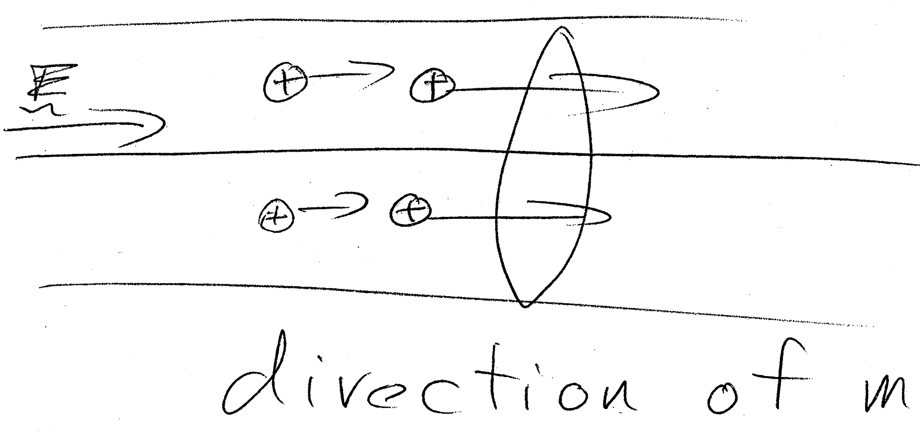
Chapter 27

Current & Resistance

§ 27.1 Electric Current

- Electric current is a flow of charge.

- Say one has +ve charge carriers moving thru an area A ~~that~~ is perpendicular to their direction of motion



In time Δt, ΔQ of charge has

27-2 moved thru A.

The average current in Δt is

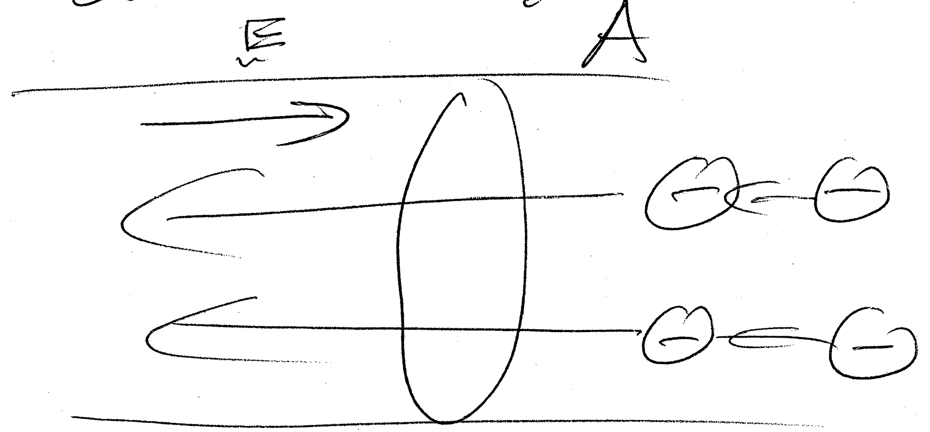
$$I_{ave} = \frac{\Delta Q}{\Delta t}$$ to the right in our diagram

The instantaneous current is

$$I = \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{dQ}{dt}$$

Actually in our developments we will usually be thinking of constant currents where $I = I_{ave}$

What of negative carriers?



flowing to the ~~right~~ left

Well we count this as a positive current to the right.

Most of the time we are thinking of electrons in metals — and so the carriers are ~~positive~~ really negative.

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But ~~conventionally~~ conventionally current is taken as flowing from +ve to -ve and electrons flow the other way.

Perhaps no matter what current is taken as flowing in direction of +ve carriers and opposite direction of -ve carriers

Usually then

Conventional current flows in the direction of the electric field. - If +ve the carriers go that way. If -ve, then they go in the opposite direction.

A convention that traces back to Ben Franklin's bad guess.

So in conventional circuit problems we ~~treat~~ the current as flowing

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opposite to the way electrons do flow.

We get away with this because in almost all ordinary circuitry nothing distinguishes +ve carriers one way to -ve carriers the other.

It wasn't untill the Hall effect in 1879, that people figured out that metal carriers were negative — and by that time it was too late to change conventions.

We may (or may not) look at the Hall effect later.

<u>MKS unit of</u> current is $1\,A = \frac{1\,C}{1\,s}$

— A for ampere.

— Now 1 C of net is a pretty big net charge.

— But 1 A is <u>not</u> such a big current.

The thing to remember is that current <u>carrying conductors</u> are mostly neutral.

e.g., in a metal,
the electrons are moving
thru positively charged
lattice of ions that are fixed.

— Wires carrying current
are close to neutral
overall. $\Longrightarrow$ But not quite actually in general.
— An important point as we'll see.

<u>Other carriers?</u>

— ions in gases.

— ions in electrolytes
↳ generally fluids with a solute that yields ions.

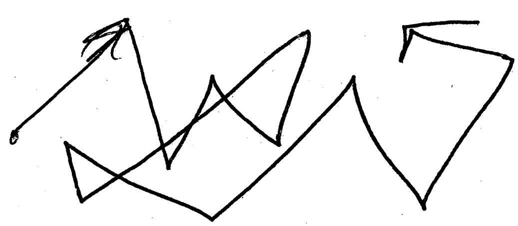
one has these in <u>wet cells</u> = chemical batteries

We are going to skirt mostly what actually goes on in a chemical battery and mainly deal with electrical power sources in a generic way.

- in semiconductor one has electrons & holes propagate
  - absences of electrons
  - +ve carriers
  - depending on doping of semicond

Microscopic Model of Conduction

- thinking of electrons really conduction



One can think of the electron ~~as something~~ as like a gas

They fly around a collide with ions and impurities and defects,

The whole subject of what the collision are is complex and inherently Quantum mechanical. So we'll large just skirt that subject.

But they are not a classical gas — like molecules in the air, but a Fermi gas.

ideal gas

Going into details is beyond our scope

typical velocities $v_{random} \sim 1 \times 10^6$ m/s (AM-36 -38)

— fast, very fast but still NOT relativistic.

$c = 3 \times 10^8$ m/s

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~~So~~ $\beta \simeq \frac{1}{3} \times 10^{-2}$

$\hookrightarrow \frac{v_r}{c}$ which is a measure of relativistic effect.

But ~~these~~ v_{random} are ~~not~~ random velocities, not ~~the~~ net velocity of ~~cur~~ current.

