Electromagnetic Radiation (EMR)

it is a wave phenomenon.

— from the 1st semester you may be familiar with mechanical waves

Some medium oscillates
- rope
- air
- solids, fluids
- the Earth (seismic waves)

34-2

EMR is different in ~~that~~ no medium is needed — the waves propagate in a ~~vacuum~~ Vacuum

but ~~they~~ it can propagate in some media too which does affect ~~their~~ its behavior.

§34.1-2 Maxwell's equations

We've actually seen them all

(James Clerk Maxwell (1831-1879))

— Maxwell ~1860 took them over from past work put them in

a set of four
→ with a little bit of
modification and showed
that all classical E+M
could be derived from
them (plus knowledge
of material E + M
properties which
can't be understood
with modern quantum
mechanics.

Vacuum form.

$$\oint \underset{\sim}{E} \cdot d\underset{\sim}{A} = \frac{q_{encl}}{\varepsilon_0}$$ Gauss's law

$$\oint \underset{\sim}{B} \cdot d\underset{\sim}{A} = 0$$ Gauss's law for magnetism (sometimes the no-name law)

$$\oint \underset{\sim}{E} \cdot d\underset{\sim}{s} = -\frac{d\Phi_B}{dt}$$ Faraday's law

$$\oint \underset{\sim}{B} \cdot d\underset{\sim}{s} = \mu_0 I + \varepsilon_0 \mu_0 \frac{d\Phi_E}{dt}$$

Ampère's law

34-4)

where the $\varepsilon_0 \mu_0 \frac{d\Phi_E}{dt}$ term is the displacement ~~curr~~ current that Maxwell added to Ampère's law to generalize it for time dependent systems

"displacement current" is a historical name. It has no meaning in modern theory

a key point.

Essential to the derivation of EMR—which we don't do.

Actually Gauss's law for magnetism is begging for a non-zero right-hand side and Faraday's law could use a term analogous to $\mu_0 I$ in Ampère's law.

This would symmetrize the equations — but nature has not so far provided us with magnetic monopoles and currents thereof.

These forms of Maxwell's equations are the vacuum forms.

They actually always apply microscopically, but at the macro-level one needs to account for material properties explicitly

(Also at the micro-level there are QM corrections from quantum electrodynamics QED).

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The forms shown are the <u>integral equation forms</u>

There are also <u>differential equations forms</u>

which are often more useful in solving E & M problems.

<u>§ 34.3 EMR waves</u>

— the text book gives a derivation from Maxwell's equations ~~that there~~ is ~~a solution~~ for a special case

in the absence of all charge ~~too~~ for coupled E- and B-fields

which has the form of
standard wave equations.

— I'll skip the derivation
which is cute in itself, but
necessarily klutzier than
one can do with vector calculus.

— and just skip to what
one gets.

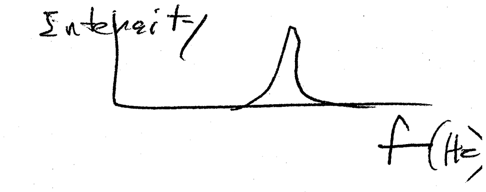
— for vacuum
— for propagation in 1-d
→ the x direction
for definiteness —

— for a single
frequency
→ real EMR
is always some
continuum of of frequencies mixed
together — but they that
continuum can be

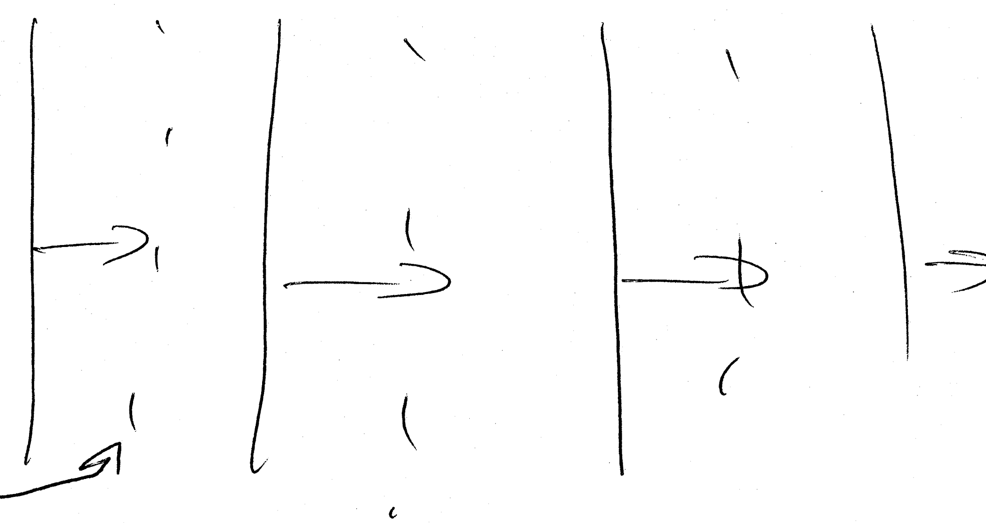
of plane
waves.

e.g., for lasers

very narrow.



— plane waves?



crests ~~extending~~ and troughs extending to infinity in the direction perpendicular to the direction of propagation.

These are Maxwell's equations manipulated & specialized recall.

What one gets is two wave equations

∂ is the partial derivative symbol.

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2}$$

&

$$\frac{\partial^2 B}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B}{\partial t^2}$$

Which need solutions which we'll get to in due time

These forms look like

E & B are

decoupled — i.e., independent

but this is not so.

