EOSC 256 so far

- Mercalli Intensity
- Historic earthquake theories
- Elastic rebound theory
- Types of faults, how slip plane and slip direction are specified
- Types of faults expected at different plate boundaries
- Seismographs, earthquake waves ← You are here
- Determining earthquake magnitude and location
- etc.

P Waves

$$V_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$

S Waves

$$V_s = \sqrt{\frac{\mu}{\rho}}$$

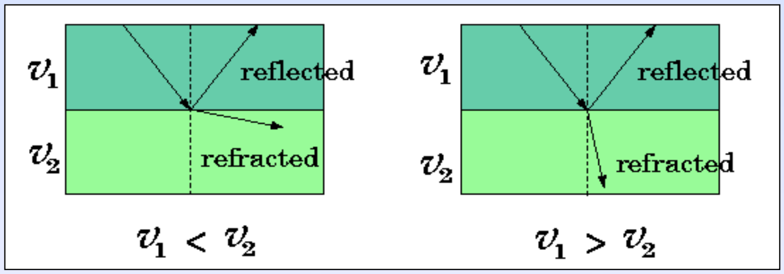
Waves travel fastest through rigid, hard-to-compress rocks.
$\mu = 0$ for fluids: fluids aren't rigid. Therefore...

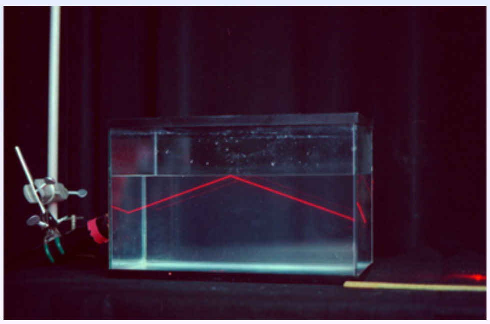
S waves do not travel through fluids!
Also, P waves are slowed down traveling through fluids.

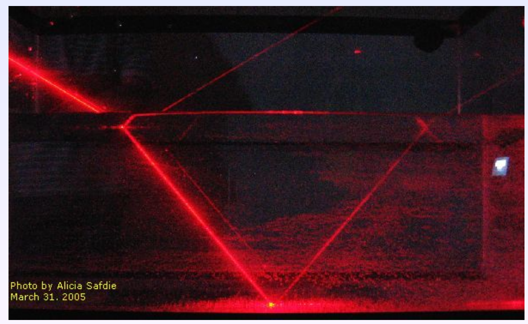
Surface waves: slower than body waves. Lowest frequencies travel fastest.

Like other waves, body waves refract and reflect

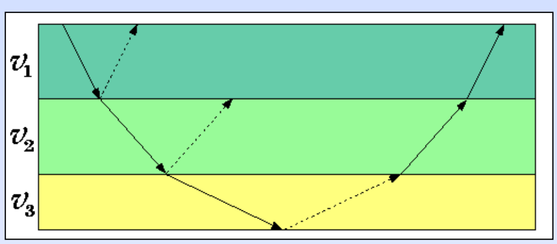
- reflection and refraction (bending) at sudden interfaces



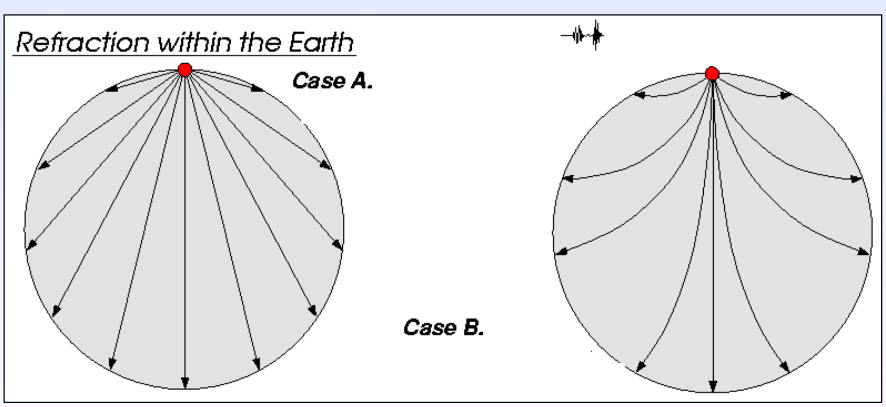




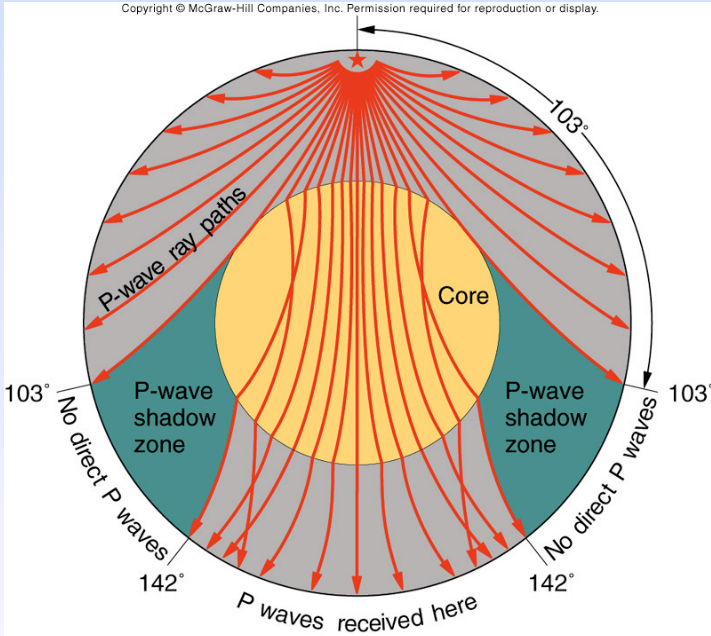
- reflection and refraction in continuously changing media



- this is why the seismic wave paths are curved...