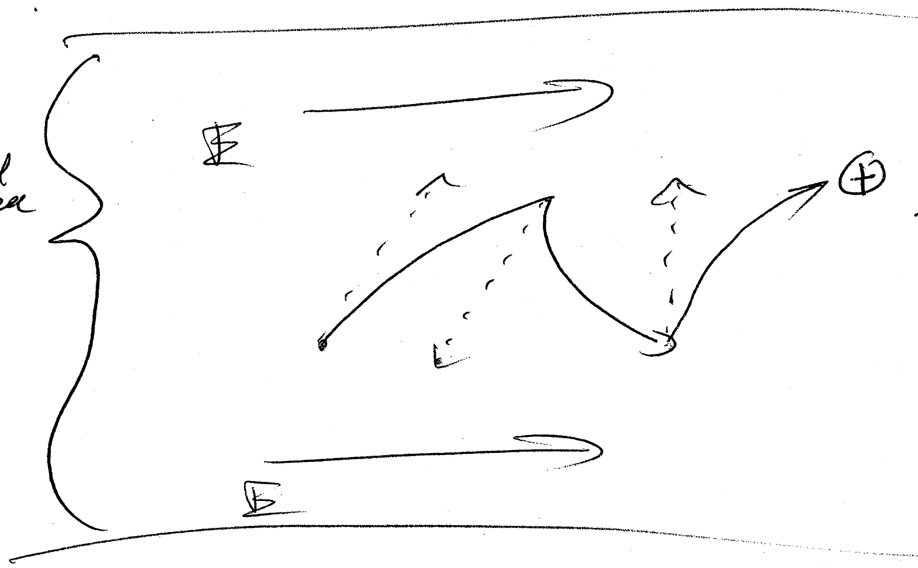
A macroscopic E-field superimposes an average velocity in some direction (we go into how in §27.2 on Ohm's law).

$\rightarrow$ The Drift velocity v_d

typically

$$v_d << v_r$$

Cross sectional area
A



After each collision the charge carrier heads in a random direction, but ~~the~~ E-field imposes a motion in the E-field direction for a +ve charge.

Opposite E-field direction for a -ve charge.

Say the charge density is n, drift velocity v_d

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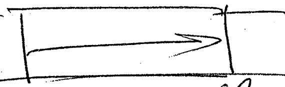
Ex 27.1

$\Delta Q = n \Delta V q = n A \underbrace{\Delta x}_{\Delta x \text{ drift}}$

Cross sectional area perpendicular to flow. A 

Δx all cleared out in Δt

$\therefore v_d = \frac{\Delta x}{\Delta t}$, $I = n q v_d$.

Drift velocity in a copper wire

I prefer fiducial numbers instead of the textbook's numbers

I don't want to get into wire ~~gau~~ gauges

Say $A = 10^{-6}\,m^2$

Crossectional area of wire

$d = 2\sqrt{\frac{A}{\pi}}$ is diameter

$\hat{=} 2\sqrt{\frac{10^{-6}}{3}} \simeq 1.1 \times 10^{-3}\,m$

Current $I = 1\,A$

$\therefore v_d = \cancel{\frac{I}{nqA}} \quad \frac{I}{nqA}$

$q = -e$ for electrons

n for copper?

$$n = \underbrace{\frac{\rho\,(\text{density of copper})}{m_{\text{mass of copper atom}}}}_{\text{number of atoms per unit volume}} \underbrace{Z_{free}}_{\substack{\text{number of free electrons per atom} \\ = 1 \text{ for Copper (Wik)}}}$$

Atomic weight

Atomic mass unit

$$m_{Cu} = A\, m_{amu}$$

$$\cong 63.5 \cdot 1.66 \times 10^{-27}\,\text{kg}$$

$$\rho_{Cu} = 8.96 \; g/cm^3$$ (Wik at ~ room temperature)

$$= 8.96 \times 10^{3}\,\text{kg}/\text{m}^3$$

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$$\cancel{1\,\frac{kg}{cm^3} = 1\,\frac{kg}{m^3}}$$

$$1\,\frac{g}{cm^3} = 1\,\frac{g}{cm^3}\cdot\left(\frac{1\,kg}{1000\,g}\right)\left(\frac{100\,cm}{1\,m}\right)^3$$

$$= 10^3\,\frac{kg}{m^3}$$

So $n \simeq \dfrac{8.96\times10^3}{63.5\cdot1.66\times10^{-27}}\cdot 1$

$= 9\times10^{28}$ electrons/m^3

$$v_d = \frac{1\cdot A}{9\times10^{28}\,m^{-3}\cdot1.6\times10^{-19}\,C\cdot10^{-6}\,m^2}\left(\frac{I}{1A_{amp}}\right)\left(\frac{10^{-6}\,m^2}{A_{area}}\right)$$

$$\simeq .6\times10^{-4}\left(\frac{I}{1A}\right)\left(\frac{10^{-6}\,m^2}{A}\right)\frac{m}{s}$$

$$= .06\,\frac{mm}{s}\left(\frac{I}{1A_{amp}}\right)\left(\frac{10^{-6}\,m^2}{A_{area}}\right)$$

— dropping the negative sign.

So typical drift velocities are quite small.
— less than 1 millimeter/s.

But when you turn on an electrical device (i.e, close a circuit) the device starts working quasi-instantly
— The electrons are already in the conductors.
↳ an electric field signal traveling at near the speed of light sets them in motion.

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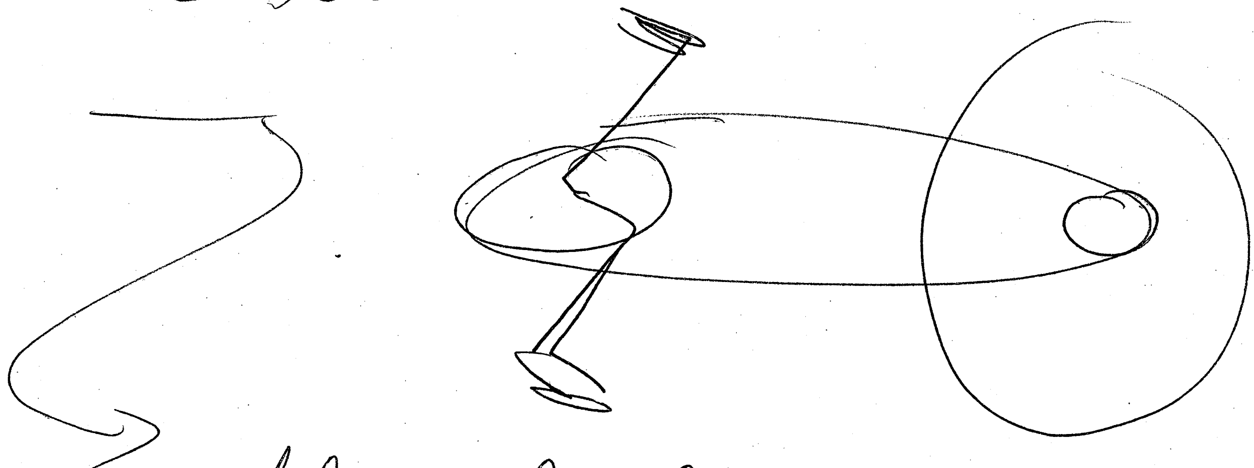
Couple of analogies

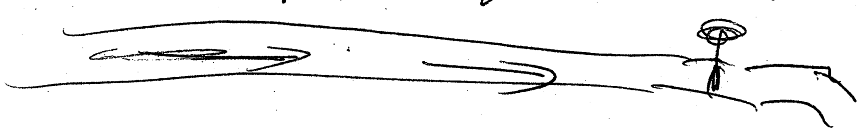
a) — starting to pedal a bike.



the wheel starts moving as soon as a tension signal in the chain reaches it.