— for the ~~solution~~ result

a time-varying B-field
creates E-field by
Faraday's law

& a time-varying E-field
creates ~~a~~ B-field
by Ampère's law (generalized
by the displacement current,
since no current
is present)

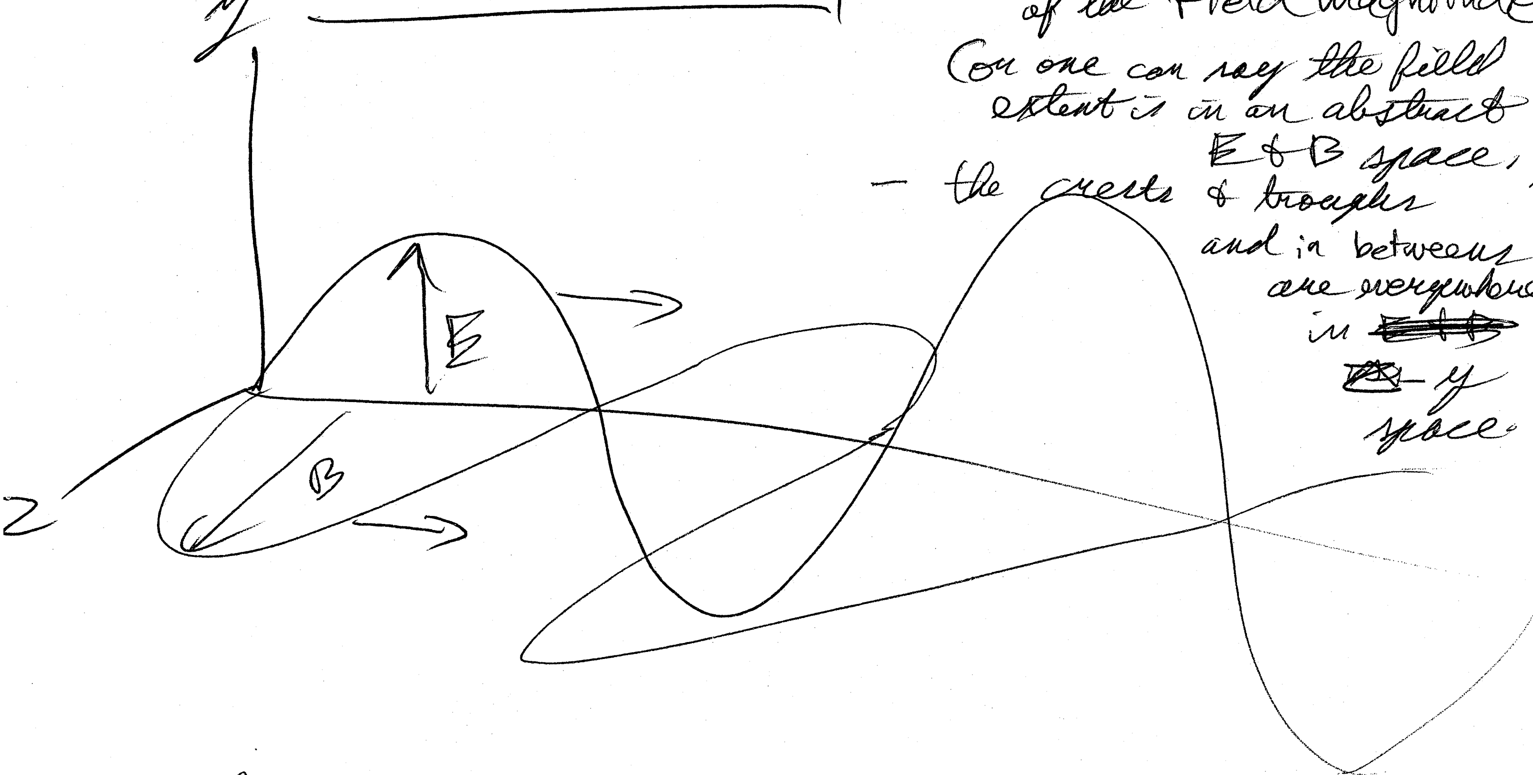
the two varying fields create
each other and this dependence
is implicit~~ed~~ in the equations.

They are coupled. That is why they are always electro-magnetic waves & radiation.

There ratio is set too by derivation $\frac{B}{E} = \sqrt{\varepsilon_0 \mu_0}$

Cartoon

The field vectors point in real space but ~~their length~~ their shown length is just a illustration of the field magnitude (or one can say the field extent is in an abstract E & B space.) — the crests & troughs and in betweens are everywhere in ~~E & B~~ ~~x~~-y space.

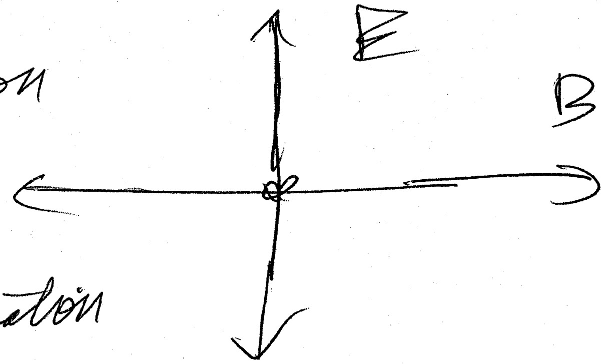


The waves are transverse

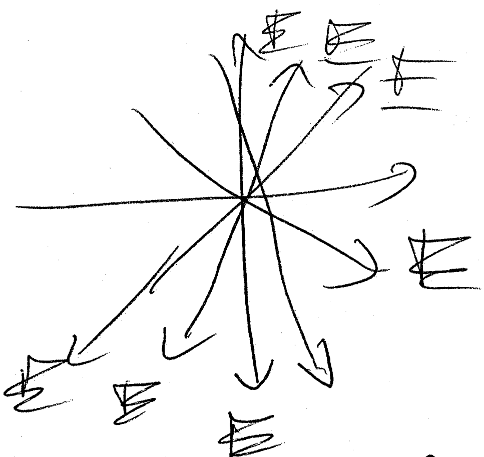
↳ i.e., the fields point perpendicular ~~opposite~~ to direction of motion (like waves on a string and unlike sound waves in fluids which are longitudinal)

$\underline{E}$ & $\underline{B}$ are perpendicular to each other for a single polarization

head-on view for a single polarization



Most natural light has a continuum mixture of polarizations



and accompanying B-fields.

— but highly polarized light can be created by some processes and reflection & transmission in some media.

