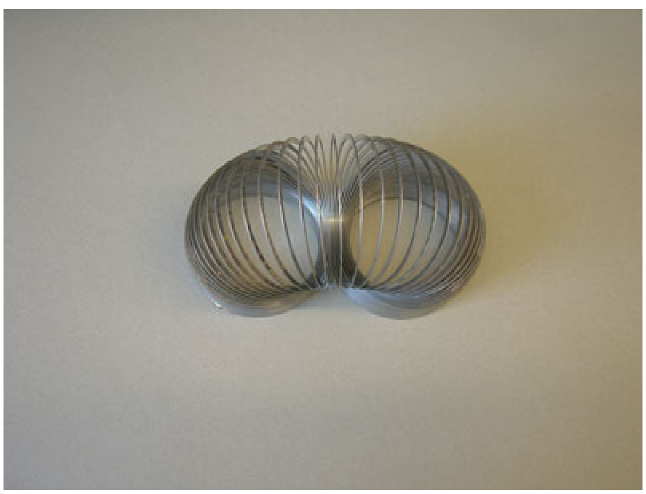
TEACHING SCIENCE BY OCEAN INQUIRY
Waves

Goals: Waves are ubiquitous in the ocean from water waves spanning from capillary waves to Tsunamis to light and sound waves, from free waves (those propagating away from a storm) to forced waves (tides, resonant response). Many phenomena associated with waves (reflection, refraction, diffraction, Doppler shift) can be readily illustrated using water waves.

The activities below are organized by categories. The first five activities focus on general properties of waves; the relation between propagation direction and motion of the medium, The Doppler effect, Resonance, the relationship of wave propagation of properties of the medium and refraction. The next four activities focus more specifically on shallow water gravity waves, including relationship between propagation speed and depth, and three activities illustrating internal waves and waves occurring within a stratified fluid. Section III focuses on illustration of wave properties using more sophisticated laboratory setups.

I. PROPERTIES OF WAVES

1. Transverse and Longitudinal Waves



Materials:

- Slinky

Instructions:

1. Use a slinky to make a transverse wave (where the direction of the wave motion is 90° to that of the displaced fluid/particles) and a longitudinal wave (where the wave and displaced fluid/particles move in the same direction).

2. Use: http://www.kettering.edu/~drussell/Demos/waves/wavemotion.html displayed on the computer next to you to learn more about them. Classify different waves you are familiar with [for example sound in air, electro-magnetic (for example light), and gravity waves (those generated when you throw a stone in a puddle)] as transverse or longitudinal.

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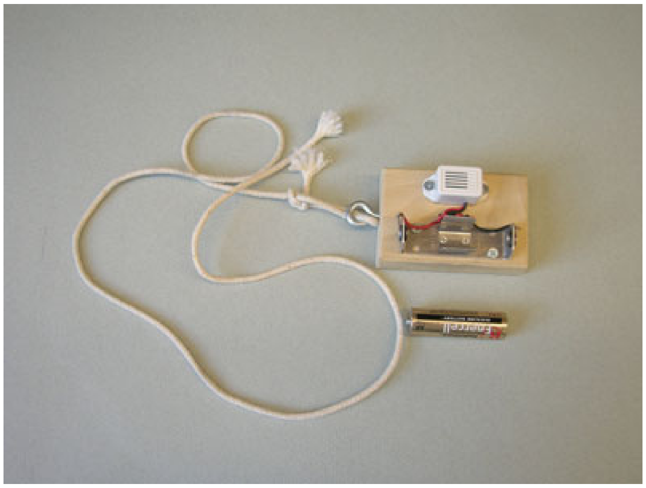
2. Doppler



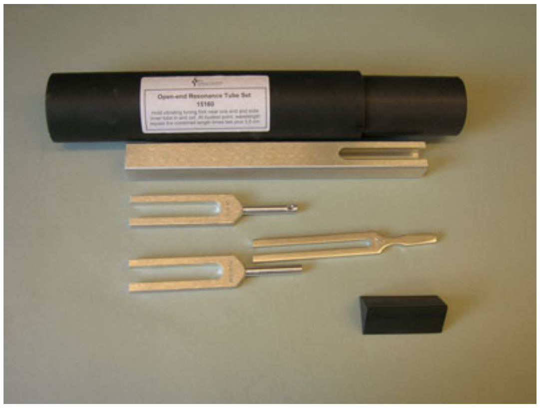
Materials:

- Doppler device (sound source that can be moved relative to an observer) (Sciencekit.com)

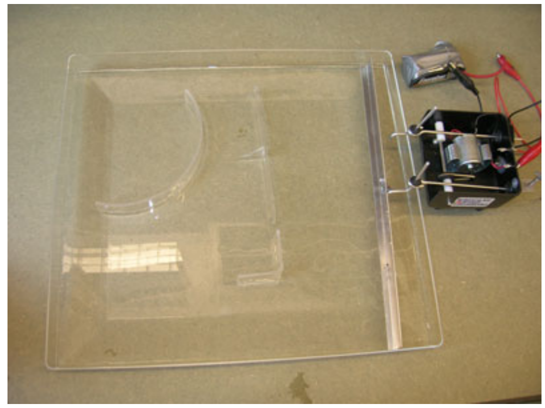
Instructions:

1. Turn on the sound source.
2. Wave the sound source in a circular motion around your head and have an observer notice the difference in frequency (higher or lower pitch than when at rest) as a function of the direction of the sound source (towards/away from observer). Is the frequency changing for the person swinging the device?
3. Change roles between the observer and source swinger.
4. The frequency of the waves equals the sound speed divided by the wavelength. Since the device is moving the effective speed of the sounds is different and thus the frequency. Is the change in frequency consistent with your expectations based on the source direction?

3. Resonance



Acoustic fork and resonator



Wave maker and wave tank

Materials:

- Acoustic fork and sound resonator (Sciencekit.com) **OR**
- Slinky **OR**
- Wave maker and wave tank (Sciencekit.com)

When systems are forced at their natural frequency they vibrate strongly.

Instructions:

Acoustic fork:

1. Knock the sound fork on a hard surface.
2. Bring a sound resonator near it and attenuate the sound fork by putting it on a cloth.
3. Do you hear a sound coming off the resonator? How did the sound pass to it?

Slinky:

1. Excite the first harmonic in the slinky by moving (slightly) one side of the slinky side way (you will get the center of the slinky oscillating back and forth, that is you will have a standing wave of a wavelength twice as long as the slinky).
2. Now, try fitting in higher harmonics. What is common to all of them?

Wave tank:

1. In the water tank, plot the amplitude of the wave as a function of the frequency of the forcing (change the frequency by changing the voltage supplied to the wave paddle). How is the amplitude changing with frequency? How is the motor power changing with frequency?
2. For the waves with highest amplitude, how would you describe them (standing, propagating)? What does it tell us about the dimension of the resonating wave relative to the cavity they propagate in? How is it related to musical instruments such as a violin or a flute?

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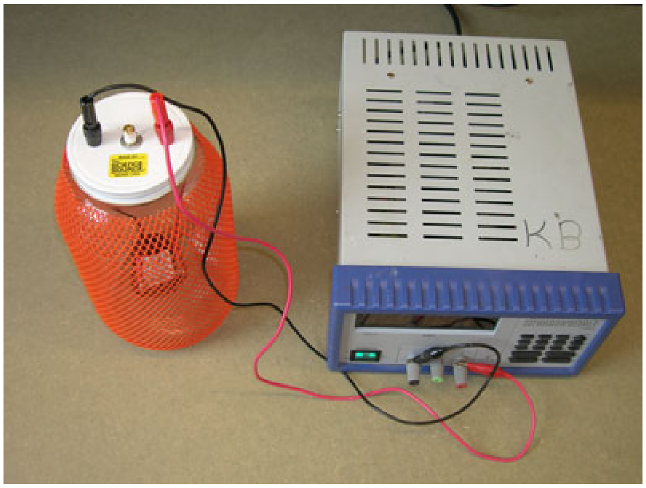
4. Wave (Sound) Propagation in a Medium



Materials:

- Power supply
- Pump
- Buzzer in jar (Sciencekit .com)

Instructions:

1. Turn on the power to the buzzer in the jar, and note the sound level.
2. What do you think will happen if air is removed from the jar?
3. Turn on the vacuum pump for about 15 seconds, and put your finger on the hole on top of the pump (to stop air from coming back in), then turn it off and listen to the buzzer. Let go of the hole (letting air get back into the jar).
4. How and why did the sound change?
5. How does sound propagate in solids and fluids compared to air?
6. How will the same experiment affect light propagation? What may be an analogous experiment for water waves?