— not the time it takes a chain link to move from pedal to wheel.

b) Opening a tap



Once you open a tap, water all along the pipe starts in motion — not on the time scale it takes water molecules to move along the pipe, but on the time scale that the sound speed of water takes to signal along the pipe that there's been a drop in pressure at the open tap.

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§27.2 Resistance & Ohm's law

Ohm's law is NOT a fundamental law of nature.

— It's just a law that many materials obey — and those materials have many important technological uses.

They are called ohmic materials.

To Understand Ohm's law we need to define current density.

Recall $I = n q v_d A$

cross sectional area perpendicular to current flow.

$$J = \frac{I}{A} = n q v_d$$

Actually average J over A but we will not usually consider non-uniform current density

— has units of A/m^2

In current density form of Ohm's law is

$$J = \sigma E$$

where the direction of E and J are the same.

in vector form $\underset{\sim}{J} = \sigma \underset{\sim}{E}$

units $[\sigma] = \left[\frac{J}{E}\right] = \left[\frac{(C/s)/m^2}{J/(mC)}\right] = \frac{C^2/m}{J\,s}$ but

and σ is conductivity

~~usually~~ $= \frac{1}{\Omega m}$

↑ ohm as we'll see on p. 27-25

(not surface charge density — we have to recycle the symbol — context has to decide which you mean)

and σ is independent of E itself.

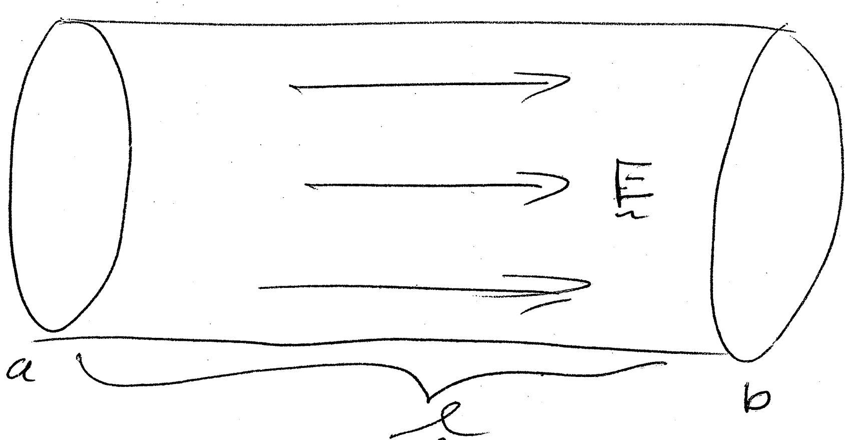
Such materials that have this property are ohmic.

Special case

~~Say we have J constant over the cross sectional area A of a conductor~~ and points normal to A

Important Special Case

Say we have a conductor with constant cross sectional shape & area A.



- the shape need not be circular.
- there is a uniform E-field normal to the cross section
- the material is ohmic

and so

$$\underset{\sim}{J} = \sigma \underset{\sim}{E}$$

It is also homogeneous and so

$\boxed{27\text{-}22}$

σ is constant.

$\underset{\sim}{J}$ must be ~~constant~~ and perpendicular to the cross section (by Ohm's law).

Now

$$\underset{\sim}{J} = \sigma \underset{\sim}{E}$$

$$\frac{I}{A}\hat{E} = \sigma \underset{\sim}{E}$$

Since $\underset{\sim}{J}$ is uniform $\underset{\sim}{J} = \frac{I}{A}\hat{E}$

Now ~~multiply by~~ dot product with $d\underset{\sim}{s}$ where $\underset{\sim}{s}$ is a path length vector normal to the cross section and integrate from a to b.

$$\int_{\underset{\sim}{s}_a}^{\underset{\sim}{s}_b} \frac{I}{A}\hat{E}\cdot d\underset{\sim}{s} = \int_{\underset{\sim}{s}_a}^{\underset{\sim}{s}_b} \sigma \underset{\sim}{E}\cdot d\underset{\sim}{s}$$

$$\frac{I}{A}\ell = \sigma(-V_{ab})$$

Recall $\Delta V = -\int \underset{\sim}{E}\cdot d\underset{\sim}{s}$

or $$V_{ba} = \frac{\ell}{\sigma A} I = \rho\frac{\ell}{A} I = IR$$

Where $V_{ba} = -V_{ab}$,

$\rho = \frac{1}{\sigma}$, is the resistivity

and we define

$R = \rho\frac{\ell}{A}$ as the <u>resistance</u>.

All ohmic conductors have resistance.
— devices designed ~~to~~ have resistance due resistance

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So dropping the subscripts ~~ab~~ ba, we have

$$V = IR$$

which is the usual form of <u>Ohm's law</u>.

Proper way to read it is that the electric force must inject energy per unit charge V to make up for the energy lost to waste heat per unit charge IR and thus maintain a constant charge flow.

The potential drop across a resistance equals the current thru it times a constant ~~that~~ is independent of current and potential, but ~~that~~ depends on the material and geometry of the resistance.

Our derivation was for a particular geometry, but result $V = IR$ is actually general for ohmic materials. — but the formula for R is in general complex and beyond our scope to go into. — Typical one measures it or the manufacturer tells you.

Units

$$[R] = \left[\frac{V}{I}\right] = \frac{V}{A}$$

$$= \frac{J/C}{C/s} = \frac{J \cdot s}{C^2}$$

$$= \Omega$$

Capital Greek omega for **ohm**

27-26

So the unit of resistance does have a special name (ohm) and sign Ω.

As well as ohms, kilo-ohms ($k\Omega$) are pretty commonly in use too.