Now the wave equations again

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2}$$

$$\frac{\partial^2 B}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B}{\partial t^2}$$

34-12

Why are they called wave equations?

Well ~~they~~ conform mathematically to the general wave equation form

$$\frac{\partial^2 f}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 f}{\partial t^2}$$

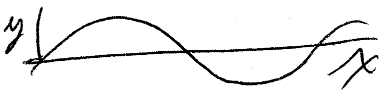
for 1-d

where v is the phase speed of the waves

Not speed of oscillations ~~but~~ of f but the speed at which the wave pattern moves along as we'll see.

This general wave equation turns up in many locations; e.g.,

waves on a string



$$\frac{\partial^2 y}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 y}{\partial t^2}$$

where $v = \sqrt{\frac{T}{\mu}}$

T is string tension

μ is mass per unit length

S J-458

TM-500

believe it or not this is derived in that context from $F = ma$

The same equation turns up for sound waves (HRW-400-401)

with v being the sound speed

& y being longitudinal displacement of gas.

So when Maxwell wrote down

$$\frac{\partial^2 E}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 E}{\partial t^2}$$

$$\frac{\partial^2 B}{\partial x^2} = \mu_0 \varepsilon_0 \frac{\partial^2 B}{\partial t^2}$$

34-14

he saw at once
~~that~~ he had wave equation

and ~~that~~ $\frac{1}{v^2} = \varepsilon_0 \mu_0$

or $v = \frac{1}{\sqrt{\underbrace{\varepsilon_0 \mu_0}}}$

These are just constants from electricity and magnetism (he ~~had~~ probably different units and values for them than us)

But when he plugged in the values he got $\sim 3 \times 10^8 \, m/s$ (in modern units) (HZ-6-7)

then "he" did <u>not</u> say Eureka being Scottish "he" said

"Hoot Jamie mon,
kent ye not
the speed of licht."

or some such words.

Whatever he said, he
was forced to consider
that light was
in fact electromagnetic
~~[illegible]~~ waves

— It was already then
known that other forms
of light invisible to
the eye existed
IR (infrared light) since
1800 (Wik)
& UV (ultraviolet light) since 1801
(Wik)

34-16

and Maxwell's ~~equation~~
discovery suggested
there should be
other forms too
that could be generated
and received by
electrical apparatus

And this was confirmed
by Heinrich Hertz in 1888 (Hz-7)
(1857-1894)
when he discovered radio

[Hertz by the way also
pioneered C&W stations
and talk radio. — Fact]

General Wave Equation

~~Wave~~ Solutions

$$\frac{\partial^2 f}{\partial x^2} = \frac{1}{v^2}\frac{\partial^2 f}{\partial t^2}$$

This is a partial differential equation (a PDE)

~~A very general~~

Which means it has two independent variable x and t.

— Which in principle makes possible solutions much more complex than ~~for~~ ordinary DEs (ODEs)

But in this case ~~there~~ is a very general

(most general? Art-680 suggests it)

34-18

The solution is any function of the form.

$$f(x,t) = f(\underbrace{x - vt}_{x'})$$

Proof

$$\frac{\partial^2 f}{\partial x^2} = \frac{\partial}{\partial x}\left(\frac{\partial f}{\partial x'}\underbrace{\frac{\partial x'}{\partial x}}_{1 \text{ a constant}}\right)$$

using the chain rule.

$$= \frac{\partial^2 f}{\partial x'^2}\left(\frac{\partial x'}{\partial x}\right)^2$$

$$= \frac{\partial^2 f}{\partial x'^2}$$

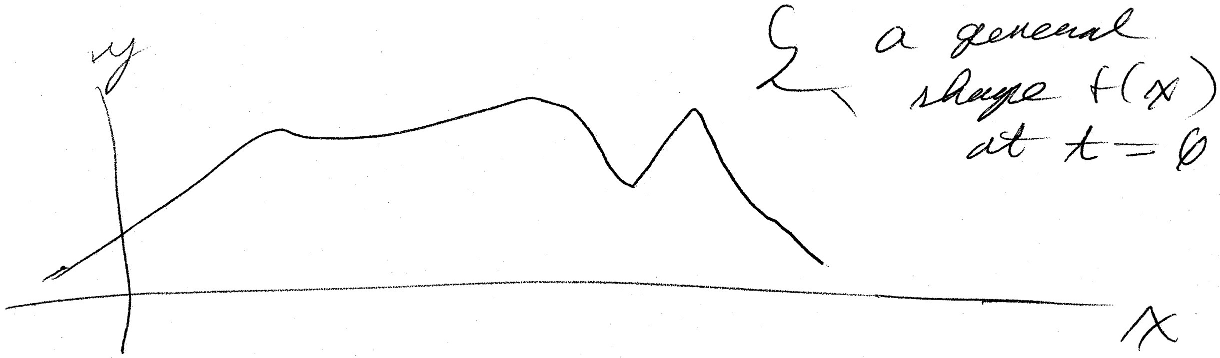
Similarly $\displaystyle \frac{\partial^2 f}{\partial t^2} = \frac{\partial^2 f}{\partial x'^2}\left(\frac{\partial x'}{\partial t}\right)^2$

$$= \frac{\partial^2 f}{\partial x'^2} v^2$$

$$\therefore \quad \frac{\partial^2 f}{\partial x^2} = \frac{\partial^2 f}{\partial x'^2} = \frac{1}{v^2}\frac{\partial^2 f}{\partial t^2}$$

and so f satisfies the PDE.

What ~~does~~ does the solution do?



~~at t = 0~~

Now say at time zero
you are at x' when $f = f(x')$
and then start running along at velocity v (which could be positive or negative)

Your position as a function of time is

$$x(t) = x' + vt$$

and at that x, t you find

$$f(x - vt) = f(x' + vt - vt) = f(x')$$

34-20

and ~~so~~ so you are still looking at the same height of f as at $t=0$.

This is true for any initial x'.

And so the whole function profile is sliding along at velocity v.

If $v > 0$, it slides in the positive x direction

If $v < 0$, it slides in the negative x direction

So as advertised earlier

v or rather $|v|$ is the phase speed.