P-wave "shadow zone": outer core has a slow P-wave velocity so ray paths refract at the core-mantle boundary

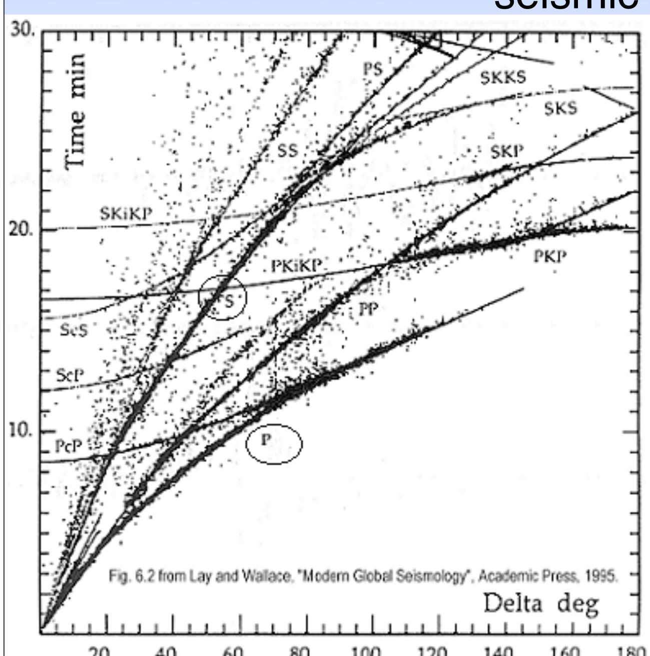


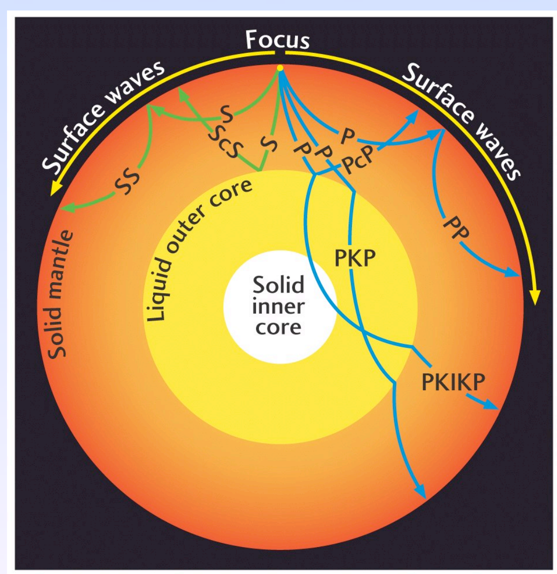
Plummer et al., 2004, Fig. 4.8

(20 minutes later)

http://www.youtube.com/watch?v=JQ27PNRe4zA&feature=player_embedded

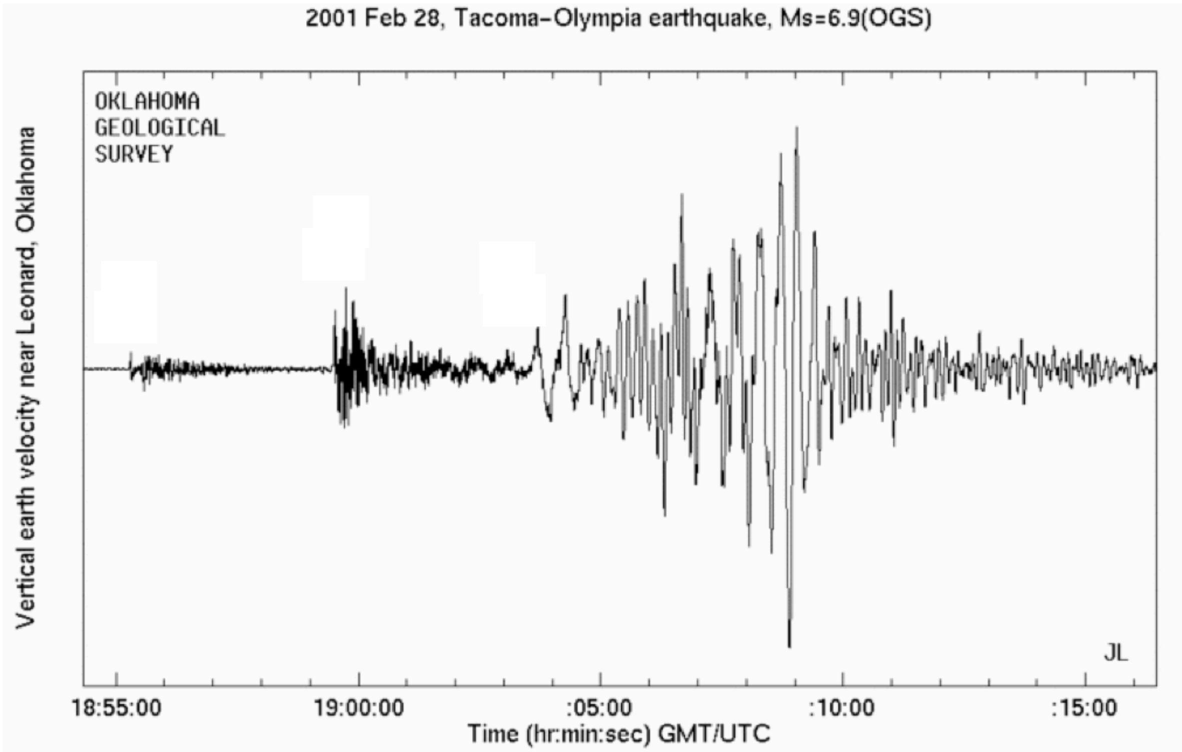
Reflection of seismic waves from boundaries can complicate seismograms recorded far from an earthquake: "seismic phases"