Units of Resistivity

$$[\rho] = \left[\frac{A}{l} R\right]$$

$$= \Omega\text{-m}$$

Some examples from the text

Restivity Table

Notes	Material	$\rho\ (\Omega\text{-m})$	Temperature Coef. α $^{\circ}C^{-1}$ (inverse celsius degree) — discuss in a bit
- bit expensive	Silver	1.59×10^{-8}	3.8×10^{-3}
- we're running out of cheap copper	Copper (a black market in Cu)	1.7×10^{-8}	3.9×10^{-3}
- expensive but corrosion free	Gold	2.44×10^{-8}	3.4×10^{-3}
not as good as copper but lots of it (more of it - very energy intensive to produce)	Aluminum	2.82×10^{-8}	3.9×10^{-3}
- ~~T~~ $T_{melt} = 3422°C$ and so used as filament in incandescent lights	Tungstun	5.6×10^{-8}	
It's magnetic properties make it useful	Iron	10×10^{-8}	5.0×10^{-3}
poor conductor so good in heating elements.	Nichrome (Nickel-chromium alloy)	1.5×10^{-6}	0.4×10^{-3}

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Carbon	3.5×10^{-5}	$-.5 \times 10^{-3}$

used in resistors (devices that give resistance)

Silicon	2.3×10^{3}	-75×10^{-3}

Not a great conductor
— semi-conductor

Glass	10^{10} to 10^{14}

an insulator
— but a some super low level
a current will flow
(even without break down — but ~~resistivity is 10^{18}~~
18 orders of mag. higher resistance than copper at least

— in some cases like wires
one wants good conductors
— low resistivity
— Cu, Al.

— Semiconductors have special properties useful in electronics

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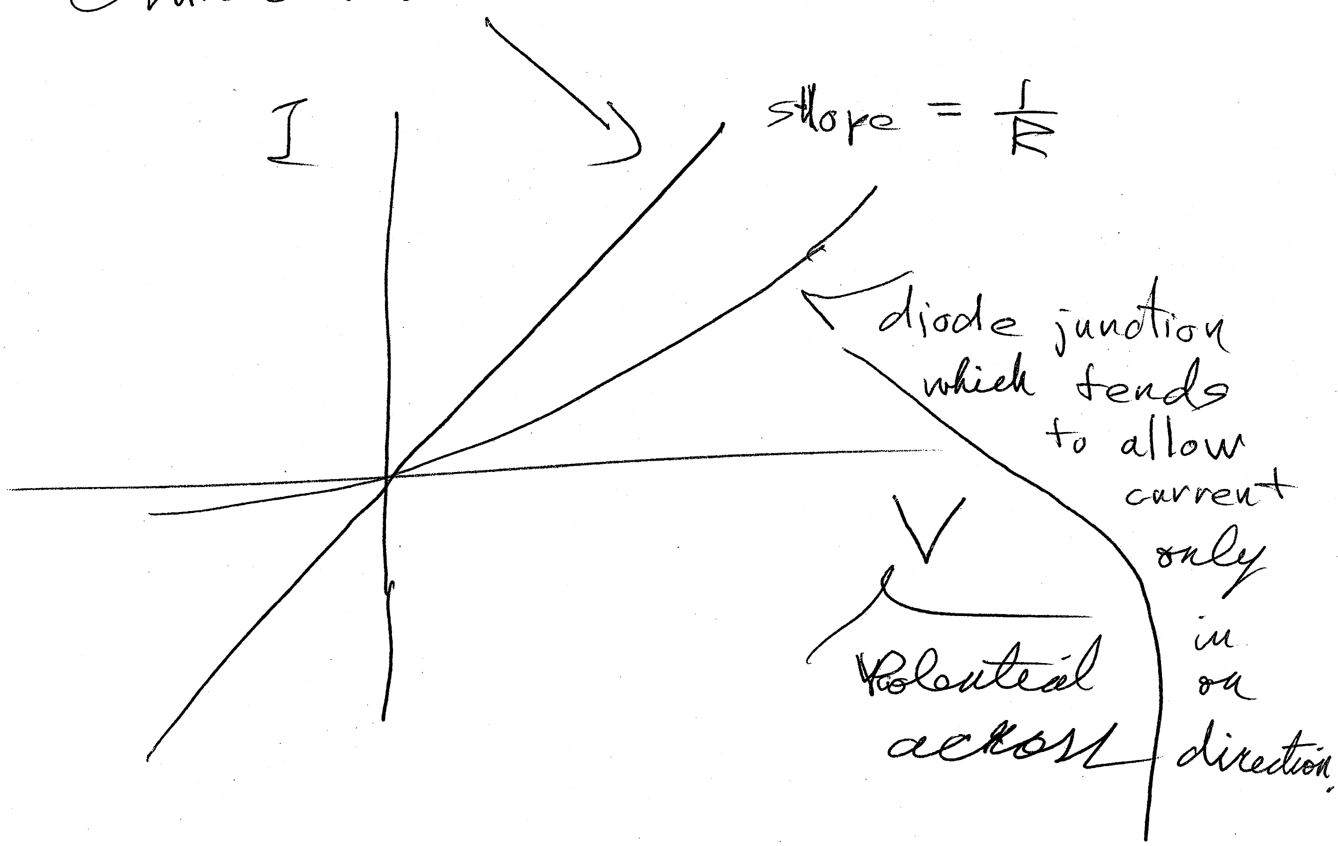
Ohmic material



§ 27.3 Model of Conduction to Prove Ohm's law

— This is ~~the~~ classical Drude model from 1900 ~~that uses~~ classical physics. — some things are right

— some things wrong.

— to go beyond you need Quantum mechanical ideas.

— But the Drude model gives some insight.

Recall from p. 27-19

We ~~Proving~~ Ohm's law in ~~the~~ Drude Model.

$$\underline{J} = n\, q\, \underline{v}_d$$

both J & v_d in the same direction for $q > 0$

and

Ohm's law for current density is

$$\underline{J} = \sigma\, \underline{E}$$

both J & E in same direction for $q > 0$

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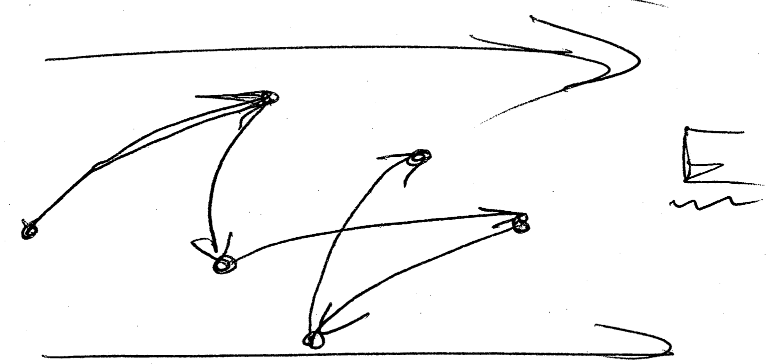
Let the charge carrier be +ve or −ve.