— the speed at which the profile slides along.

Now ~~light~~ EMR radiation can usually be decomposed into sinusoids ⟹ i.e., it is a linear combination of sinusoids of different wavelength (or frequency)

⟹ So one can learn a lot by considering

34 – 22

a single sinusoid solution

$$E = E_0 \cos(kx - \omega t)$$
$$B = B_0 \cancel{\cos} (kx - \omega t)$$

Just the magnitudes.
– recall E-fields
& B-fields are
vector fields.

These solutions
do conform to our
general solution

$$\cos(kx - \omega t)$$
$$= \cos\left[k\left(x - \frac{\omega}{k} t\right)\right]$$
$$= f\left(x - \frac{\omega}{k}\right)$$

For EMR in vacuum $|v| = \left|\frac{\omega}{k}\right| = c$ always.

$$v = \frac{\omega}{k} = c$$

is ~~the~~ ~~wave ve~~ phase velocity.

What are are k and ω?

Well at any one place x

$\cos(kx - \omega t)$

ω is always positive.

oscillates with angular frequency ω.

A full perod is $\omega \Delta t = 2\pi$

$\therefore \Delta t = T$ period.

$\therefore \quad T = \frac{2\pi}{\omega}$ is a period

$f = \frac{1}{T} = \frac{\omega}{2\pi}$

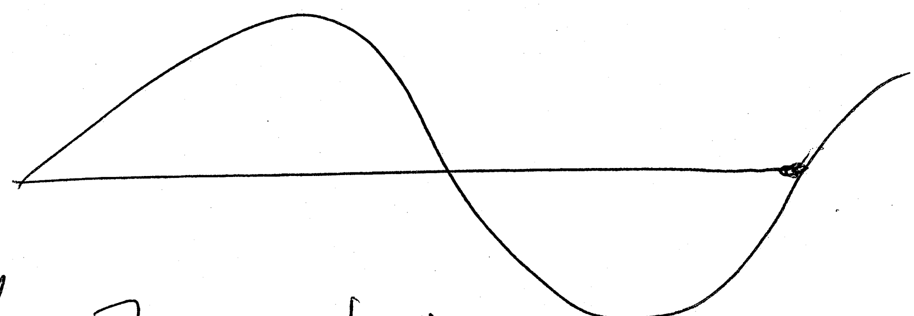
is ordinary frequency or cycles per second

Now at any one time t

$\cos(kx - \omega t)$

oscillates in space with x.

If completes one period



when $2\pi = k\Delta x$

$\therefore$ $|\Delta x|$ is the wavelength λ

Nearly always small Greek lambda is used for wavelength.

$$\lambda = \frac{2\pi}{|k|}$$

or $|k| = \frac{2\pi}{\lambda}$ frequently $k = \frac{2\pi}{\lambda}$ and one just thinks of the magnitude of k.

k is called the wavenumber.

When one is thinking of k as having a sign.

If $k > 0$, the waves propagate to the positive x direction

$$v = \frac{\omega}{k} > 0$$

If $k < 0$, the waves propagate to the negative x direction

$$v = \frac{\omega}{k} < 0.$$

In 3-d, one actually has a wavenumber vector $\underset{\sim}{k}$. But that is beyond our scope.

~~Speed of light~~

~~Light in vacuum always has speed c as measured~~

$\boxed{34-26}$

Relationships to recall

$$c = \frac{\omega}{k}$$

$\Big\{$ k without the sign is meant,

$$T = \frac{2\pi}{\omega}$$

$$f = \frac{1}{T} = \frac{\omega}{2\pi} \quad \text{or} \quad \omega = 2\pi f$$

$$k = \frac{2\pi}{\lambda} \quad , \quad \lambda = \frac{2\pi}{\lambda}$$

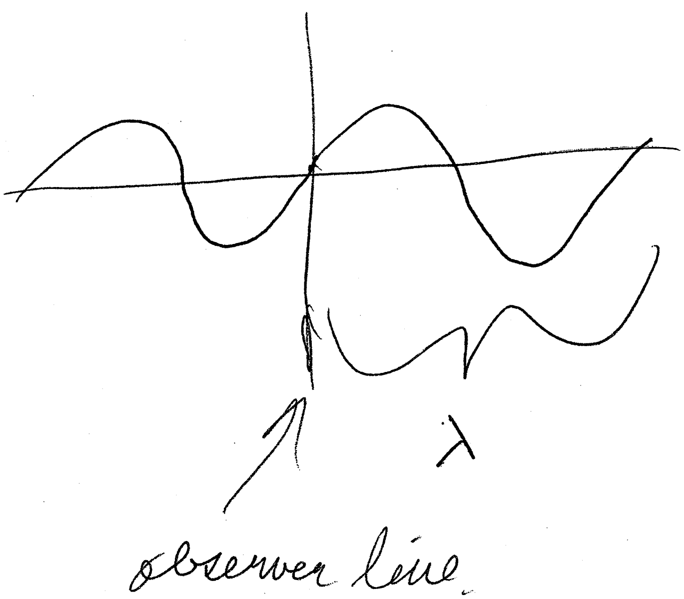
$$\cancel{\frac{= f/(2\pi)}{2\pi}}$$

$$c = \frac{\omega}{k} = \frac{2\pi f}{2\pi/\lambda} = f\lambda$$

$$c = f\lambda$$

$\Big\{$ frequently ~~meo~~ memorized expression

Another way to get (or remember) $c = f\lambda$ is to think of wavelengths passing a point



In time $\Delta t = T$ one wavelength goes by

$$\therefore \quad c = \frac{\lambda}{T}$$

But in NT, N wavelengths go by

$$\therefore \quad f = \frac{N}{NT} = \frac{1}{T}$$

$$\therefore \quad c = f\lambda.$$

Speed of Light Problem.

— When Maxwell found his equations

34 - 28

gave c ~~the~~
known speed of light
as the speed of electromagnetic
radiation,

a natural question
was speed relative
to what?

