SO... particles as waves, huh?

How come you're not waving?

Move specifically... Justin Verlander's 2 seam fast ball

13th all time fastest pitch ever recorded 101 mph.

~ 45.5 m/s

what's the λ?

$$m = 140g$$

$$\lambda = \frac{h}{mv} = \frac{6.63 \times 10^{-34} J \cdot s}{(0.140 kg)(45.5 m/s)}$$

$$\lambda = 1 \times 10^{-34} m$$

30 orders of magnitude smaller than

a proton → no diffraction with anything!

so, no way to discern wave

character.

So, what "matter" can diffract?

Consider an electron accelerated through voltage, V.

$$\frac{1}{2} m v^2 = eV$$

$$\frac{p^2}{2m} = eV \quad \Rightarrow \quad p = \sqrt{2meV}$$

and

$$\lambda = \frac{h}{p} = \frac{h}{\sqrt{2meV}}$$

how about 50V

$$\lambda = \frac{6.63 \times 10^{-34}\ \text{J}\cdot\text{s}}{\left[(2)(9.11 \times 10^{-31}\ \text{kg})(1.6 \times 10^{-19}\ \text{C})(50\text{V})\right]^{1/2}} \quad *$$

$$= 1.74 \times 10^{-10}\ \text{m}$$

or.

$$\lambda = \frac{h}{\sqrt{2meV}} = \frac{hc}{\sqrt{2mc^2\, \underset{\sim}{eV}}}$$

energy in eV = 50eV

$$= \frac{1240\ \text{eV}\cdot\text{nm}}{\sqrt{(2)(0.511 \times 10^6\ \text{eV})(50\ \text{eV})}}$$

$$\lambda = 0.17\ \text{nm} = \underline{1.7 \times 10^{-10}\ \text{m}}$$

that's doable!

~2 Å ⇒ a crystal

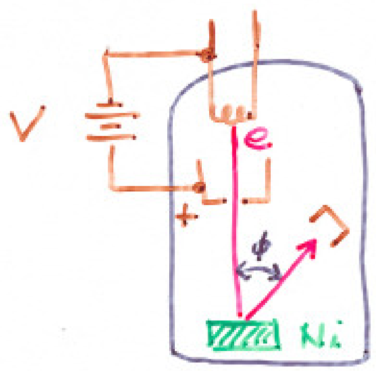
* remember: $1\,\text{eV} = 1.6 \times 10^{-19}\ \text{J}$ so

$(1.6 \times 10^{-19}\ \text{C})(50\ \text{V}) = 8 \times 10^{-22}\ \text{J}$

THE PHONE COMPANY.

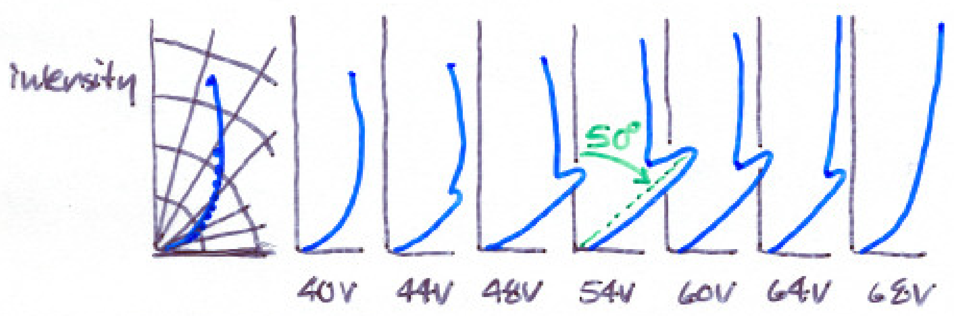
1927 Bell Lab physicists Clinton Davisson & Lester Germer

Trying to study the surface of Nickel by scattering electrons ... and goofed.



V ~ 10's of volts

after putting things back together... including heating target, their results changed.



BINGO.