~~Let us think of +ve charge for definiteness even though in metals $q = -e$~~

Recall our drift velocity picture

randomizing collisional impacts.



between impacts and superimposed on the random thermal velocity (really high $\sim 1 \times 10^{6}$ m/s) /

there is the velocity caused by acceleration due to the macroscopic electric field.

We assume the field is uniform and points to the right

Both F and a are constants.

$F = qE$ Force on charge carrier

$a = \frac{qE}{m}$ is the acceleration of the charge carrier divided by mass m

If $q > 0$,
$a > 0$ and
the charge carrier accelerates to the right.

If $q < 0$, $a < 0$ and the carrier accelerates to the left.

After a collision the carriers initial non-random velocity $= 0$

27-3~~4~~

Let τ be the mean time between collisions

$\therefore$ the mean velocity at the end of ~~flight or step~~ between collisions is

$$v = a\tau$$

Serway - 761 asserts without proof (SJ just use "because" like a parent) that $v = a\tau$ is also the average ~~car~~ charge-carrier velocity.

See P. 27-37 for proof.

$$\therefore \quad v_{drift} = v = a\tau$$

$$\therefore \quad J = nqv_d = nqa\tau = \frac{nq^2E}{m}\tau$$

Note the q^2.

This means that J always points in the direction of E no matter what the charge carrier sign. (In this model of conduction)

Reason

If $q > 0$, the E-field gives $v_d > 0$ and the charge flow right — we call this a positive current.

If $q < 0$, the E-field gives $v_d < 0$ and charge flows to the left — but it's negative charge and so we call this a positive current.

As we've mentioned earlier, physically for many (but not all) purposes, it doesn't matter ~~which way the~~ what the sign of the carriers — we take current as flowing in the E-field direction.

p. 27-36-72-45.

Optional Reading

{ Beyond the scope of the ~~clas~~ course and so only for your interest.

Proof that $v_d = a\tau$

where a is the constant non-random acceleration caused by ~~an~~ uniform E-field.

And τ is the mean time

between collisions.

Assume collisions happen randomly, but with a constant probability of happening per unit time

$\frac{1}{\tau}$ where τ is a time constant (that ~~turns~~ out to be the mean time between collisions)

Say ~~there is a collision~~ we observe the carrier at ~~and that sets~~ $t = \emptyset$ and it is not colliding at that instant.

What is the probability that it has not collided up to time t?

27-38

Say it is $P(t)$

Now in dt, $P(t)$ decreases

by $dP = - \underbrace{P(t)}_{\substack{\text{Probability}\\\text{of not}\\\text{colliding}\\\text{to } t}} \underbrace{\frac{dt}{\tau}}_{\substack{\text{Probability}\\\text{of}\\\text{colliding}\\\text{in } dt}}$

You could think of this as n survivors out of N

$dn = -n\frac{dt}{\tau}$

$\therefore$

$n(t+\tau)$
$= n(t) - dn$
$= n(t) - n(t)\frac{dt}{\tau}$

the number surviving after $t+\tau$.

This is a trivial differential equation

$$\frac{dP}{P} = - \frac{dt}{\tau}$$

$$\ln P = -\frac{\cancel{t}}{\tau} + C$$

$$P(t) = e^{-t/\tau} \quad \left\{ \begin{array}{l} \text{survival} \\ \text{Probability} \\ \text{to } t \end{array} \right.$$

The coefficient is 1, since at $t=0$ the probability of surviving since $t=0$ is 1.

$$P_d = 1 - P = 1 - e^{-t/\tau}$$

is the probability of having had a collision by t

$$\rho = \frac{dP_d}{dt} = \frac{e^{-t/\tau}}{\tau}$$ is the

Probability density of a collision at t.

We can now find the moments of distribution ρ.

27-40

$$\underbrace{\langle t^l \rangle = \int_0^\infty t^l \rho(t)\, dt}$$

definition of a moment of $\rho(t)$

$$\langle t^l \rangle = \int_0^\infty t^l \frac{e^{-t/\tau}}{\tau} dt$$

$$= \tau^l \underbrace{\int_0^\infty x^l e^{-x} dx}_{l!}$$

It is the factorial function (Arf - 453).

$$= \begin{cases} l!\,\tau^l & \text{in general} \\ 1 & \text{for } l = 0 \text{ which just show } \rho(t) \text{ is normalized.} \\ \tau & \text{for } l = 1 \text{ which is the mean time between collisions} \\ 2\tau^2 & \text{is the mean squared time between collisions.} \end{cases}$$

$$\sigma \equiv \sqrt{\langle (t - \langle t \rangle)^2 \rangle}$$ is the standard deviation by definition

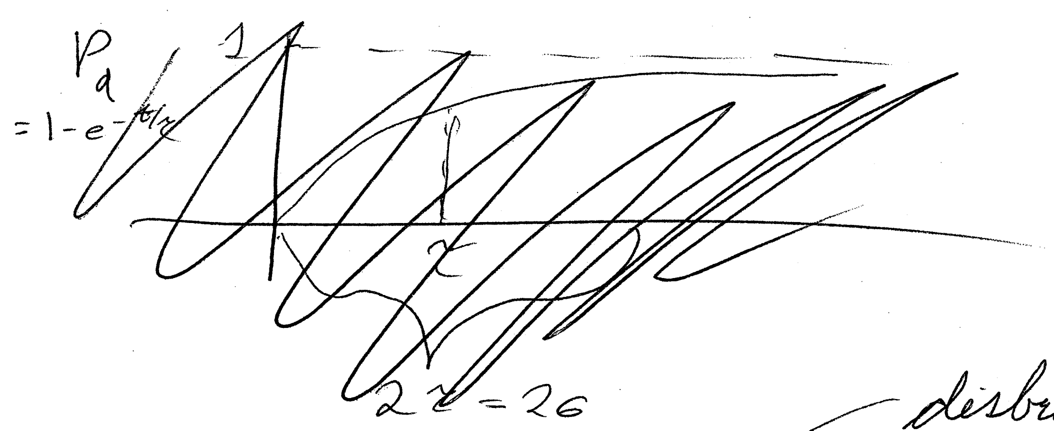
$$= \sqrt{\langle t^2 - 2t\langle t \rangle + \langle t \rangle^2 \rangle}$$

$$= \sqrt{\langle t^2 \rangle - 2\langle t \rangle^2 + \langle t \rangle^2}$$

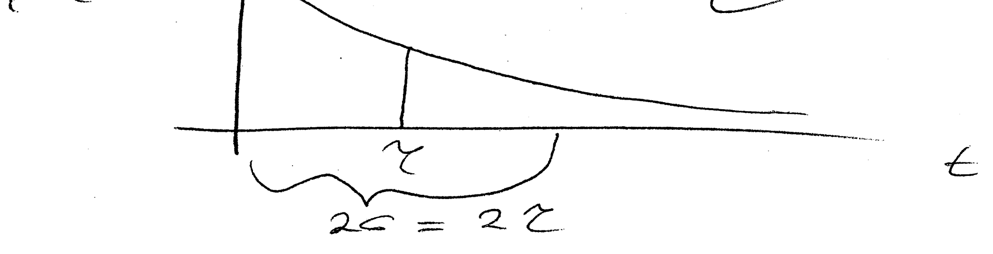
$$= \sqrt{\langle t^2 \rangle - \langle t \rangle^2}$$

$$= \sqrt{2\tau^2 - \tau^2} = \tau$$

is the standard deviation which we don't need for the proof, but is an interesting result in it's own right.



distribution and 2σ width.