The equations just
gave a unique speed,
but classically
speeds & velocities
depend on the motion

of the observer.

He & his contemporaries
came to the idea that

~~c was rela~~

the speed of light was relative
to a special medium

- the ether (or aether)
- or luminiferous ether
as they called it

this is what is oscillating
in Electromagnetic waves
too.

If you are at rest relative
to the ether, then light has

34-30

speed c.

If not, then not.

This idea seems natural.

— the speed of sound is a speed relative to air.

— if you move at the speed of sound (which is possible in jets) you can see sound waves at rest.

Even easier to see water waves at rest, e.g.) walking beside them in a pool.

— The same Maxwell & Co. thought for EMR & ether.

<u>But</u> air has other noticeable

properties,

the ether except filling the bill as the medium of EMR has none it seems.

It is spread ~~thru~~ throughout empty space doing nothing but being the medium for EMR.

There were attempts to measure variations in the speed of light depending on the motion of the Earth.

the ether was at rest in absolute space and the Earth moved with respect to it.

34-32

$$v_{\substack{orbital \\ Earth}} \approx 3 \times 10^6 \ m/s$$

and thus $v_{light} \in [c - v_{orb}, c + v_{orb}]$

Michelson & Morley experiment of 1887 history's most famous null result. An interferometry experiment.

But there was a null result.

$v_{light} = c$ no matter what.

various attempts to fix things up were not satisfying.

In 1905 — long after the death of Maxwell & Hertz

Einstein in his Special relativity theory (SR) cleared things up.

Maxwell was such a clever fellow, I wonder if he would have anticipated Einstein if he'd lived longer. (1831–1879)

"He" ~~stated~~
~~that~~ Maxwell's equations
were exact in all ~~frames~~
inertial frames of reference

unaccelerated frames of reference to which Newton's laws apply.

and all ~~inertial frame~~
observers measured
the same speed of light c.

But ~~then~~ what happens
to relative velocity

light beam
c

∘ you measure c

Person in rocket moving
at $v = \frac{1}{2}c$
In ordinary thinking he/she

should measure

$v_{light} = c - \frac{1}{2}c$
$= \frac{1}{2}c$.

But nonetheless they measure c.

To fix things up time and length must be inertial-frame dependent.

which blew people's minds in 1905 (still does sometimes)

But you know Newton himself wondered if time flowed the same in all frames — but

34-35

the simple hypothesis was that it did.

and for low speed motion ~~that~~ was ~~is true~~ to within observable error for a long time.

So in Einstein's ~~S~~R Maxwell's equations are exactly right

and Newtonian physics & old notions of time and space needed fixing up.

But that's another story

Of course SR needed fixing up with general relativity and

34-36)

to some degree for QM (quantum mechanics)

§34.4 Energy Carried by EMR

— EMR is self-propagating electric and magnetic fields.

we know such fields have associated energy

— it is no surprise that EMR transports energy

in fact, one of the major transport mechanisms — arguably the most important since EMR transports energy and information across the whole universe and to us from the Big Bang epoch.

Without proof ~~the~~ the rate of energy ~~transfer~~ is given by the Poynting vector

$$\underset{\sim}{S} = \frac{1}{\mu_0}\,\underset{\sim}{E} \times \underset{\sim}{B}$$

Can be derived from Maxwell's equations with vector calculus.

it's energy per unit time per unit area.

energy flowing thru an area perpendicular to direction of transport.

an intensity actually.

$$[\mu_0] = T\cdot m/A$$
$$[E] = V/m$$
$$[B] = T$$

$$\frac{V/m \; T}{T\cdot m/A} = \frac{J\cdot A}{C\, m^2} = \frac{J}{s\, m^2}$$

So the units are right.

~~transports energy~~ and information across the whole universe and to us from the Big Bang epoch.

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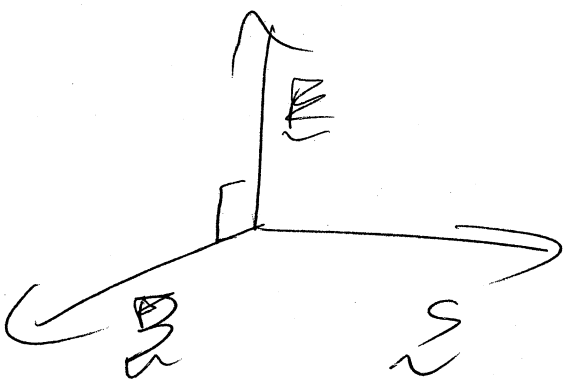
$$\frac{V/m \; T}{T \cdot m/A} = \frac{J \cdot A}{C\, m^2} = \frac{J}{s\, m^2}$$

So the units are right.

34-38)

But if we take the usual case

$\underset{\sim}{E}$ & $\underset{\sim}{B}$ are perpendicular



$$S = \frac{EB}{\mu_0}$$

Recall the $\frac{B}{E} = \sqrt{\varepsilon_0 \mu_0}$ } p. 34-9

$$= \frac{1}{c}$$

for the coupled fields of EMR.

$$\therefore \quad S = \frac{EB}{\mu_0} = \frac{E^2}{\mu_0 c} = \frac{cB^2}{\mu_0}$$

$$= c\frac{E^2}{\mu_0 c^2} = c\,\varepsilon_0 E^2$$

This is an instant in time result.
— remember the E- & B-fields

are oscillating.

Since they are sinusoidal or linear combinations of sinusoids at different frequencies.

$$\langle E^2 \rangle \ \& \ \langle B^2 \rangle = \frac{E_{max}^2}{2} \ \& \ \frac{B_{max}^2}{2}$$

$$\therefore \underbrace{I}_{\text{Intensity as usually defined.}} = S_{avg} = c\,\frac{\varepsilon_0 E_{max}^2}{2} = c\,\frac{B_{max}^2}{2\mu_0}$$

$$= c\,u_{Avg} = c\,u_{Avg}$$

~~average energy in E-field~~ ~~average energy in B-field~~

This is the average energy in the sum of the E & B-field.