@ 54 V and 50° a peak
54V and other angle ... nothing
some other voltage ... nothing

They studied the surface with xrays and found

$$\lambda(\text{Ni})_{\text{xrays}} = 1.65\ \text{Å}$$

... finally by 1927, after lots of consideration:

using $$\lambda = \frac{h}{\sqrt{2Vem}} = \frac{1240\ \text{eV}\cdot\text{nm}}{\sqrt{(2)(54)(0.511\times10^6)}}$$

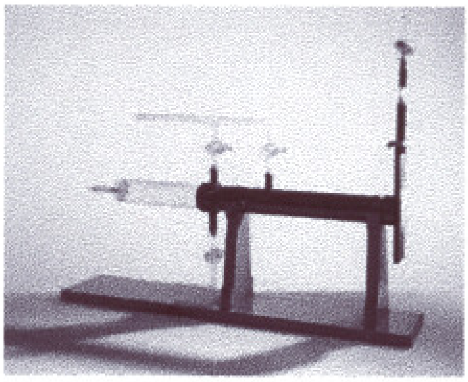
$$= 1.67\ \text{Å}$$

These are rather broad "lines" -- the regular Bragg analysis holds for scatters from single Bragg planes

- the low energy - 50 eV - electrons really scatter from more than one
- higher energy electrons do hold to the Bragg relation $2d\sin\theta = n\lambda$.

Remember JJ? -- well his son was G.P.

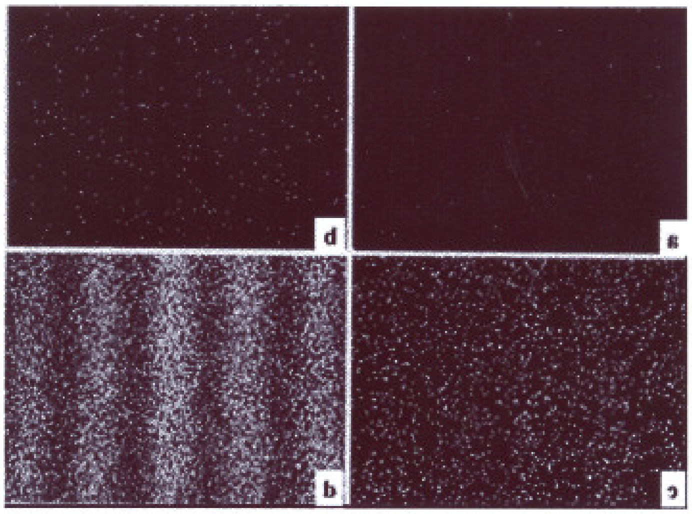
he found electron diffraction by passing electrons through materials.



Consistent with the both particle and wave theme:

- JJ got the Nobel for showing that electrons are particles

GP got the Nobel for showing that electrons aren't



Advances in Research

Electron phase microscopy

Double-slit experiment

You may be familiar with an experiment known as the " double-slit experiment," as it is often introduced at the beginning of quantum-mechanics textbooks. The experimental arrangement can be seen in Fig. 1. Electrons are emitted one by one from the source in the electron microscope. They pass through a device called the "electron biprism", which consists of two parallel plates and a fine filament at the center. The filament is thinner than 1 micron (1/1000 mm) in diameter. Electrons having passed through on both sides of the filament are detected one by one as particles at the detector. This detector was specially modified for electrons from the photon detector produced by Hamamatsu Photonics (PIAS). To our surprise, it could detect even a single electron with almost 100 % detection efficiency.