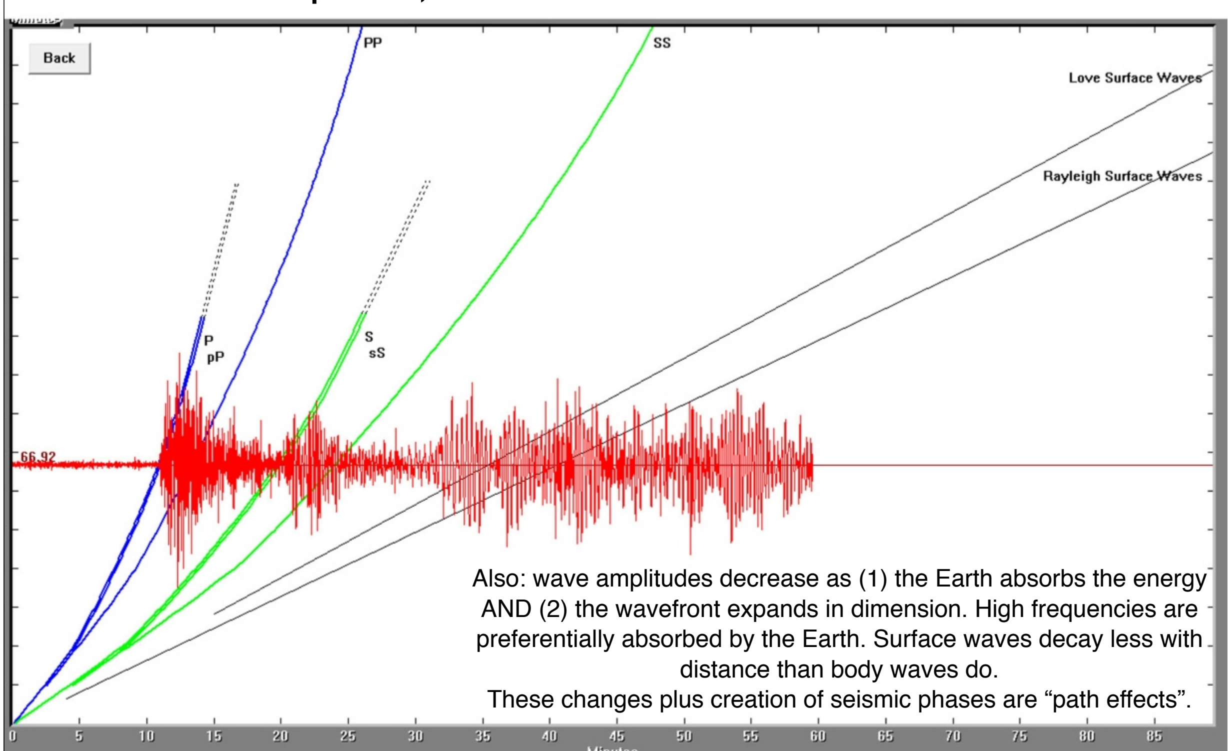


http://www.youtube.com/user/IRISEnO#p/c/8FDF28B8FD0C2E56/3/wSqxDDFZZpM

Seismogram - Tacoma WA quake, seismometer in Oklahoma (pretty straightforward)



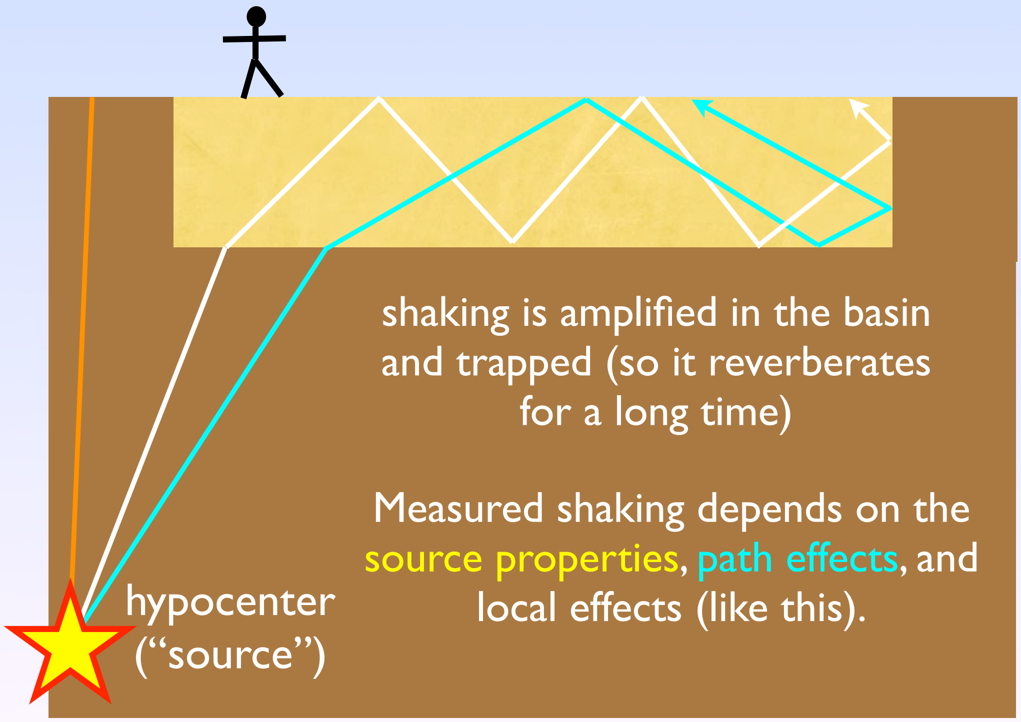
Another Seismogram - March 2011 M9 Japan quake, seismometer in Portland