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Now if $v = at$ at ~~the~~ time of collision

The mean final velocity at the time of a collision is of ~~the particle is~~

$$\langle v \rangle = \int_0^\infty v \, P(t) \, dt$$

$$= \int_0^\infty at \, \frac{e^{-t/\tau}}{\tau} \, dt$$

$$= a\tau$$

But what is the mean velocity itself? The drift velocity?

Well one might be tempted to say well $v_{ave} = \frac{1}{2}(0 + at)$

$$= \frac{1}{2}at$$

is the mean velocity from $t = 0$ to t the collision.

$$\therefore \underbrace{\langle v_{ave} \rangle}_{\text{false}} = \frac{1}{2} a\tau$$

But this is WRONG.

It's wrong because it doesn't take into account how long ~~you~~ the carrier ~~are~~ is moving at average velocity $\frac{1}{2}at$.

~~Now the~~

$\frac{1}{2}at$ is a sort of average velocity but it ~~does~~ is NOT the average that tells you how far the carrier has gone in a long time t_{long}.

The real way to find the average velocity is to divide total distance traveled by total time. ~~In~~

$v_d = \cancel{\frac{x}{t}}$

From the constant acceleration kinematic equations in time t the carrier travels

$$x = \frac{1}{2}at^2$$

Now let's sum distances and times over a large number of steps i.

$$v_d \cong \frac{\sum_i \frac{1}{2} a t_i^2}{\sum_i t_i} = \frac{\text{total displacement}}{\text{total time.}}$$

But the times t_i of each step i occur with probability $P(t_i)\,dt_i$

$$\therefore \quad v_d = \frac{\int_0^\infty \frac{1}{2} a t^2 \frac{e^{-t/\tau}}{\tau} dt}{\int_0^\infty t e^{-t/\tau} dt}$$

$$= \frac{\frac{1}{2} a (2\tau^2)}{\tau} = a\tau = \langle v \rangle$$

A sort of curiosity that the drift velocity, the true average velocity, is the same as mean final velocity of a step.

It's a peculiarity of the particular probability distribution of step times.

Since it has taken 9 pages to prove this, one can understand — but not excuse — SJ-761 for a proof by because.

What if the time between collisions was a constant τ.

Then $v_{drift} = \frac{\frac{1}{2} a \tau^2}{\tau} = \frac{1}{2} a \tau$,

but random times to collisions is the physically right assumption

27-46

OK $J = \frac{nq^2 \cancel{E}}{m}\tau$

$= \frac{nq^2\tau}{m} E$

$\therefore \quad \sigma = \frac{nq^2\tau}{m}$

which is independent of E if τ is independent of E which it is.

— The mean time between collisions τ depends on the thermal velocity of the carriers and other properties of the material.

and these actually must be treated using quantum mechanical ideas (AM-9, ~~50~~ 49-52)

27-47

$$\rho = \frac{1}{\sigma} = \frac{m_e}{n q^2 \tau}$$

in the Drude model

§ 27.4 Resistance & Temperature

— $\rho(T)$ depends on T and in general in some more or less complex way.

But in some cases for metals is pretty linear e.g., copper TM-846

But one can Taylor expand ~~any~~ smooth function (and nature usually allows us

27-48)

to asume smooth behavior — but not always)

So if one takes a reference or fiducial temperature T_0, one can Taylor expand around T_0

$$\rho \cong \underbrace{\rho_0}_{\rho(T_0)} + (T-T_0)\left.\frac{\partial\rho}{\partial T}\right|_{T_0} + \text{higher order terms}$$

~ we can drop these if $T-T_0$ is small enough.

$$= \rho_0 + (T-T_0)\left.\frac{\partial\rho}{\partial T}\right|_{T_0}$$

$$= \rho_0\left[1 + (T-T_0)\frac{1}{\rho_0}\left.\frac{\partial\rho}{\partial T}\right|_{T_0}\right]$$

We define

$$\alpha \equiv \left(\frac{1}{\rho} \frac{\partial \rho}{\partial T} \right) \Bigg|_{T_0}$$

$$= \left(\frac{\partial \ln \rho}{\partial T} \right) \Bigg|_{T_0}$$

Units of α

$$[\alpha] = \frac{1}{{}^\circ C}$$

a Celsius degree

as the temperature coefficient of resistivity.

Say we set $\rho = 0$

and solved for $\Delta T = T - T_0$

$$0 = 1 + \Delta T \alpha$$

$$\Delta T = -\frac{1}{\alpha}$$

So if our linear expression for ρ were exact (which it is <u>not</u>)

then $-\frac{1}{\alpha}$ is the temperature change from T_0 needed to take resitsivity to zero.