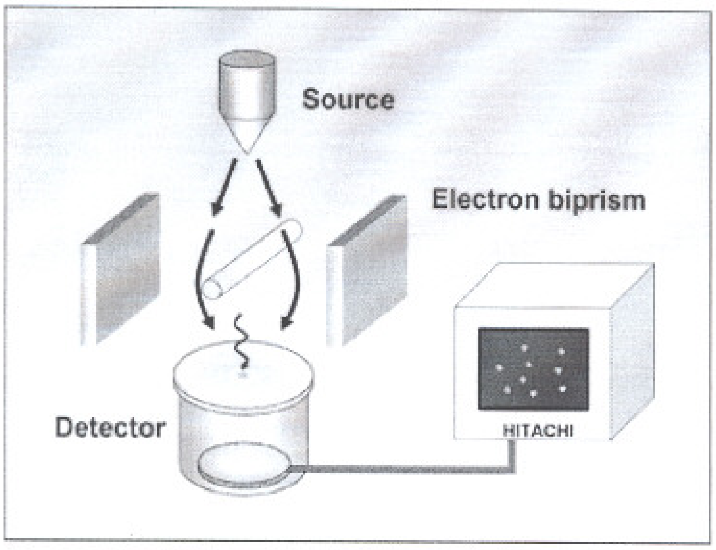


Fig. 1 Double-slit experiment with single electrons

Let's start the experiment and look at the monitor (movie Video clip 1). At the beginning of the experiment, we can see that bright spots begin to appear here and there at random positions (Fig. 2 (a) and (b)). These are electrons. Electrons are detected one by one as particles. As far as these micrographs show, you can be confident that electrons are particles. These electrons were accelerated to 50,000 V, and therefore the speed is about 40 % of the speed of the light, i. e., it is 120,000 km/second. These electrons can go around the earth three times in a second. So, they pass through a one-meter-long electron microscope in 1/100,000,000 of a second. It is all right to think that each electron is detected in an instant after it is emitted.

Interference fringes are produced only when two electrons pass through both sides of the electron

This works for everything

How about "thermal neutrons" --

$$K = u = \tfrac{3}{2} kT$$

&

$$K = \frac{p^2}{2m}$$

"thermal" ⇒ sorta room temp.
$T = 300\,K$

$$p^2 = \tfrac{3}{2} \cdot 2mkT$$

$$p = \sqrt{3mkT}$$

$$\lambda = \frac{h}{\sqrt{3mkT}}$$

$k = 8.617 \times 10^{-5}\ eV/K$

$$\lambda = \frac{hc}{\sqrt{3mc^2 kT}}$$

$$\lambda(\text{electrons}) = \frac{1240\ nm \cdot eV}{\sqrt{(3)(0.511 \times 10^6)(8.617 \times 10^{-5})}} \frac{1}{\sqrt{T}}$$

$$\lambda(\text{electrons}) = 0.058\ nm = 0.58\ \text{Å}$$

$$\lambda(\text{neutrons}) = \frac{1240}{\sqrt{(3)(938 \times 10^6)(8.617 \times 10^{-5})}} \frac{1}{\sqrt{T}}$$

$$= 0.145\ nm = 1.45\ \text{Å}$$

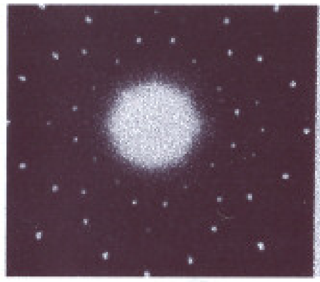
not so different from xrays.

⇒ crystals diffract

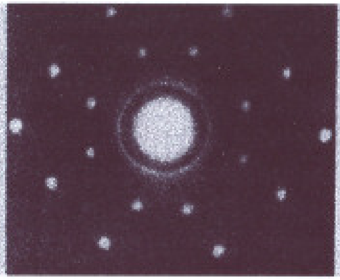
- neutrons are like xrays --. neutral

- neutrons are unlike xrays — they penetrate materials deeply.