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5. Diffraction (Snell's Law) and Total Internal Reflection

Materials:

- Water tank
- Half moon shape tank
- Laser pointer

Instructions:

1. Snell's law states that when a wave crosses a boundary between two mediums (e.g., air-water, warm and cold water), the transmitted component of the wave propagates according to $\sin(\theta_2)=\sin(\theta_1)v_2/v_1$ where $\theta_{1 \text{ or } 2}$ is the angle in each media relative to a line perpendicular to the boundary between the media (a cartoon will help here) and $v_{1 \text{ or } 2}$ is the propagation speed in each media (this is because the ratio of the indices of refraction is the reciprocal of the ratio of propagation speed). How will the angle change (increase or decrease) propagating from a 'slow' medium (a medium with slower wave speed) to a 'fast' medium (a medium with a faster wave speed)? How will it change propagating from 'fast' to 'slow'?
2. Given that the speed of light is faster in air, how would you predict the angle will change when moving from air to water? Try shining the laser from the side into the tank towards a black background.
3. Total internal reflection occurs when a wave attempts to propagate from a slow to a fast medium at an angle for which Snell's law does not have a solution (for example, when $\sin(\theta_2)>1$). Shine the laser from the side of the tank to the air water interface at different angles. Can you create conditions for which the light is totally reflected down into the tank and does not propagate into the air? Use the half moon shape tank to observe that angle.

II. GRAVITY WAVES IN WATER

6. Surface Gravity Waves

Materials:

- A water tank marked at 1.5 cm above the bottom and 6 cm above the bottom.
- Stopwatch

Instructions:

You are about to measure the period of a wave sloshing back and forth in a small tank (this period is the length of the tank divided by the speed of the waves).

1. Which will propagate faster: a wave in a tank with shallow water or a wave in a tank with deeper water?
2. Have one student raise one side of the tiny aquarium and another record the time. Measure (using a stopwatch) how many times the wave sloshes back and forth in a tank with little water (1.5 cm), and one with 4 times the depth (6 cm) within a period of 5 seconds. Is your prediction consistent with your observation?
3. Use your results to calculate wave velocity [the length of the tank (30.5cm) divided by the period a crest moves from one end of the tank to the other].
4. How did they compare with the theory of wave propagation in shallow water? [If you do not know the theory you can still derive the wave speed from a dimensional argument assuming it is likely to depend on some combination of the property of the fluid and the forces acting on it, (e.g., gravity, depth and the density of water). Which combination of these quantities gives you dimensions of velocity, (e.g., length/time)?]
5. Was the ratio of the wave speed with 6cm depth and 1.5 cm depth consistent with this theory?
6. What is the natural (or intrinsic) period of the tank (1st mode) at each depth? (Hint: you should be able to calculate it using only the length of the tank (30.5cm) and the wave

speeds computed above. The length is half the wavelength for the 1st mode as there is only one high and one low). FYI: The period of a Seich (natural oscillation) in a lake or bay can be calculated similarly. This is the resonant frequency associated with a body of water (e.g., the tides in a lake or the Bay of Fundy).

7. Based on your observations, think about a wave propagating from the deep ocean to a shallow beach that is parallel to the beach. How will the speed of the wave change as it approach the shallow part of the beach? What is likely to happen to the wave as a consequence? How is it related to your experience?
8. Assume the wave is not parallel to the beach. How will the front of the wave look as it approaches the beach at an angle to it? You ask the question, then answer it. Should you save this for the explanation section? This phenomenon is refraction, the change in direction as a consequence of change in propagation speed due to changes in the properties of the medium the wave propagates in (see Snell's law below).