Consider ~~the~~ α for about $T_{room} \simeq 300$ on p. 27-27 for metals

$$\Delta T \cong -\frac{1}{3\times10^{-3}} = -\frac{10^3}{3}\,K \simeq -300K$$

Which is about right ρ should go to zero at about $T = 0K$

$$\rho = \rho_0\left[1 + (T - T_0)\alpha\right]$$

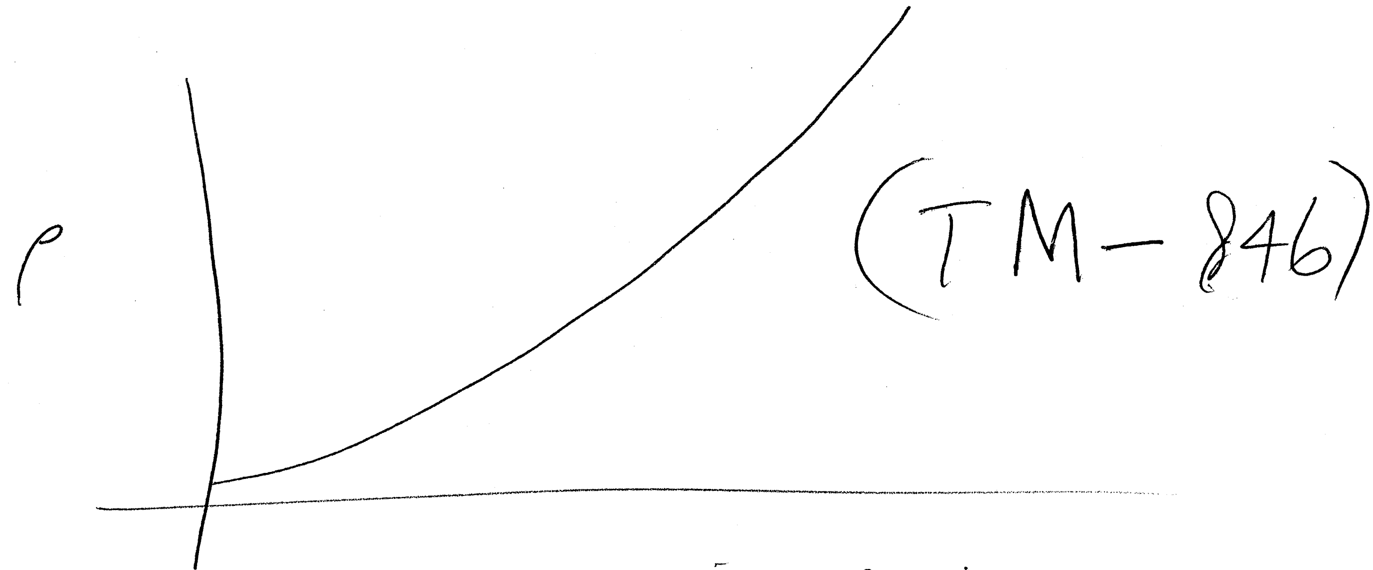
actually applies over a limited range since our Taylor's expansion does.

Since Resistance for any ~~[illegible]~~ ~~cond~~ ohmic conductor is proportional to resistivity ρ,

$$R = R_0\left[1 + \alpha(T - T_0)\right]$$

For metals $\alpha > 0$

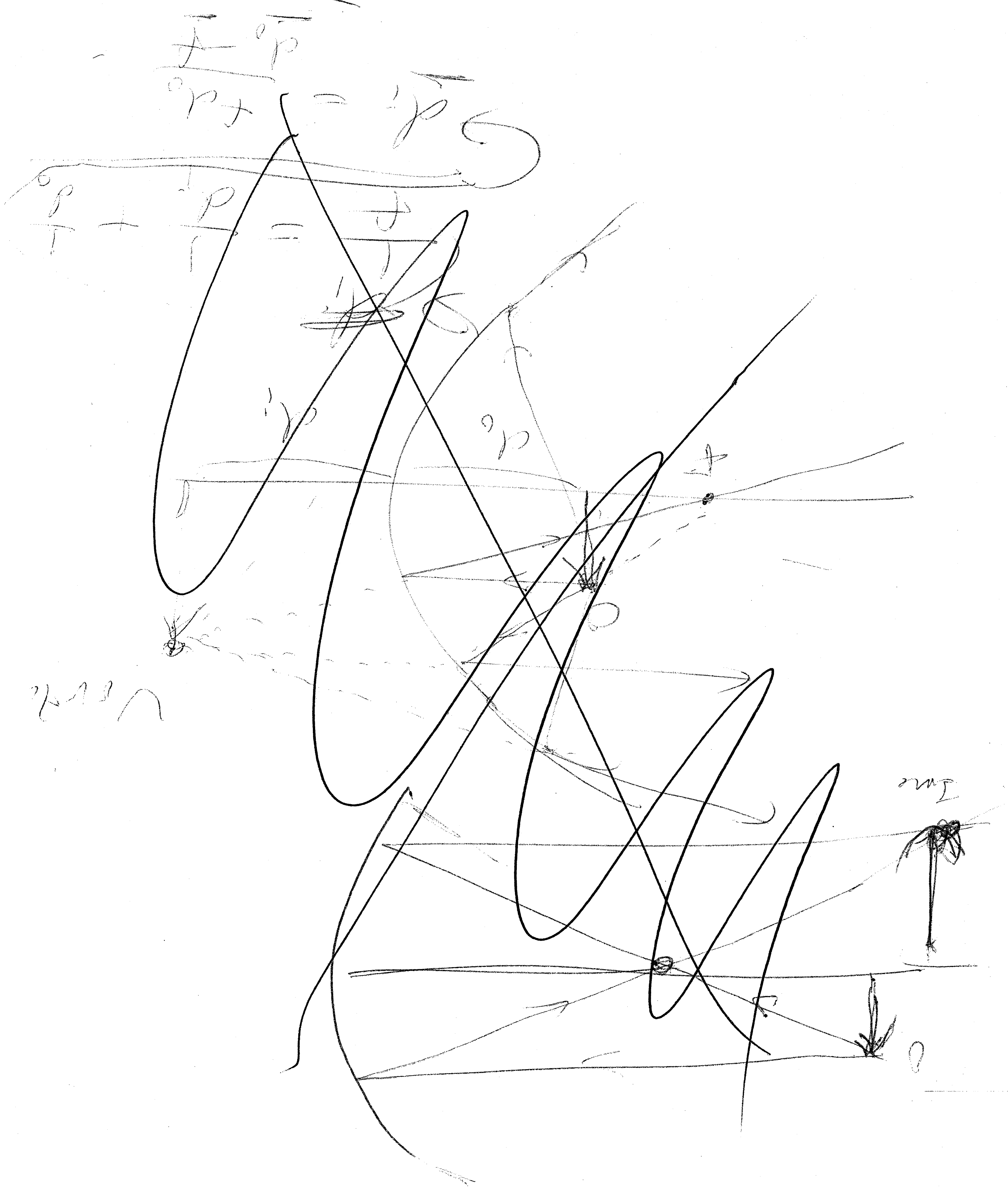
and often ρ is rather ~~al~~ linear



- the higher the temperature the more interactions are possible it turns out in Quantum mechanically.

- as $T \to 0$, $\rho \to \rho_{residual}$ ~~which~~ where $\rho_{residual}$ is due to defects and impurities (Wik)

27-52



if impurities and defects didn't exist

$\rho_{residual} \rightarrow 0$ ~~near~~ one

guesses.

— no resistance and the electrons would be able to move without a driving force

But this is not superconductivity

that is $\rho \rightarrow 0$

for finite although small T (~~on the~~ absolute scale)

27-54)

Semi-conductors have $\alpha < 0$. (SJ-758)

This means resistivity decreases as temperature increases.

The reason for this is higher T, frees more charge carriers

$$\rho = \frac{m}{n q^2 \tau}$$

as $n \uparrow$, $\rho \downarrow$.