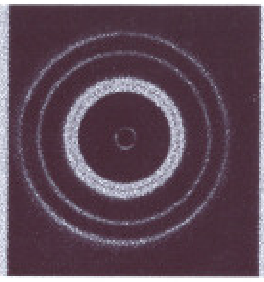
All kinds of uses of neutron beams —



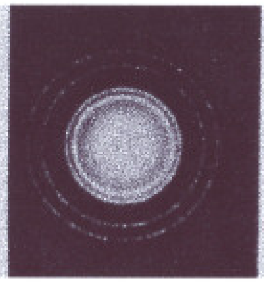
X-ray
diffraction on
NaCl



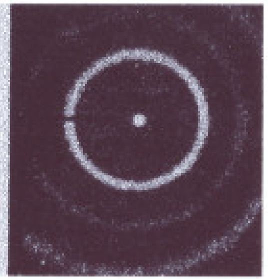
neutron
diffraction on
NaCl



0.071nm X-ray
diffraction on
a polycrystal



600 Ev electron
diffraction on
a polycrystal



0.057 ev
neutron
diffraction on
a polycrystal

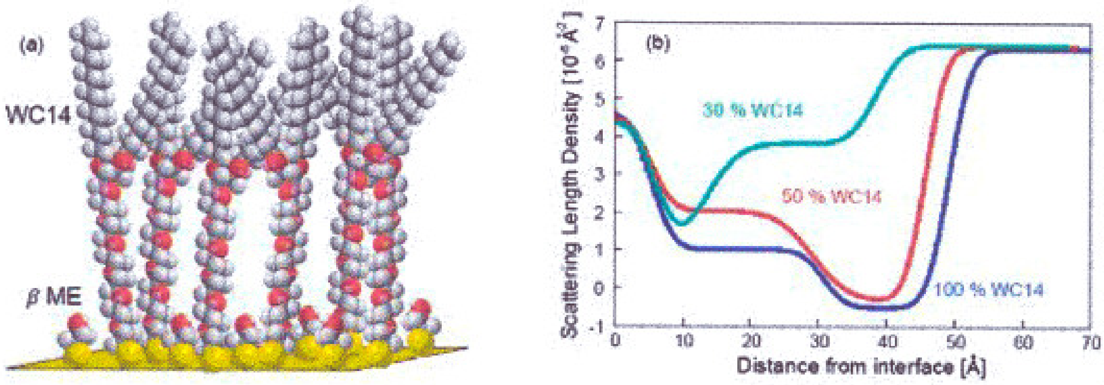


FIGURE 1: *a) Illustration of the surface-supported layer on gold, consisting of the artificial lipid WC14 spaced out from the surface by small bME molecules. b) Scattering length density profiles derived from reflectometry that show the decreasing amount of WC14 on the surface as its proportion in the SAM-forming solution decreases, with the collapse of the WC14 in sparsely-tethered systems.*

It is for these "sparsely-tethered" membrane systems that the rapid-solvent exchange technique is most powerful, as the lower hydrophobicity means that more traditional vesicle-rupture techniques have proven unfruitful. However, using solvent exchange with a variety of completing lipids produces bilayer membranes that EIS shows are electrically sealing, with low capacitance and conductivity. Importantly, we can determine uniquely from the AND/R measurements that there is a distinct hydrated reservoir of about 20 Å under a sparsely-tethered membrane (Fig. 2) [3].

The ability to exist in two states at once is another peculiar property of quantum physics known as "superposition." The NIST ions were placed in the most extreme superposition of spin states possible with six ions. All six nuclei are spinning in one direction and the opposite direction simultaneously or what physicists call Schrödinger cat states. The name was coined in a famous 1935 essay in which German physicist Erwin Schrödinger described an extreme theoretical case of being in two states simultaneously, namely a cat that is both dead and alive at the same time.

Schrödinger's point was that cats are never observed in such states in the macroscopic "real world," so there seems to be a boundary where the strange properties of quantum mechanics—the rule book for nature's smallest particles—give way to everyday experience. The NIST work, while a long way from full entanglement of a real cat's roughly 10^{26} atoms, extends the domain where Schrödinger cat states can exist to at least six atoms. The Austrian team used a different approach to entangle more ions (eight) but in a less sensitive state.

For further information, see www.nist.gov/public_affairs/releases/cat_states.htm.

* D. Leibfried, E. Knill, S. Seidelin, J. Britton, R.B. Blakestad, J. Chiaverini, D. Hume, W.M. Itano, J.D. Jost, C. Langer, R. Ozeri, R. Reichle, and D.J. Wineland. Creation of a six atom 'Schrödinger cat' state. *Nature*. Dec. 1, 2005, 639-642.