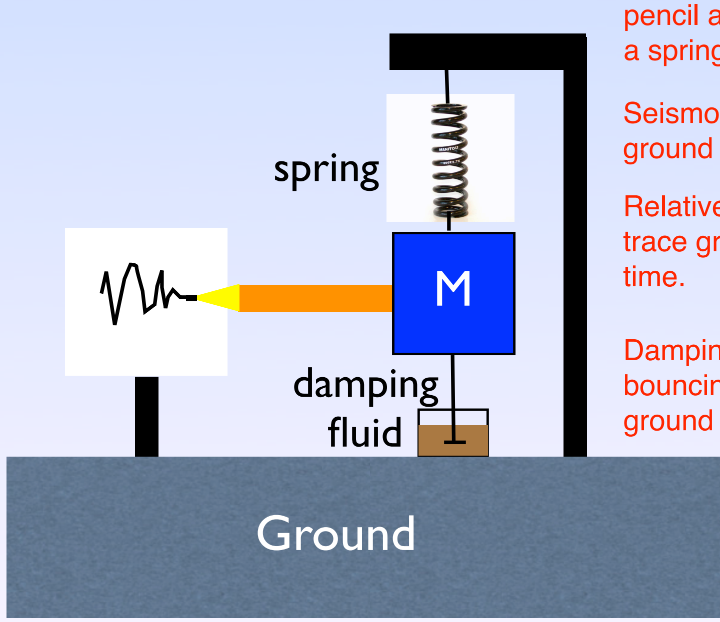
Also: wave amplitudes decrease as (1) the Earth absorbs the energy AND (2) the wavefront expands in dimension. High frequencies are preferentially absorbed by the Earth. Surface waves decay less with distance than body waves do.

These changes plus creation of seismic phases are “path effects”.

Reflection also results in seismic waves being trapped in sedimentary basins...



Mechanical seismographs: the basic idea



Heavy mass (shown here with pencil attached) is suspended by a spring.

Seismograph moves with the ground but the mass stays put.

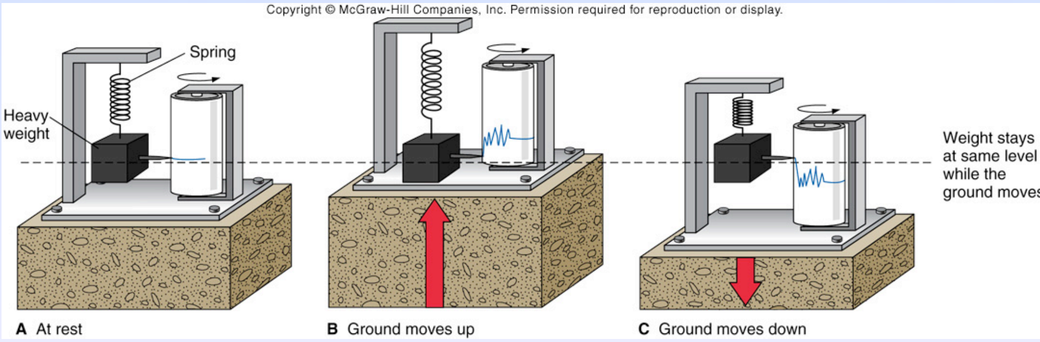
Relative motion causes pen to trace ground displacement over time.

Damping fluid stops mass from bouncing around after the ground has stopped shaking.

Vertical spring-pendulum seismograph

http://www.youtube.com/watch?v=DX5VXGmdnAg&NR=1

Seismographs: the basic idea

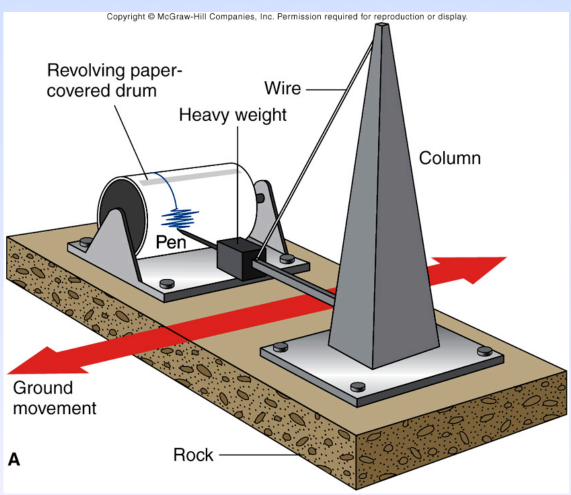


Plummer et al., Physical Geology, 2004

Vertical seismograph

http://www.youtube.com/watch?v=DX5VXGmdnAg&NR=1

Seismographs: the basic idea



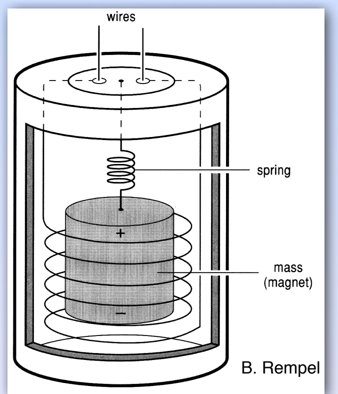
http://www.iris.edu/hq/gallery/photo/1608

- heavy mass (shown here with pen attached) is suspended by a spring
- seismograph moves with the ground but the mass stays put
- relative motion causes pen to trace ground displacement over time

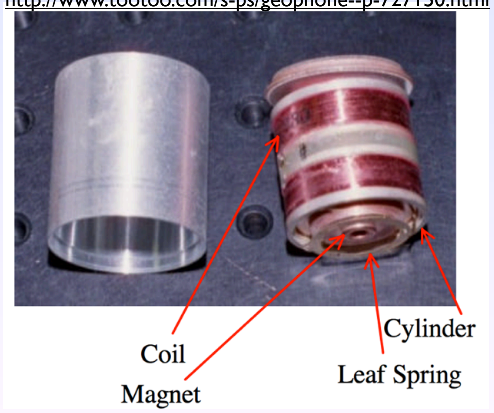
Horizontal seismograph

http://www.youtube.com/watch?NR=1&v=83GOKn7kWXM

Seismometer ("geophone"): a more modern version



http://www.tootoo.com/s-ps/geophone--p-727150.html



- heavy mass suspended by spring, same as before
- mass is a magnet, so it generates electric current in the wire coil when coil (and the ground) moves
- electric current readings are converted to shaking velocity
- record is velocity vs. time, can be converted to displacement vs. time