— the ability of semiconductors to change their resistivity greatly thru the ~~release~~ freeing of charge carriers and by means other than temperature increase

is an aspect
of their electronic properties
that make them so useful
in electronics.

§27.5 Superconductors

— left as a reading

§27.6 Electrical Power

If you have a
Potential change V
and a charge Δq goes
thru that change then

$\Delta E = \Delta q\, V$ is the
energy ~~converted~~ transformed

27-56)

Which way and into what?

Well it depends.

If $\Delta q > 0$ and it goes down a potential ~~hat~~ hill, energy has come out of the PE form.

- in a vacuum it could go into kinetic energy
- in a resistance into thermal energy of material.

the collision events slow down the carriers and turn their KE into heat.

27-57

In a electric motor the
PE gets transformed
to the macroscopic
mechanical energy of
the motor which does
some kind of work.

If $\Delta q > 0$ and the
charge goes up a potential
hill, then energy from
somewhere ~~pushing the force charge~~
~~against the electrostatic force~~
is being transferred to electrical
PE thru some force.

If $\Delta q < 0$, it's mutatis mutandis.

27-58

What if the Δq is transferred ~~thru the potential~~ in Δt.

Then $P_{average} = \frac{\Delta q}{\Delta t} V$

average power.

assume a continuous process of charge movement. So Δq goes every Δt in a continuous stream

$$P = \lim_{\Delta t \to} \frac{\Delta q}{\Delta t} V = IV$$

So $P = IV$

$$[P] = \left[\frac{\cancel{C}}{s}\frac{J}{C}\right] = J/s = \text{Watt} = W$$

This is a very general formula. Which way the energy is being transferred depends on the case — but it's to or from electrical PE.

2-7-69

Resistors

— devices designed to have resistance

— unlike wires which ideally should have zero resistance.

Why do ~~y~~you want them.

— electric space heaters
(electrical PE into heat)

— incandescent light bulbs.

the tungsten filaments heats up from energy deposited ~~at~~ in it and glows.

unfortunately not very efficiently. Most energy comes out as IR rather ~~than~~ than visible light.

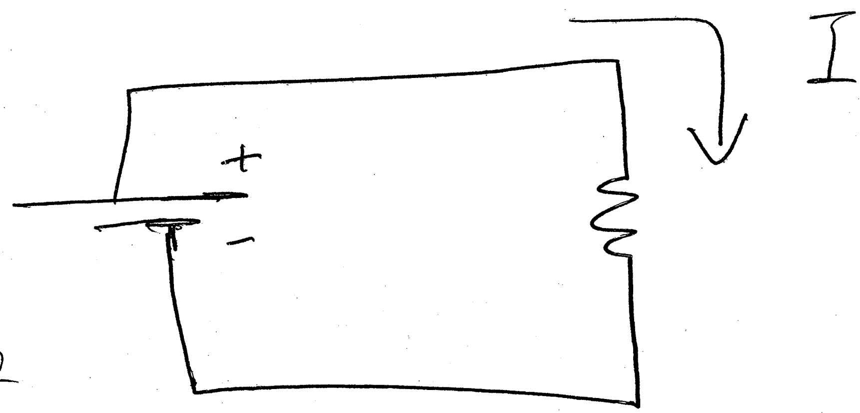
only ~7 to 20% efficient

27-60

— and of course standard circuit devices with many uses.

Resistor symbol 

So a simple circuit



Battery — a source of emf

electromotive force to be defined in Ch 28

$\mathcal{E}$

There is a potential rise $V_B = \mathcal{E}$ across the battery where the emf pushes charge up a potential hill of V_B

$P_{in} = I V_B = I\mathcal{E}$

where we assume

I constant ~~for near~~

which is normal for reasons

we'll discuss in Ch. 28. Constant in time and around the circuit.

— Now potential is actually due to ~~to~~ charge separation ~~that~~ the EMF originally causes.

~~— no pole~~

— remember the electric ~~E~~ force is conservative.

— If you go around a closed loop $\Delta V = 0$

∴ V_B is a rise across battery from negative to

27-62

positive end.

- there must be a drop by any path from +ve to -ve end.
- So ~~a~~ drop going around the wire.
- Ideal wires have $\Delta V = 0$
- so the whole drop is across the ~~battery~~ resistor

$\therefore$ $V_d = I R$ $\left(\sum V_{rise} = \sum V_{drop} \right.$

$\therefore$ $\mathcal{E} = IR$ in this case

drop across resistor

current thru resistor

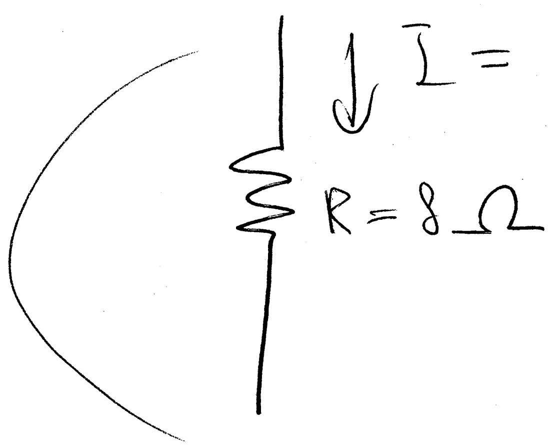
$\therefore$ $I = V/R$

27-64

— DC = direct current.

So $V = 120\,V$ is constant and so is the current

V=120 is potential drop



$$I = V/R = \frac{120}{8} = 15\,A$$

$$P = IV = 15 \cdot 120 = 1\,800\,W = 1.8\,kW$$

If you run the heater for 1 hour you energy

$$P_{\text{into PE}} = IV$$

going thru battery

$$P_{\text{out to heat in resistor}} = IV = \frac{V^2}{R}$$

$$= I^2 R$$

These formula only apply to the resistor.

Ex 27.4 Say $V = 120\,V$ across a Nichrome space heater.

~~Het~~ We'll assume DC for the moment.

27-65

consumption from the ~~grid~~ source is $E = 1.8\,\mathrm{kW} \cdot 1\,\mathrm{h}$

$$= \underbrace{1.8\,\mathrm{kW \cdot h}}$$

a kilowatt hour
— a unit of energy
— a stupid unit.

$$= 1.8\,\mathrm{kW \cdot h}\left(\frac{3600\,\mathrm{s}}{1\,\mathrm{h}}\right)$$

$$\cong 7000\,\mathrm{kJ}$$

$$\cong 7\,\mathrm{MJ}$$

The electric companies should bill us in megajoules.

— I think part of the problem with public understanding of

27-66

energy is the insistence on useing odd energy units in different contexts.

— Why not bill electric ~~pow~~ energy use in MJs and report energy content of food in MJs.