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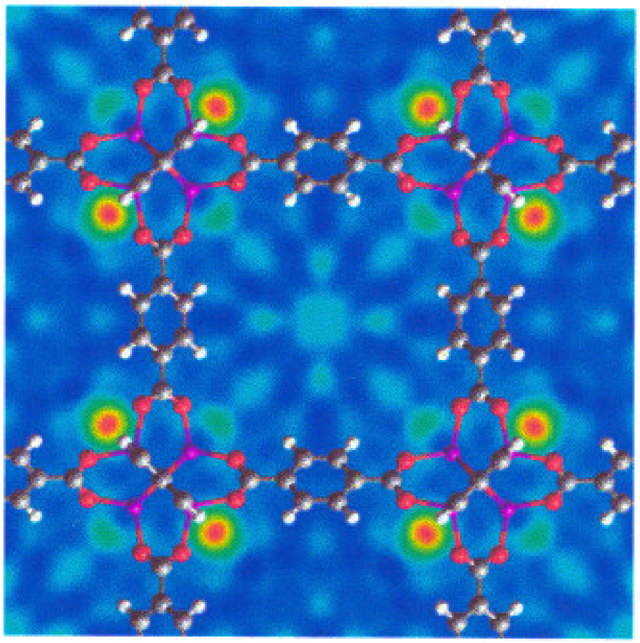
Nano-Cages 'Fill Up' with Hydrogen

A "cagey" strategy to stack more hydrogen in nanoscale scaffoldings made of zinc-based boxes may yield a viable approach to storing hydrogen and, ultimately, replacing fossil fuels in future automobiles, according to new results from National Institute of Standards and Technology (NIST) researchers.

Using beams of neutrons as probes, NIST scientists determined where hydrogen latches onto the lattice-like arrangement of zinc and oxygen clusters in a custom-made material known as a metal-organic framework, or MOF. Called MOF5, the particular nanoscale material studied by Taner Yildirim and Michael Hartman has four types of docking sites, including a "surprising" three-dimensional network of "nano-cages" that appears to form after other sites load up with hydrogen.



Neutron-scattering image reveals where hydrogen molecules (red-green circles) connect to a metal organic framework (MOF), a type of custom-made compound eyed for hydrogen storage applications. The ball-and-stick model of the MOF is superimposed on the neutron image.

Image credit: T. Yildirim/NIST

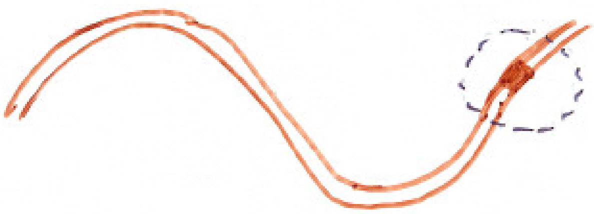
View a high resolution version of this image.

This finding, reported in *Physical Review Letters*,* suggests that MOF materials might be engineered to optimize both the storage of hydrogen and its release under normal vehicle

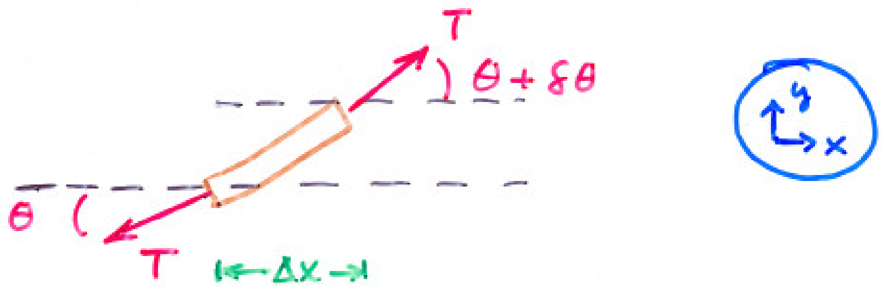
WAVE MOTION

see "classical physics" notes...

Imagine a rope (string theory? nah) with mass density [mass per unit length] μ



pick a little chunk



short enough hunk of rope... T constant at both ends, but angles are slightly different.

y direction: $$(F_{net})_y = T\sin(\theta + \delta\theta) - T\sin\theta$$

look at θ very small

$$\sin\theta \approx \tan\theta = \frac{\partial y}{\partial x}$$ slope at point x

y is going up and down in time

so, transverse velocity is $\frac{\partial y}{\partial t}$

$$(F_{net})_y \simeq T\left[\left(\frac{\partial y}{\partial x}\right)_{x+\Delta x} - \left(\frac{\partial y}{\partial x}\right)_x\right]$$

which looks like a derivative...

