric current > 0.015 A (15 mA) thro' human body may be fatal

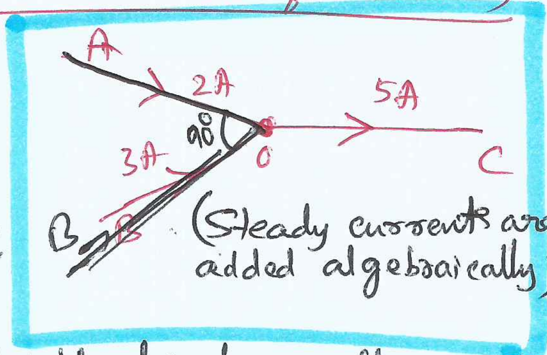
P.T.O

Conventional current (Direction of electric current)

(We will use "electric current" as "current" now onwards)

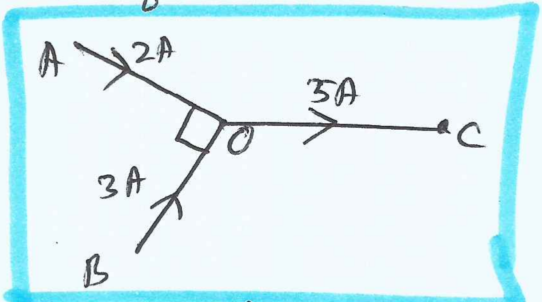
- Direction of flow of +ve charge gives direction of current. This current is known as "Conventional current". The direction of electron current is opposite to conventional current.

Nature of electric current (or just Nature of Current)



The current in a conductor is a characteristic property of that particular conductor, and it is a scalar quantity. Although, in diagrams, we represent current in a wire by an arrow, but it does not mean that current is a vector quantity. The arrow simply indicates the direction of flow of the +ve charge in the wire. If we bend the wire at any point, the strength of current does not change.

- Moreover, the arrows donot follow the "laws of vector-addition". As shown in figure, currents 3 and 4 amperes, flowing in two mutually ⊥r wires AO and BO meet at O and then go in a third wire OC.



- The current in OC is just 3+4 = 7 A which is a 'scalar' addition of 3 and 4 amperes. (their vector-addition would be 5 A)
- From this, it is very clear that "electric current" is not a vector, but is a scalar quantity.

Current density: The current density at a point in a conductor is the ratio of the current at that point in the conductor to the area of cross-section of the conductor at that point. $J = I/A$

→ Thus, if a current I be distributed uniformly over the area of cross-section A of ~~the~~ a conductor, then the current density J at a point on that area is given by $J = I/A$. The current density is a characteristic property of a point inside the conductor (not ~~the~~ of the whole conductor). It is a vector quantity.

P.T.O.

IMP

Contd: Current density J

$$\boxed{J = \frac{I}{A}} \longrightarrow (1)$$

J is a vector quantity and its direction is same as that of the direction of the conventional current (flow of +ve charges).

→ The current (dI) thro' an element of surface area $\vec{dA}$ of a conductor is given by

$$dI = \vec{J} \cdot \vec{dA}$$

∴ total current flowing thro' the surface S is given by

$$\int dI = \int_S \vec{J} \cdot \vec{dA}$$

$$\boxed{I = \int_S \vec{J} \cdot \vec{dA}} \longrightarrow (2)$$

It is clear from eqn (2) that "current" is a scalar quantity which is dot product of two vectors $\vec{J}$ and $\vec{dA}$.

→ SI unit of $\vec{J}$ is $A\,m^{-2}$

→ Dimensional formula of $\vec{J}$ $= [M^0 L^{-2} T^0 A]$

Q:: How many electrons/sec flow thro' the cross-section of a conductor so that the conductor carries I = 1A ?

We know that $I = \frac{Q}{t} = \frac{ne}{t}$; Given I = 1 A in conductor, t = 1 s, $e = 1.6 \times 10^{-19}$ C

$I = \frac{ne}{t}$ ∴ $n = \frac{It}{e}$

∴ $n = \frac{1A \times 1s}{1.6 \times 10^{-19} C} = \frac{1\,\cancel{A \cdot s}}{1.6 \times 10^{-19}\,\cancel{A \cdot s}}$ → Since $Q = It = A \cdot s$

$n = \frac{1}{1.6 \times 10^{-19}} = 6.25 \times 10^{18}$ electrons

Thus, flow of 6.25×10^{18} electrons/second thro' a conductor gives rise to 1A electric current in the conductor.