Both fields have the same energy

$u_{E\,av} = \frac{1}{2}\varepsilon_0 \frac{E_{max}^2}{2}$

$= \frac{1}{2}\varepsilon_0 \frac{c^2 B_{max}^2}{2}$

$= \frac{1}{2}\frac{B_{max}^2}{2\mu_0}$

$= u_{B\,av}$

But

$F_E \sim qE$

$F_B \sim q\frac{v}{c}B$

and is ... ~

Recall

$u_E = \frac{1}{2}\varepsilon_0 E^2$, $u_{E\,avg} = \frac{1}{2}\varepsilon_0 \frac{E_{max}^2}{2}$

$u_B = \frac{B^2}{2\mu_0}$, $u_{B\,avg} = \frac{1}{2}\frac{B_{max}^2}{\mu_0}$

Circular antenna can sense B-field by Faraday's law induction of an EMF (CJ-856).

34-40

$$u_{avg} = u_{E\,ave} + u_{B\,ave}$$

$$= \frac{1}{2}\left(\frac{1}{2}\varepsilon_0 E_{max}^2 + \frac{1}{2}\frac{B_{max}^2}{\mu_0}\right)$$

which are equal in this case.

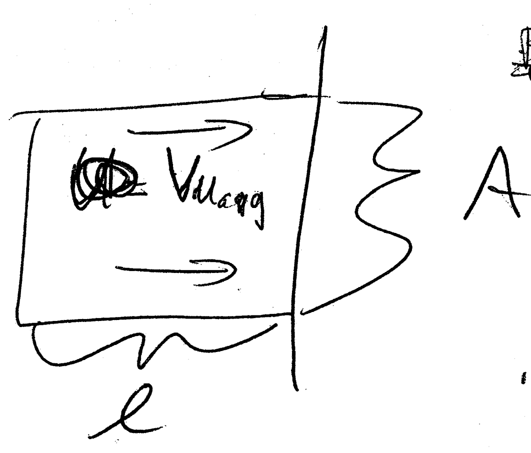
That $I = c\,u_{avg}$ needs just a bit of explanation

— the case we are studying are plane waves.

— all the radiation is going in one direction.

$\cancel{E_{\text{in}} = I\,dt\,A}$

$V = Al$



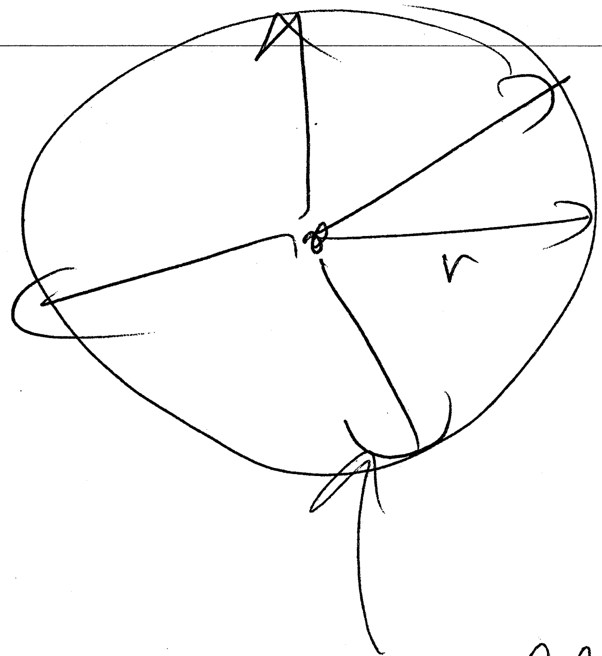
Energy in A in dt $= I\,dt\,A$

$= V u_{avg}$

$\therefore I = \frac{l}{dt} u_{avg}$

$= c\,u_{avg}$.

term we use in astrophysics).



What is intensity at radius r from the source.

all the beams are heading radially outward.

$$I = \frac{L}{4\pi r^2}$$

In time dt the energy that passes out at radius r is

$I \cdot 4\pi r^2 dt$

but in steady state with

Now plane waves
to some approximation
exist.

But a better case for
simple analyses is the
light from a point
that emits isotropically.

much like a light bulb
filament
or
~~the~~ a star from
far enough away.

say the power output
by the source is L
(L for luminosity which is

No sinks or sources

then energy = $L\,dt$

34-43

$\therefore$ $I = \dfrac{L}{4\pi r^2}$

Ex The Sun

$L = 3.86 \times 10^{26}\ W$

$r \simeq 1.5 \times 10^{11}\ m$

The mean Earth-Sun distance. — Earth orbital radius

$\therefore$ $I_E = \dfrac{L}{4\pi r^2}$

$\simeq \dfrac{3.86 \times 10^{26}}{12.2 \times 10^{22}}$

$\simeq 1.5 \times 10^{3}\ W/m^2$

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The actual measured
average value
is $I_E = 1366\ W/m^2$

Solar constant

→ it varies mainly due
to the slight eccentricity
of the Earth's orbit

– we are nearest the in
early January

$$I_E = 1412\ W/m^2$$

(and farthest in early July

$$I_E = 1321\ W/m^2$$

There are also smaller
variation due to other
things — mainly

sunspots

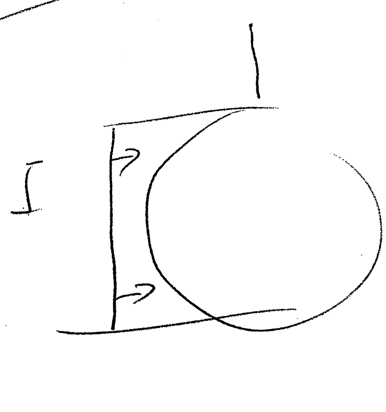
sunspots are cooler patches on the Sun – when there is a lot, the I_E is smaller.