$$\frac{(F_{net})_y}{\Delta x} = T\left\{\left[\frac{\left(\frac{\partial y}{\partial x}\right)_{x+\Delta x} - \left(\frac{\partial y}{\partial x}\right)_x}{\Delta x}\right]\right\}$$

take limit

$$\lim_{\Delta x \to 0}\{\} \longrightarrow \lim_{\Delta x \to 0} \frac{\left(\frac{\partial y}{\partial x}\right)_{x+\Delta x} - \left(\frac{\partial y}{\partial x}\right)_x}{\Delta x}$$

$$= \frac{\partial}{\partial x}\left(\frac{\partial y}{\partial x}\right) \equiv \frac{\partial^2 y}{\partial x^2}$$

note $y = y(x, t)$.

so, $(F_{net})_y = T\left(\frac{\partial^2 y}{\partial x^2}\right)\Delta x$

The mass of this segment of rope is $m = \mu \Delta x$

From Newton's 2^{nd}

$$(F_{net})_y = \Sigma F_y = m a_y$$

$$T\left(\frac{\partial^2 y}{\partial x^2}\right)\Delta x = m \frac{\partial^2 y}{\partial t^2} = \mu \Delta x \frac{\partial^2 y}{\partial t^2}$$

and

$$\frac{\partial^2 y(x,t)}{\partial x^2} = \left(\frac{\mu}{T}\right) \frac{\partial^2 y(x,t)}{\partial t^2}$$

$$\left[\frac{\mu}{T}\right] = \frac{\left(\frac{M}{L}\right)}{\left(\frac{ML}{T^2}\right)} = \frac{T^2}{L^2} = \left[\frac{1}{v}\right]$$

$\sqrt{\frac{T}{\mu}}$ is the velocity in the longitudinal direction of individual points on the rope

v.

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

called: THE Wave Equation.

It has real solutions...

$$y(x,t) = A \sin \frac{2\pi}{\lambda}(x - vt + \delta)$$

generally.

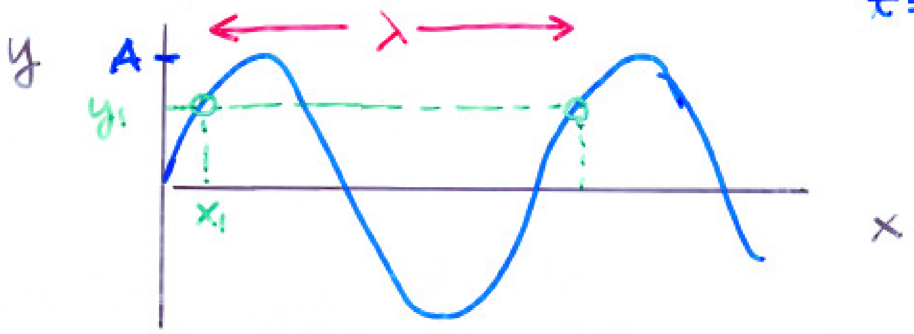
this phase has to do with how the time origin, $t=0$, is chosen.

Forget it here: $\delta = 0$

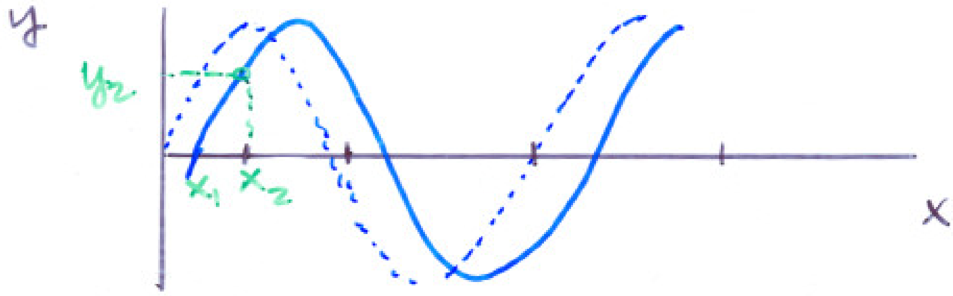
$$y(x,t) = A \sin \frac{2\pi}{\lambda}(x - vt)$$

oscillates in both space and time...