Q: Calculate the amt. of current flowing thro' a conductor if 10^6 electrons cross thro' the cross-section of the conductor in 1.6 ms, Given $e = 1.6 \times 10^{-19}$C

Given $n = 10^6$ electrons

$e = 1.6 \times 10^{-19}$ C

$t = 1.6$ ms $= 1.6 \times 10^{-3}$ s

Formula $I = \frac{ne}{t}$

$$I = \frac{10^6 \times \cancel{1.6} \times 10^{-19}\,C}{\cancel{1.6} \times 10^{-3}\,s} = 1.0 \times 10^{-10}\,C/s$$

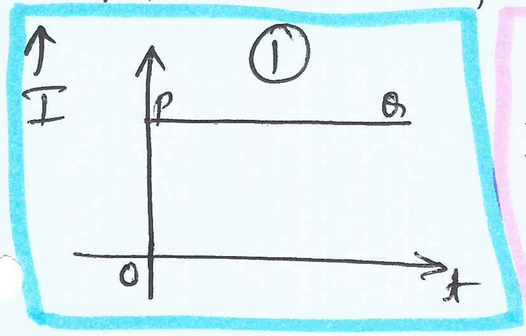
$$= 1.0 \times 10^{-10}\,A$$

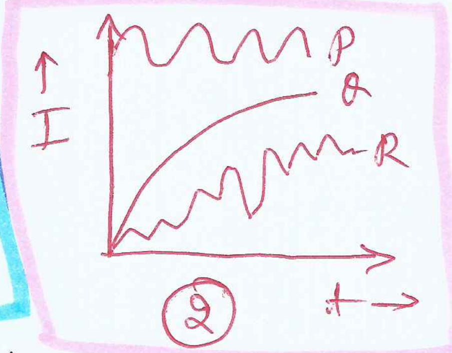
Types of Current

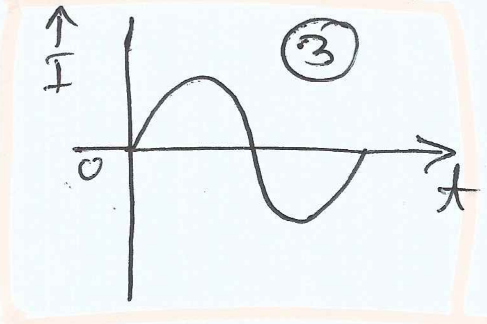
① Steady Direct current (Steady DC) : An electric current is said to be steady (or constant) DC if its magnitude and direction do not change with time.

② Variable DC → An electric current is said to be varying DC if its magnitude changes with time & polarity remains same.

③ AC → An electric current is said to be AC if its magnitude changes with time and polarity (i.e. + or −) reverses periodically.



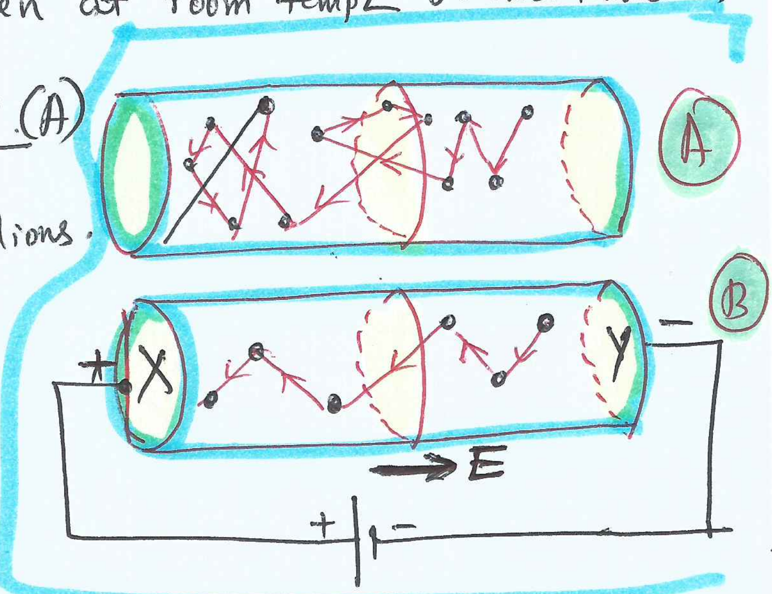




Thus, (i) current which does not reverse its polarity is DC
e.g. Steady DC and Variable DC (with same polarity)
(ii) current which reverses its polarity periodically is called AC.