But actually the Sun is overall brighter at Solar Max on average by a tiny bit
$S_{max} = 1366.6$ W/m²
$S_{min} = 1365.5$ W/m²

Wik

So the solar constant is not constant actually,

but often one means the time average value 1366 W/m²



But there is energy coming at us in nearly plane wave fashion since Earth is just a pinprick on the

34-46)

sphere surrounding the Sun at the Earth's orbital radius

So the amount of Power captured by the Earth is

$$I_E \pi r_E^2$$

$r_E = 6.37 \times 10^6 m$ is the Earth radius.

and the ~~average~~ Power ~~intensity~~ at the top of the atmosphere must be spread over the whole Earth's surface.

So $$I_{top\ of\ atmosphere} = \frac{I_E \pi r_E^2}{4 \pi r_E^2}$$

$$= \frac{I_E}{4}$$

$\hat{=}$ 340 W/m²

But only $\sim \frac{1}{2}$ of this makes it to the ground.

So average Earth ~~insolution~~ insolation $\sim 170\ \text{W/m}^2$

In ~~A~~ Arizona & NM maybe $\gtrsim 250\ \frac{\text{W}}{\text{m}^2}$ (Wik)

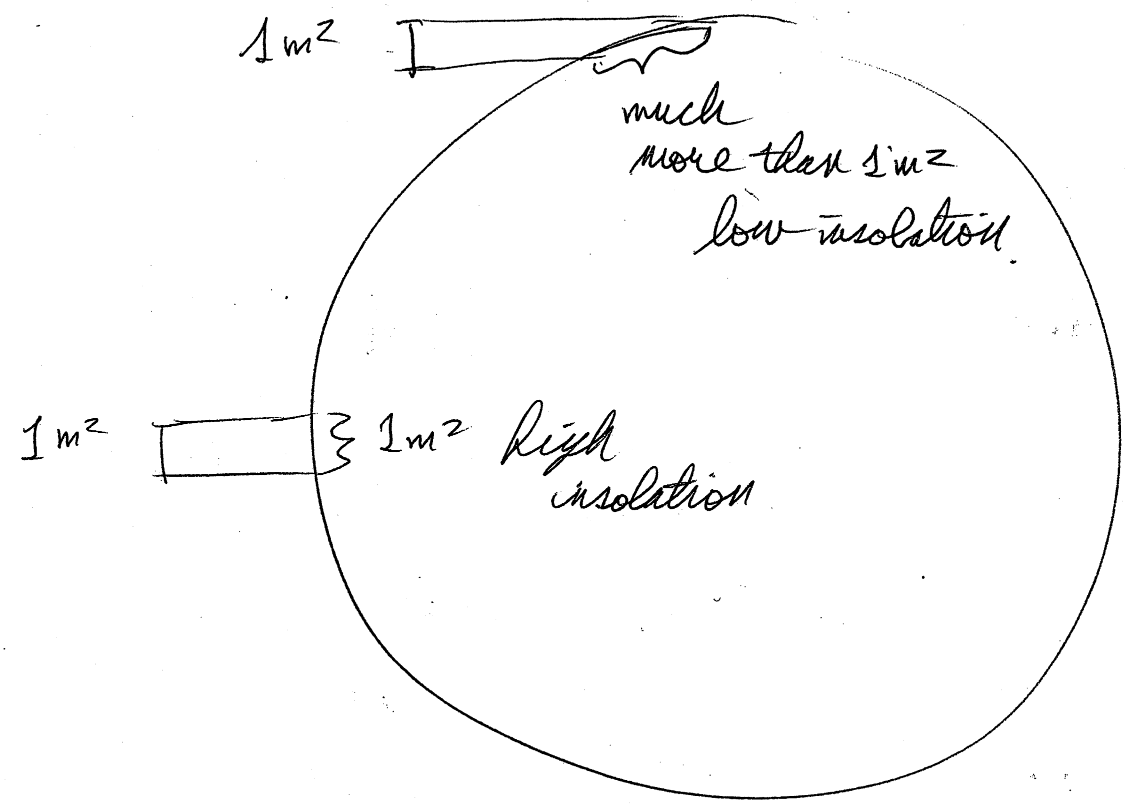
Not insalation

$$\frac{1\ \text{kWh}}{\text{m}^2\ \text{day}} = \frac{3.6 \times 10^6\ \text{J}}{1\ \text{m}^2\ 10^5\ \text{s}} = 36\ \text{W/m}^2$$

Obviously this is a day & night average.

- higher near equator & in deserts.
- lower towards the poles that receive much less direct light

34 – 48



Modern photovoltaic cells get $\gtrsim 10\%$ efficiency and higher is possible.

So solarpower could get ~ 17 W/m² on average.

Which is actually a lot better than is possible with biofuels.

— biomass from ice-free land gives $\sim .5$ W/m² and at highest productivity ~~24~~ - ~~49~~

~ 1 W/m^2 (Smil 264)

in rainforests

or intense cultivation

---

biomass fuel in the opinion of some experts

can help out a bit

with energy needs

but in fact is just too

small to become a major energy

source.

— Solar & Wind are the

big renewables.

§ 34.7 Electromagnetic Spectrum

The range of all

electromagnetic radiation

34 – 50

Recall $c = f\lambda$

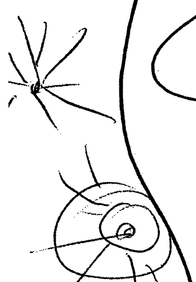
c is fixed for vacuum absolutely in our physical ~~theory~~

but ~~there~~ are no finite limits on f & λ.

— ~~Mean~~ which form a continuum

accelerated charge emits EMR

of course mechanisms of production of EMR set limits.



from astrophysical sources the current ~~limit~~ records seem to be

$f_{low} = 30\,Hz$, $\lambda = \frac{3\times10^{8}}{30} = 10^{7}\,m$

ripple goes outward.

$f_{high} = 3\times10^{27}\,Hz$, $\lambda = \frac{3\times10^{8}}{3\times10^{27}} = 10^{-19}\,m$

$u = \frac{1}{2}\varepsilon_0 E^2$

has mass $E = mc^2$

- Means of production
do give main divisions to
the EM ~~e~~ spectrum, but

there are no sharp lines
between these divisions in nature.