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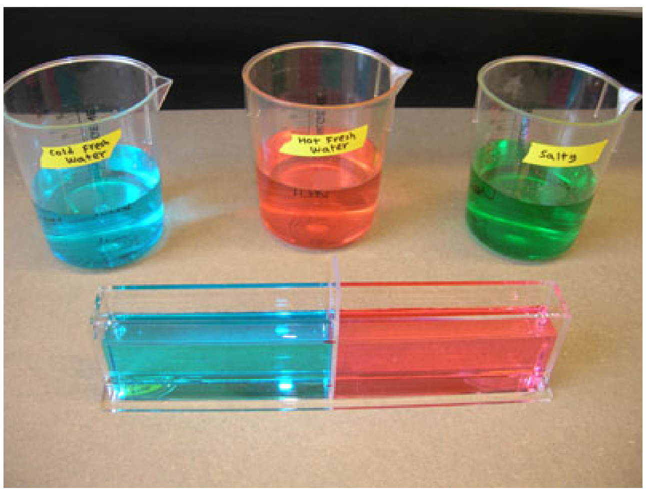
7. Internal Waves in a Two-Layer System



Materials:

- A small tank with a partition
- Salt water (dyed)
- Cold water
- Food coloring

Instructions:

1. Fill one side of the partition with cold fresh water and the other with hot/fresh <u>or</u> cold/salty water.
2. What will happen when you remove the partition between the fluids?
3. Remove the partition and observe the amount of time it takes for the perturbation to propagate within the fluid from one side of the tank to the other. What is happening?
4. How does the speed of the perturbation compare with those in the surface gravity waves Activity 1 above (if you haven't done it yet make sure to compare them when you do Activity 1)?

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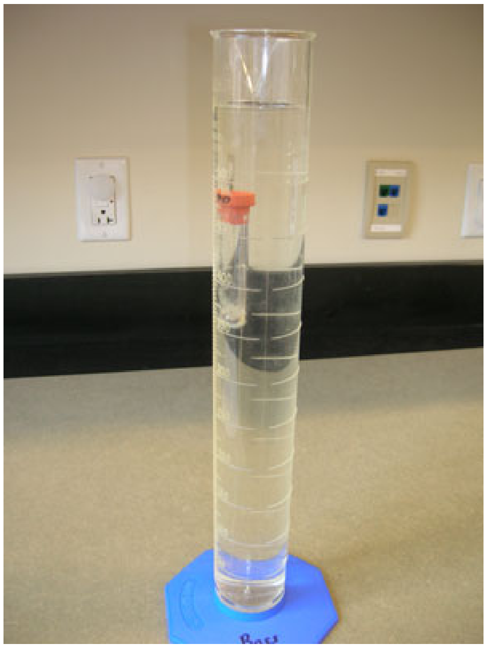
8. Buoyancy Oscillations



Materials:

- A tall graduated cylinder with a stratified fluid (salty water on the bottom and fresh water on top)
- A ping-pong ball with clay attached as ballast such that the ball stays put near the interface between the two fluids **OR** small closed test tube with a bead.

Instructions:

1. What do you think will happen if you push the ping-pong ball/tube down?
2. Push the ball/test-tube down and observe what happens.
3. How will the period of the oscillation change if the water is more stratified or less stratified (think about which case will result in a larger restoring force for the same vertical displacement)? What is the period in an almost non-stratified fluid?

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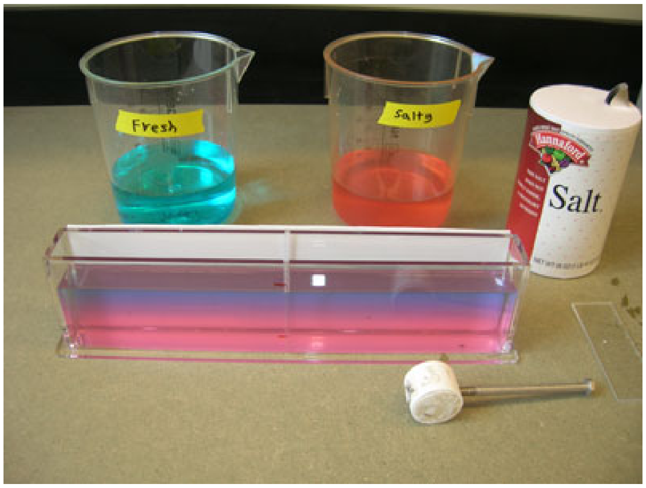
9. Internal Wave Generation in a Tank



Materials:

- A tank with 2-layered stratified fluid (hot/cold or fresh/salty water dyed with food coloring)
- A plastic "paddle" (or other paddle –like object)
- Food coloring
- 'Beach' a piece of cardboard like material set as a beach at one side of the tank.