IMP Electric Current in Conductors (Sec. 3.3) NCERT book
(Explain the flow of electric current in solid conductors)

Let us focus our attention to "Solid" conductors (not liquid nor gas).
Current carrier → electrons (ions in solid are fixed).
Every matter is made up of atoms and molecules. In a "Solid" conductor, atoms are closely packed and the valence electrons of an atom are not attached firmly to its nucleus. These valence electrons are free to move throughout the volume of the solid even at room temp^re & hence known as "free electrons".



- Case(i) : No electric field applied (A)

At room temp^re, due to thermal motion, electrons collide with fixed ions. An electron colliding with an ion emerges with the same speed as before collision. However, the direction of its velocity after collision is completely random. There is no definite direction for electrons after collision (random movement). Thus, on the average, the number of electrons travelling thro' a given cross-section of a conductor in any direction = no of electrons crossing the same cross-section in opposite direction. SO, there will be no net electric current.

- Case(ii): Fig (B) : when an electric field is applied.

ⓐ Attach +vely charged disc to ~~each~~ cylinder side X and −ve charged disc to side Y. An electric field is set-up from X → Y. Electrons will be accelerated towards side X and try to neutralize the +ve charges. The electrons as long as they are moving, will result in a current. In this case, there will be current for a short period of time and no current thereafter (since it is neutralized).

ⓑ Fig (B) ⟶ Applying external supply (battery) as shown in fig B.

In ⓐ, we can imagine a mechanism where the ends of the cylinder X and Y are replinished with fresh charges to make up for any charges neutralized by electrons moving inside the conductor. In that case, there will be steady electric field in the conductor. This will result in a continuous current rather than a current for a short period of time.

⟶ The above mechanism of replinishing fresh charges by some means is realised by devices such as cells or batteries that maintain a steady electric field and hence a steady electric current.

P.T.O

IMP

Drift Velocity and Mean Freepath and Relaxation time :

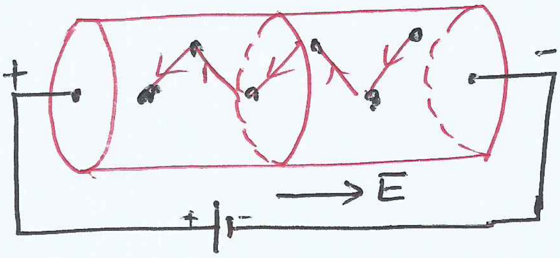
- Among the solids, all metals are good conductors of electricity and there are large number of free electrons loosely bound to their atoms.
- In the absence of external electric field (eg. battery), there is movement of electrons only due to thermal energy (at room temp^r). The electrons move randomly with a thermal speed ($\approx 10^5$ to $10^6\ ms^{-1}$) at room temp^r. In any portion of the conductor, the flow of electrons is so oriented that the average thermal velocity of total number of free electrons in a conductor is zero.

$$\vec{u}_{av} = \frac{\vec{u_1} + \vec{u_2} + \vec{u_3} + \cdots \vec{u_n}}{n} = 0$$

where $u_1, u_2 \ldots u_n$ are thermal velocities of free electrons and n is the total number of free electrons.

It means that there is no net motion of the free electrons in any particular direction. If an imaginary plane is drawn thro' the metal, then the rate at which the electrons pass through the plane from right to left is same as from left to right. So, the net rate remains zero.

- When external voltage applied (when an electric field is applied) across the conductor, free electrons accelerate towards +ve terminal (opposite to electric field E as shown)



→ Due to this acceleration, electrons gain extra velocity but for a short time since accelerated electrons collide with +ve ions and their velocities decrease (or become zero). After collision, the electron again gains velocity in a different random direction. So, the velocity of the electron does not increase continuously because it collides again and again with the +ve ions of the metal and thus continues to lose energy taken from the battery (This energy appears in the form of heat).

→ Also collisions do not occur at regular intervals but at random times. Let us denote the average time bet^n successive collisions as τ. This implies some electrons would have ~~spent~~ accelerated more time than τ before colliding with +ve ions; some electrons would have spent less time ~~before~~ than τ before collision. So, collisions do not occur at regular intervals, but occur randomly at different time periods. If we take the average time τ bet^n two successive collisions, τ is called "mean free time" or "relaxation time"

P.T.O.

Contd...