Electromagnetic seismographs

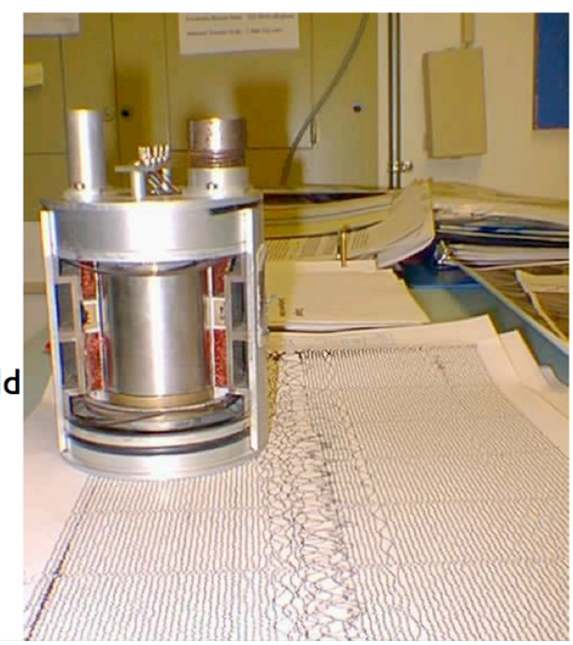
SHORT/LONG PERIOD SEISMOMETERS & GEOPHONES

> used prior to 1990's
(still used but not top of the line)

> work on damped pendulum theory

> resonant frequency at 1 Hz, 0.1 Hz (short and long period)

> mass incorporates solenoid which moves in a magnetic field



MODERN BROADBAND SEISMOMETERS

> record motions faithfully between 100 - 0.001 Hz

> driven by sophisticated feedback electronic circuits

> motion is measured through voltage required to keep masses stationary

STRONG MOTION SEISMOGRAPHS

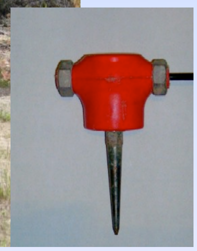
> made from MEMS & sensitive to large accelerations

> regular seismometers go off scale

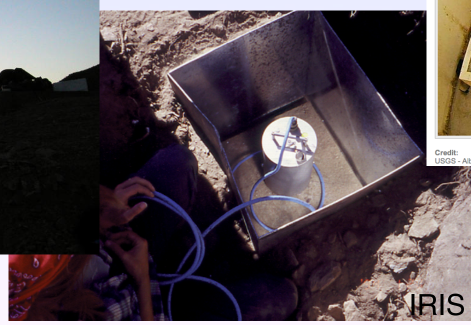
> used in triggered mode to study effects of large eq's

> employed by engineers to aid in design of earthquake resistant infrastructure

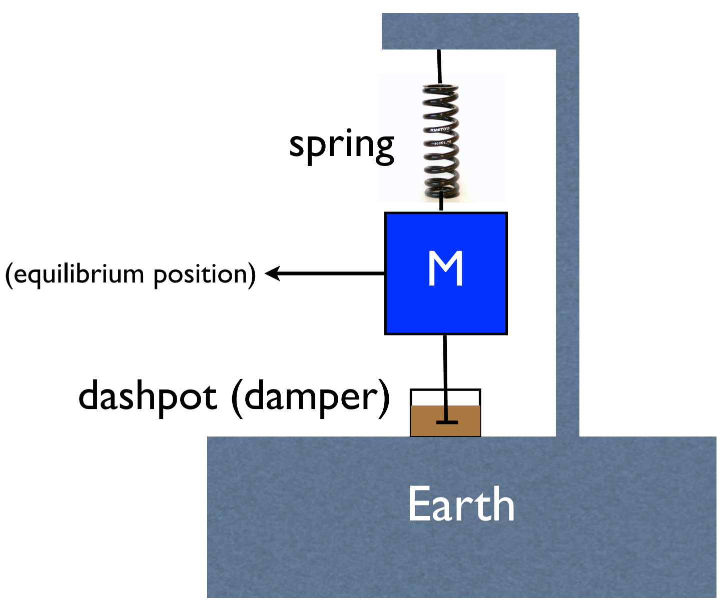
Deploying geophones near Williams Lake, BC



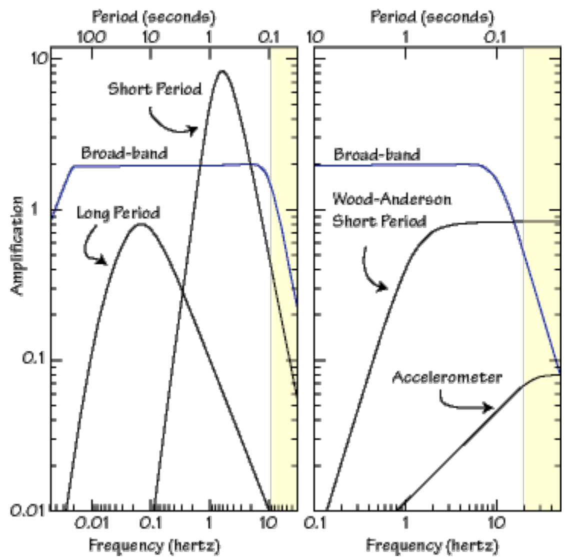
Broadband seismometer installations ($$$)



How faithfully does a seismometer represent the Earth's movement?