Instructions:

1. Use the "paddle" to create waves within the tank (move it up and down at one side of the tank).
2. Can you create internal gravity waves without creating surface gravity waves?
3. Which type of wave has higher frequency (or lower period)?
4. How do you tune your "paddle" frequency to create waves of a given frequency?
5. What happen when the waves 'hit' the beach? Can you think of an oceanographic application?

Note: depending on how much mixing occurred you may need to restratify the tank between groups.

III. OPTIONAL ACTIVITIES

Additional activities requiring more sophisticated equipment (you may not be able to use it in class with your students, but we thought it might provide a nice insight into waves).

10. Measurements of Wave Properties

Materials:

- A wave tank with a paddle (Sciencekit .com)
- A current meter (Acoustic Doppler Velocimeter) attached to a computer.
- A power supply (attached to the paddle allowing us to change the frequency of the forcing).

Instructions:

1. How do you think the wave amplitude will change with the frequency of the paddle?
2. Use the ADV to measure the velocity at a point within the middle of the fluid. Change the voltage from 12 to 17 Volts in increments of 1 Volt and plot the change in the amplitude of the along channel velocity as a function of voltage.
3. Explain your observations.
4. Observe particles within the fluid. How are they distributed? Why?
5. Observe the behavior of the "beach" as you change the forcing. How is the beach changing? Can changes to the beach affect the waves (e.g., *feedback*)?
6. Observe some particles floating on the water or suspended at depth. Are they simply oscillating or can they be observed drifting in a given direction?

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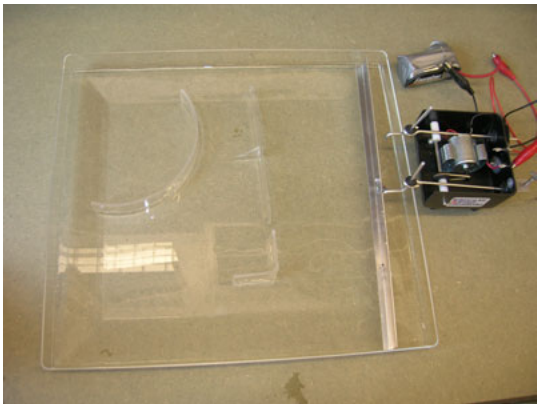
11. Diffraction and Reflection of Waves



Materials:

- Overhead wave tank with linear and point wave makers and a variety of plastic objects to insert in the tank.

Instructions:

1. Diffraction is the apparent bending of waves around obstacles and the spreading out of waves past small openings. Using the tank set up and the objects, observe how a linear wave front emanating from the straight wave maker propagates through a small opening between to objects. Can you explain your observations by assuming that every point along the wave front can be thought as a point source of a wave and the wave front being the sum of all these waves (known as the Huygens principle)?
2. Reflection occurs when a wave encounters a boundary or a change in the medium properties (the last is harder to visualize as some of the energy is transmitted). Using the tank setup and the linear wave maker, investigate how the angle of the wave is reflected from a hard boundary related to the angle of incidence.

IV. CLASS DEMONSTRATION (presented in the density lab associated with internal waves)

Related class demo from density lab: 'dead-water' – famous oceanographic problem- boat in stratified fluid can encounter large resistance compared to sailing in unstratified waters. Many different explanations existed until Ekman (1904) provided the correct one. (see movies of the experiment with and without stratification at the following two links:

http://misclab.umeoce.maine.edu/movies/Internal-Wave-halocline.MPG

http://misclab.umeoce.maine.edu/movies/Internal-Wave-No-Halocline.MPG

Note the wave generated by the vessel in stratified water when it moves much slower.

See: Ekman V. W., 1904. On dead water. Sci.Results Norw. North Polar Expedi. 1893-1896, 5(15)

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WAVES: EXPLANATIONS FOR LAB ACTIVITIES

I. PROPERTIES OF WAVES

1. Transverse and Longitudinal Waves

Sound is a longitudinal wave, while both light is a transverse waves. Particles in gravity waves have circular motion with both a component that is longitudinal and a component that is transverse.

2. Doppler

As the sound source moves towards the observer, the sound speed is accelerated. Since the frequency is proportional to the velocity, it also increases (sound has a higher pitch). The opposite occurs when the sound source moves away from the observer.