Sometimes hard lines are
defined for human purposes,
but they can be changed
by convention

	λ	
Gamma rays	~ 0.1 Å	Just characteristic values.
X-ray	~ 1 Å	
UV	~ 100 nm	
visible	400 - 700 nm	
Infrared	700 nm — 1000 nm	
Microwaves	~ 1 cm	
radio, TV	~ 1 m	

37-52

Actually humans
can see out to
~900 nm in IR
for intense sources
(Pedrotti & Pedrotti)
which may not be too safe
to look at actually.

But it's no revelation,
the IR light just looks red.

Birds can see into the UV

and some <u>snakes</u>
have facial pits ~~that~~
act as IR sensors
— they can "see" ~~into~~
~5 — 30 μm
rattlesnakes for example
→ they can see you in the dark
when you can't see them.

34-53

You glow infrared light

$\lambda_{max} = 2.897... \times 10^3 \text{ μm-K} / T$

$$\lambda_{max} \cong \frac{3000 \text{ μm-K}}{T_{Kelvin}}$$

Wien's displacement law for the peak of blackbody emission

T on the absolute scale.

Human's have $T \approx 300\text{K}$

$\therefore \lambda \cong 10 \text{ μm}$

The wavelength ~~of most~~ peak of human emission.

$T = \cancel{6}000\text{ K}$ sun

$\lambda_{max} = .5 \text{ μm}$ right middle of visible

blackbody radiation

- this emerges from all dense materials.
- it's not due to reflection, hence the not too comprehensible name.
- it's what you get when you subtract reflection.

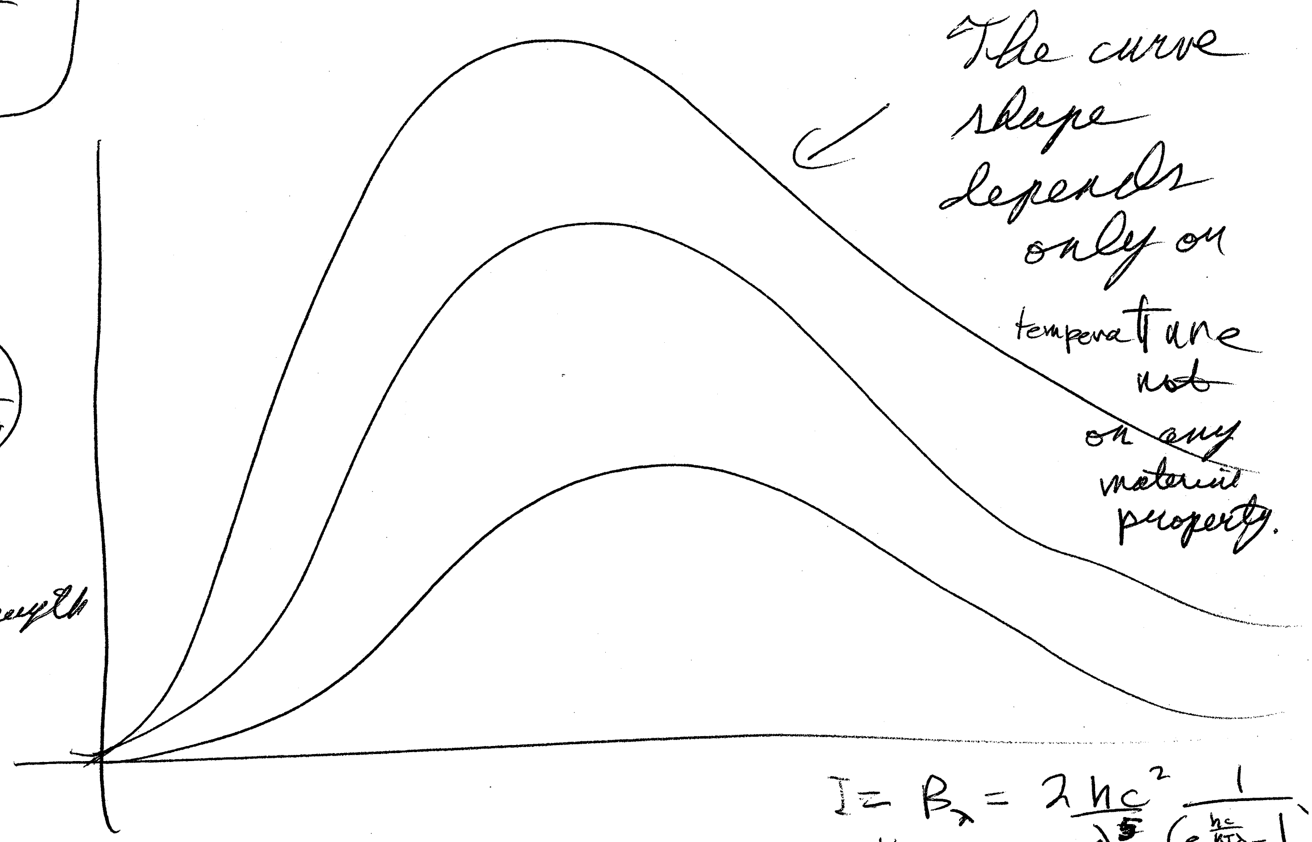
at single temperature

34-54

I

$\left(\dfrac{W}{m^2 \; m \; str}\right)$

rea per wavelength



The curve shape depends only on temperature not on any material property.

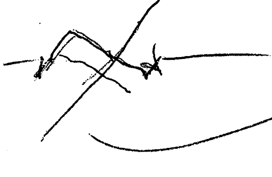
$$I = B_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{(e^{\frac{hc}{k T \lambda}} - 1)}$$

units

$$\frac{J}{s \, m^2 \, m \cdot str}$$

This is intensity per unit wavelength per steradian

The unit of solid angle.



Because of the single temperature specification, very exact blackbody radiators are rare in nature — but we can build them for experiments.

Cosmic Microwave ~~Background~~ ~~Radiation~~ Background CMB is a pretty good one.

But many sources are approximately blackbody radiators — to one degree or another i.e., humans, stars,