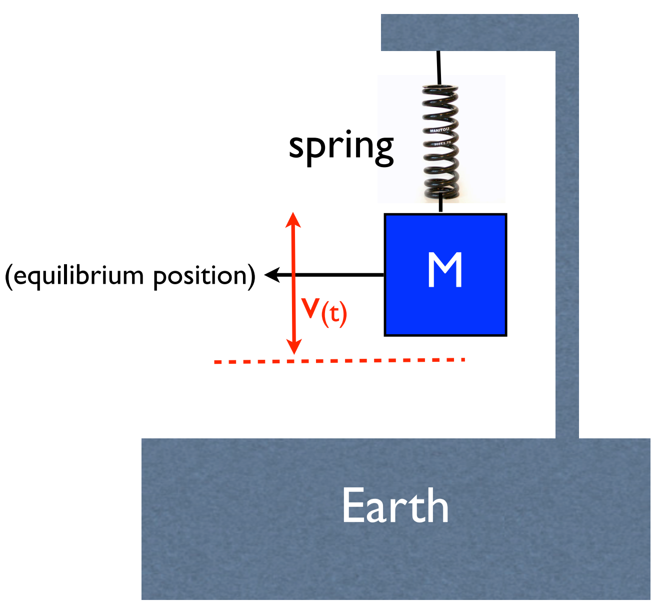


Sensitivity of different kinds of seismometers to different frequencies of shaking



Note - Amplification factors are much bigger than shown here. The amplifications here are scaled to be about 1, just to make the different seismometers easier to compare. Graphic by Charles Ammon.

Resonant frequency?



force due to spring stretching:
Hooke's Law

$$-k\ v(t)$$

force due to the weight of M:
Newton's second Law

$$M\frac{d^2v(t)}{dt^2}$$

These forces must balance:
Newton's third law. So

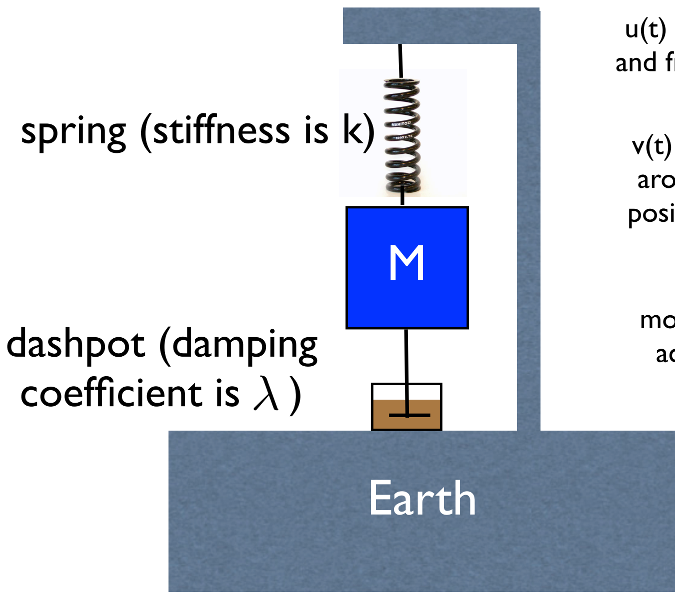
$$M\frac{d^2v(t)}{dt^2} = -kv(t)$$

A solution to this is: $v(t) = cos((\sqrt{k/M})t)$

If you pull the spring and let go, it will bounce up and down with a "resonant" frequency of: $\omega_o = \sqrt{k/M}$

What happens to M if the Earth suddenly moves down?

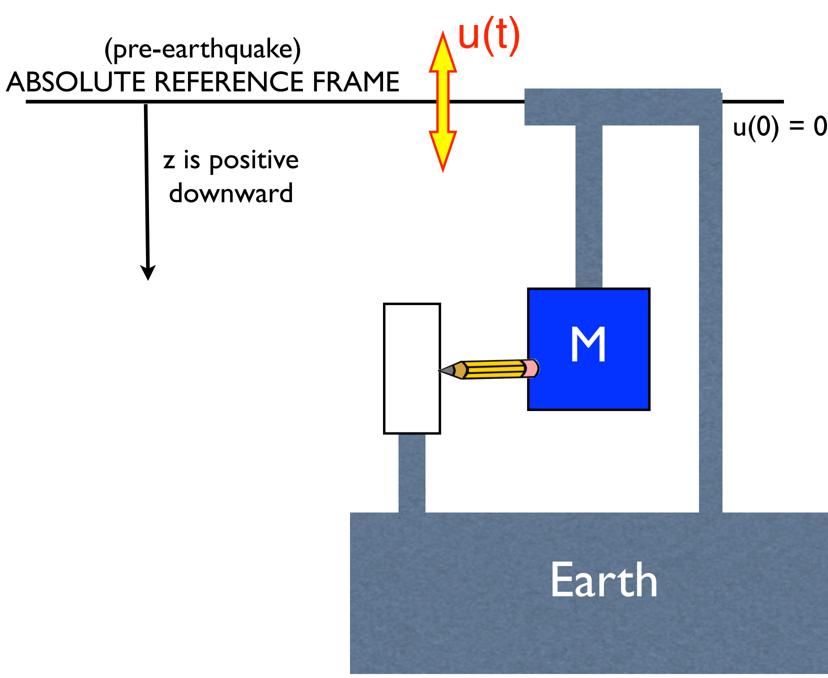
What if the Earth's surface suddenly stops moving?



u(t) = motion of ground and frame (what we want)

v(t) = motion of spring around its equilibrium position (stretching and contracting).