3. Resonance

When systems are forced at their natural frequency, they vibrate strongly. In the case of the sound resonator, the sound vibrations were transmitted through air and excited the resonator box as they match the natural frequency of sound waves in that cavity. In the case of the water waves, the resonant waves are the standing waves (crest and troughs are not traveling which are associated with waves for which the lengths of the tank equals an integer amount of half their wavelengths). Thus, even though we put more energy into the system with increased voltage, the response (in terms of wave amplitude) is not monotonically increasing with the voltage but rather is maximal at certain voltages, which excite waves having the natural frequency of the basin. A musical instrument such as a flute selects out of all the frequencies coming off the mouthpiece that which resonates with the natural frequency associated with the length between the mouth piece and the open hole(s). Changing the hole we cover changes the natural frequency and hence the sound that emanates from the instrument.

4. Wave (Sound) Propagation in a Medium

Sound and water waves both need a medium to propagate within. Sound, being a pressure wave, propagates by condensing and rarifying the density of the material. When there is no material (e.g., vacuum) sound cannot propagate. Sound propagates in dense solids and fluids much better than in air. Light can propagate through a vacuum because it does <u>NOT</u> need a medium to propagate through (which was one of Einstein's big insights).

5. Diffraction (Snell's Law) and Total Internal Reflection

Total internal reflection can only occur when propagating from 'slow' to 'fast'. In the case of seawater to air $v_2/v_1=1.34$ and the critical angle for total internal reflection is about 48° ($\sin^{-1}(1/1.34)$).

II. GRAVITY WAVES IN WATER

6. Surface Gravity Waves

The two water depths are approximately 1.5 and 6 cm. The first mode of the tank has a wavelength that is twice the length of the tank (2 x 30.5cm) and thus the generated wave is a shallow water wave. Shallow water waves have phase and group speeds which are equal to $\sqrt{gh}$, where g is the gravitational acceleration and h is the depth of the water. For 1.5 and 6cm, the wave speed equals: 38.4 and 76.7cm/s respectively. In 5 seconds we therefore expect to have a crest go approximately 6.3 and 12.6 lengths of the tank (that is 'sloshes'), respectively. We calculated it from: wave speed x time / length of tank.

The natural period of the tank is its length divided by the velocity = 0.8s and 0.4s for the 1.5cm and 6cm deep setups, respectively.

7. Internal Waves in a Two-Layer System

Internal gravity waves occur in the boundaries between fluids of different densities and within continuously stratified fluids. They propagate much slower than surface gravity waves. This is so because the restoring force is still gravity, but within a fluid, its effect is much weaker (due to the relatively small contrast in density between the layers) than at the surface (where the difference between the density of water and air is very different).

8. Buoyancy Oscillations

In the previous activity you generated waves that propagated laterally. In this process, the interface between the fluids is displaced up and down. Here you can use the ping pong ball to compute the period of these oscillations. As the stratification weakens (the layers are more similar), the period of these oscillations increases (a parcel of water displaced vertically takes longer to get back to the position where it started as the restoring force is weaker).

9. Internal Wave Generation in a Tank

The easiest way to 'excite' waves is by forcing them at their natural frequency. Within a tank, one can excite the seiche by exciting it at the natural frequency. Moving the paddle up and down at a frequency much smaller (a longer period) than the surface gravity waves does not excite them but can excite the internal waves.

III. OPTIONAL ACTIVITIES

10. Measurements of Wave Properties

When the frequency of the paddle matches that of the tanks natural modes (seich), a standing wave can be generated that has a much larger amplitude than when exciting at higher or lower frequencies (which do not match a natural mode). This is basically a resonance response.

Particles have very different trajectories than the wave (isn't that similar to the trajectory of water molecules, assuming the particle is naturally buoyant?). Near the surface they have relatively circular patterns, while at depth they move back and force parallel to the bottom.

Waves can also set a mean circulation, accumulating particles in specific parts of the tank.

11. Diffraction and Reflection of Waves

Every point along the wave front can be considered a point source of a wave and the wave front being the sum of all these waves (known as the Huygens principle). When the wave approaches a constriction, only a small part of the front can propagate through and the pattern looks much like a wave propagating from a single point (e.g., when throwing a stone into a pond), that is the wave propagates radially out from the slit.

When reflected from a boundary, the angle of reflection = angle of incidence, just as in a mirror.