$t = t_1$



at some later time



$$y_1(x_1, t_1) = A \sin \frac{2\pi}{\lambda}(x_1 - vt_1)$$

and @ t_2

$$y_2(x_2, t_2) = A \sin \frac{2\pi}{\lambda}(x_2 - vt_2)$$

But these equal-phase points are the same height –

$$y_1 = y_2$$

so

$$x_1 - vt_1 = x_2 - vt_2$$

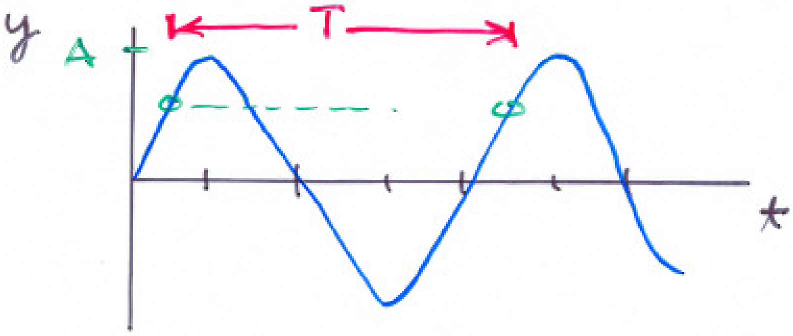
$$v = \frac{x_2 - x_1}{t_2 - t_1} \quad \Rightarrow$$

$\sin \frac{2\pi}{\lambda}(x - vt)$ represents a wave moving to the RIGHT

$+ \Rightarrow$ LEFT

Of course, it also can be projected against time.

At a given x... x=x, the wave is going up & down.



the ~~per~~ period, T, is the time difference between points of equal phase.

T = time for one vibration...

so $\frac{1}{T}$ is the rate of vibration... frequency.

$$f = \frac{1}{T}$$

and so $\lambda = v T$

or $v = f \lambda$

So,

$$y(x,t) = A \sin 2\pi \left(\frac{x}{\lambda} - \frac{v}{\lambda} t \right)$$

$$= A \sin 2\pi \left(\frac{x}{\lambda} - \frac{t}{T} \right)$$

$$= A \sin 2\pi \left(\frac{x}{\lambda} - f t \right)$$

standard definitions:

$k \equiv \frac{2\pi}{\lambda}$ the wave number L^{-1}

$\omega \equiv \frac{2\pi}{\cancel{t}} f$! the angular frequency T^{-1}

$y(x,t) = A \sin(kx - \omega t)$ of course for $\delta = \pi/2$ ...

$y(x,t) = A \cos(kx - \omega t) = A \sin(kx - \omega t + \pi/2)$

The velocity of the single wave is called

phase velocity $v_p = \lambda f$

which can also be written $v_p = \frac{\omega}{k}$

SUPERPOSITION ...

Suppose we have 2 waves... they can be made to superimpose... sines or cosines.

$y = y_1 + y_2$

$= A \cos(k_1 x - \omega_1 t) + A \cos(k_2 x - \omega_2 t)$

same amplitude

slightly different λ and f...

use $\cos a + \cos b = 2\cos\frac{1}{2}(a-b)\cos\frac{1}{2}(a+b)$

$$y = 2A\cos\frac{1}{2}\left\{(k_2-k_1)x - (\omega_2-\omega_1)t\right\}\cos\left\{\left(\frac{k_1+k_2}{2}\right)x - \left(\frac{\omega_1+\omega_2}{2}\right)t\right\}$$

make the λ and f slightly different.

$$\left.\begin{array}{l}\Delta k = k_2 - k_1 \\ \Delta\omega = \omega_2 - \omega_1\end{array}\right\} \text{small } k, \text{ large } \lambda$$

$$\left.\begin{array}{l}k_1 + k_2 \\ \omega_1 + \omega_2\end{array}\right\} \text{large } k, \text{ small } \lambda \qquad \begin{array}{l}\bar{k} = \frac{k_1+k_2}{2} \\ \bar{\omega} = \frac{\omega_1+\omega_2}{2}\end{array}$$

$$y = 2A\cos\left\{\frac{\Delta k}{2}x - \frac{\Delta\omega}{2}t\right\}\underbrace{\cos\left\{\bar{k}x - \bar{\omega}t\right\}}_{\text{traveling wave}}$$

inside of

a modulating envelope