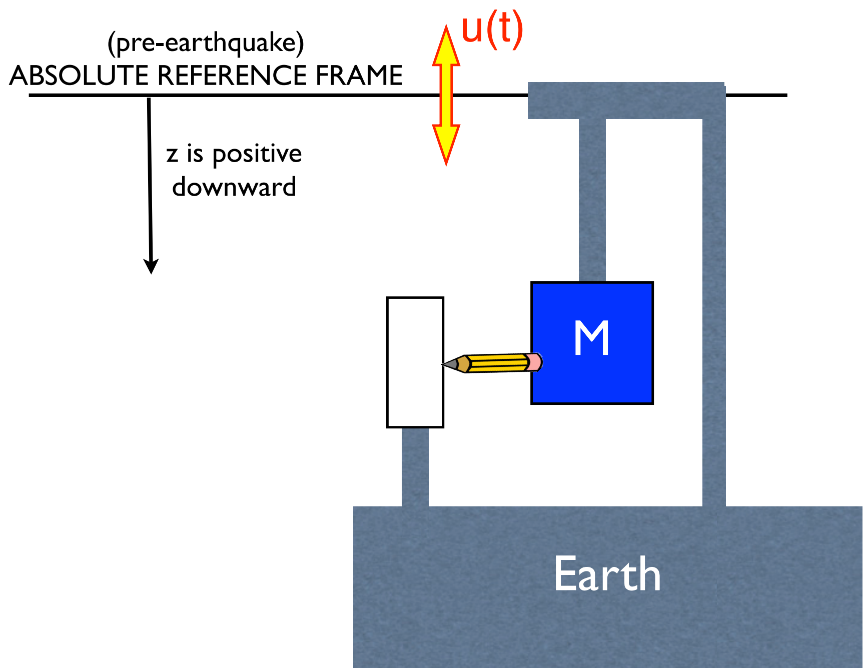
motion of the mass is actually the sum of these two!



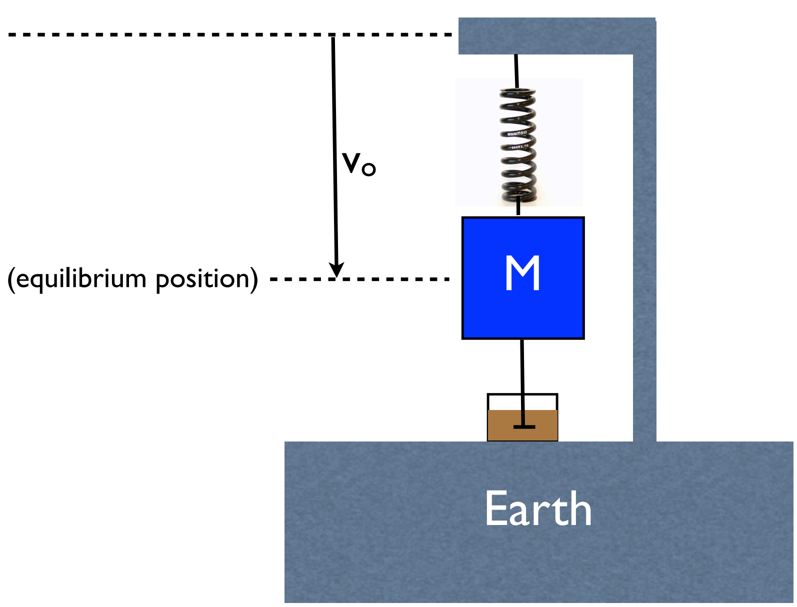
Just u(t)

u(t) = motion of ground and frame relative to pre-earthquake position (absolute reference frame) <u>= motion of M if the spring is replaced with a rigid connection to the frame</u>

What would be recorded on a revolving paper drum attached to the ground?



What would be recorded on a revolving paper drum attached to the ground?

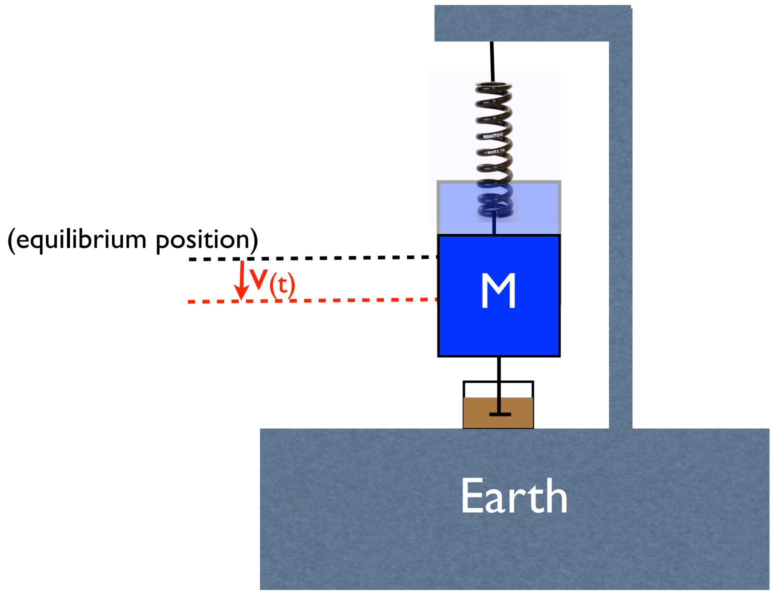


Just v(t)

v(t) = motion of spring around its equilibrium position (stretching and contracting)

note: Before shaking, the mass M is just sitting there at rest in its equilibrium position.

At this point, the mass is experiencing acceleration = g (that is, 9.8 m/s^2).



v(t) = motion of M around its equilibrium position due just to stretching and contracting of the spring

$v_{(t)}$ is what would be recorded on a revolving paper drum attached to the ground and centered at v_o

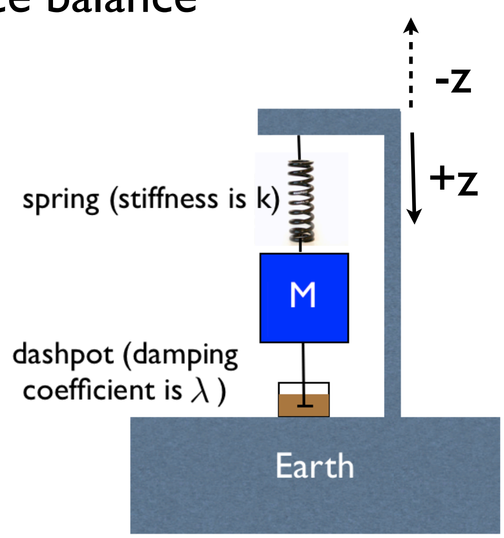
QUESTION: How close is v(t) to u(t)?