The average time interval γ between two successive collisions between electron and +ve ion in the conductor is called "mean free time" (γ) or "Relaxation time".

$$\therefore \text{Relaxation time } \gamma = \frac{\text{mean free path}}{\text{rms velocity of electrons}} = \frac{\lambda}{V_{rms}}$$

V_{rms} increases with increase in temperature, so γ decreases with increase in temp^{r}. ($\gamma \approx 10^{-14}\,s$)

- $$\gamma = \frac{\text{mean free path}}{V_{rms}}$$

→ mean free path: under the influence of external applied voltage, the distance travelled by electrons will not be same between collisions. ~~Same~~ Sometimes, electrons travel more distance before colliding with +ve stationary ions and some other time, the electrons travel less distance before ~~collis~~ collision. So, even the path traversed by electrons between successive collisions will not be same. If we take the average (mean) distance transversed by electrons between two successive collisions, it is termed as "mean free path" (λ) of the electron. And the average time-interval between two successive collisions is called the "relaxation time" of the electron.

→ So, the motion of electrons in a conductor under the influence of electric field is like a pause and start motion. As a net result, the electrons acquire a small velocity (even with external applied voltage due to collisions) called drift velocity $\vec{v_d}$ in the direction opposite to that of the applied electric field. The flow of electrons with this "drift velocity" from one end to the other end of the conductor constitutes an electric current.

P.T.O.

Drift velocity Def^n ($\vec{v}_d$)

Drift velocity is defined as the average velocity with which free electrons in a conductor get drifted in a direction opposite ~~the~~ to the direction of the applied electric field.

→ Consider a conductor under the influence of external electric field $\vec{E}$

→ The force experienced by a free electron in the conductor placed in the electric field is given by

$$\vec{F} = -e\vec{E} \longrightarrow (1)$$

−ve sign shows that the directions of $\vec{F}$ (electron direction movement) and $\vec{E}$ (applied external voltage) are opposite to each other.

→ The accn. produced ~~by~~ to the electron is given by

$$\vec{a} = \frac{\vec{F}}{m}$$, where m = mass of the electron (9.1×10^{-31} kg)

From (1) $$\vec{a} = -\frac{e\vec{E}}{m} \longrightarrow (2)$$ charge of electron $= 1.6 \times 10^{-19}$ C

This accn. $\vec{a}$ lasts for a short time and is interrupted (i.e. made zero), when the accelerated electron collides with +ve ion of the conductor. This small interval of time between two successive collisions betn electron and ion in the conductor is called "relaxation time" or "mean free time" (τ). In time interval τ, the electron is accelerated.

∴ ⟹ the electron accelerates for an average time interval τ.

∴ Drift velocity is given by

$$\vec{v}_d = \vec{u} + \vec{a}\tau = \vec{a}\tau$$

We know that
$v = u + at$
$u = 0$

using (2) $$\boxed{\vec{v}_d = -\frac{e\vec{E}}{m}\tau} \longrightarrow (3)$$

$$|\vec{v}_d| = \boxed{v_d = \frac{eE\tau}{m}} \longrightarrow (4)$$

✱ Imp: The drift velocity v_d is of the order of $10^{-4}\,ms^{-1}$, which is negligible as compared to the average electron thermal velocity of $10^{6}\,ms^{-1}$ at room temp$\underline{re}$.

Mobility (μ)

Mobility of a current carrier is the ratio of the drift velocity v_d of current carrier in a material to the applied electric field E across the material.

$$\mu = \frac{v_d}{E} \quad \therefore \quad \text{Since } v_d = \frac{eE\tau}{m}$$

$$\mu = \frac{eE\tau}{m} \cdot \frac{1}{E} = \frac{e\tau}{m}$$

$$\boxed{\mu = \frac{e\tau}{m}}$$

Thus, μ is inversely $\propto^{l}$ to the mass of the current carrier. For example, in a semiconductor, $\mu_{electron} > \mu_{hole}$ because electron is lighter than hole.

SI unit of mobility is $m\,s^{-1}\,N^{-1}\,C$ $\left(\frac{v_d}{E}\right)$ or $m^2 s^{-1} V^{-1}$

Mobilities of electrons in some materials at room temp^2 is ...

Material	Electron mobility (cm^2/Vs)
Diamond	1800
Silicon	1350
Germanium	3900
GaAs	8500

Mobilities of electron $\mu_e = \frac{v_e}{E}$; Mobility of hole $\mu_h = \frac{v_h}{E}$