We must invoke Newton's Second Law (F = ma) and force balance

$$\Sigma F = M\ a$$

inertial force from acceleration of mass M

forces from spring stretching and dashpot damping

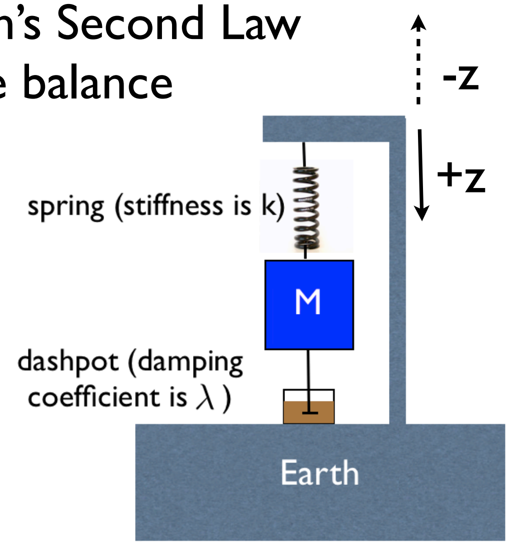


$$M\ a = M\frac{d^2}{dt^2}(u(t) + v(t))$$

inertial force due to acceleration of mass M

in which direction does this force act? When is this positive (acting in +z direction)?

We must invoke Newton's Second Law (F = ma) and force balance



$$\Sigma F = M\ a$$

inertial force from acceleration of mass M

forces from spring stretching and dashpot damping

force due to spring stretching: Hooke's Law

$$-k\ v(t)$$

damping force from dashpot is proportional to velocity of M (which is attached to that paddle in the can of oil)

$$-\lambda\ \frac{dv}{dt}$$

which way do these forces act?

why the negative signs?

$$\Sigma F = M\ a$$

inertial force from acceleration of mass M

forces from spring stretching and dashpot damping

$$-\lambda \frac{dv}{dt} - k\ v(t) = M \frac{d^2(v(t) + u(t))}{dt^2}$$

- divide all by M
- a couple of substitutions $\omega_o = \sqrt{k/M}$ (resonant frequency of the spring)

$$\alpha = \frac{\lambda}{2\ M\ \omega_o}$$

$$\boxed{\frac{d^2v(t)}{dt^2} + 2\alpha\omega_o \frac{dv(t)}{dt} + \omega_o^2 v(t) = -\frac{d^2u(t)}{dt^2}}$$

$$\boxed{\frac{d^2v(t)}{dt^2} + 2\alpha\omega_o\frac{dv(t)}{dt} + \omega_o^2 v(t) = -\frac{d^2u(t)}{dt^2}}$$

- this is an ordinary differential equation (ODE)
- it tells us that u(t) isn't equal to v(t) (too bad)

let's put in a sinusoidal motion for u(t)*

$$u(t) = \boxed{cos(\omega t)}$$

*remember - you could represent <u>any</u> seismogram as the sum of shifted and scaled cosine or sine functions

because this is a linear system (from the ODE above), v(t) must have the same time-dependence as u(t)

$$v(t) = X(\omega)cos(\omega t - \Delta(\omega))$$

frequency-dependent scaling
(motion of mass M will be more sensitive to some frequencies than others)

frequency-dependent delay (shift)

Knowing your derivatives of sines and cosines, this leads to

$$-X(\omega)\omega^2 cos(\omega t - \Delta(\omega)) - 2X(\omega)\alpha\omega\omega_o sin(\omega t - \Delta(\omega)) + \omega_o^2 X(\omega)cos(\omega t - \Delta(\omega))$$
$$= \omega^2 cos(\omega t - \Delta(\omega))$$

This can be solved for X(ω):

$$X(\omega) = \frac{\omega^2 cos(\omega t)}{(\omega_o^2 - \omega^2)cos(\omega t - \Delta(\omega)) - 2\alpha\omega\omega_o sin(\omega t - \Delta(\omega))}$$

It can be shown that X(ω) is independent of time for certain values of $\Delta(\omega)$. In this case the solution for X(ω) is:

$$X(\omega) = \frac{\omega^2}{\sqrt{((\omega_o^2 - \omega^2)^2 + 4\alpha^2\omega^2\omega_o^2)}}$$

This is a solution for the equation at the top of this page when

$$\Delta(\omega) = \Phi(\omega) = atan(\frac{2\alpha\omega_o\omega}{\omega_o^2 - \omega^2})$$

$$X(\omega) = \frac{\omega^2}{\sqrt{((\omega_o^2 - \omega^2)^2 + 4\alpha^2\omega^2\omega_o^2)}}$$

$$\Delta(\omega) = \Phi(\omega) = atan(\frac{2\alpha\omega_o\omega}{\omega_o^2 - \omega^2})$$

$$v(t) = \boxed{X(\omega)} cos(\omega t - \boxed{\Delta(\omega)})$$ seismograph trace

$$u(t) = cos(\omega t)$$ Earth's motion (shaking)

People like to write the equation for X in terms of Ω, which is $\frac{\omega}{\omega_o}$

$$X(\Omega) = \frac{\Omega^2}{\sqrt{(1 - \Omega^2)^2 + 4\alpha^2\Omega^2}}$$

Class activity (some hints will be supplied)