SCIENCE

PAUL DOHERTY & PAT MURPHY

BIG WAVE SURFING

RECENTLY, the Exploratorium* decided to do a web page about surfing *(http:// www.exploratorium.edu/theworld/surfing)*. Paul, as one of the museum's senior scientists, was called upon to research the science of surfing. This meant traveling to the beach and riding some waves while thinking about wavelength and wave velocity. (It's a tough job, but someone has to do it.)

While he was waiting to catch a wave, Paul mused about surfing scenes in science fiction. One of the most famous surfing scenes of all of science fiction is in Larry Niven and Jerry Pournelle's novel, *Lucifer's Hammer*. When a comet strike in the Pacific sends a tsunami rolling toward the coast of California, surfers grab their boards and head out to surf the big one.

In this column, we'll give you Paul's ruminations about waves and wave speed. We'll describe a few experiments to perform next time you're at a pond or at the ocean. We'll consider physics of waves (as viewed by physicists and surfers). And we'll introduce you to the biggest waves in the history of the Earth. Don't worry, we'll get back to Paul on his surfboard and science fiction eventually. But let's start by going to the beach.

OBSERVING AT THE BEACH

Next time you are at an ocean beach, watch the waves. Most waves are made when winds blow over the water. Those wind-generated waves then travel hundreds of miles or more to arrive at your beach.

To observe how the water is

*The Exploratorium is San Francisco's museum of science, art, and human perception — where science and science fiction meet. Pat Murphy and Paul Doherty both work there.

moving as a wave passes, watch floating bits of seaweed that aren't anchored to the bottom, blobs of floating foam, or even seagulls floating in the water. Out beyond the breakers, the waves move toward shore but the seaweed, the foam, and the gulls do not. They just bob up and down as each wave passes. If you go for a swim and float out beyond the breakers, the waves will make you bob up and down but they won't carry you toward shore.

A water wave is a traveling disturbance. The disturbance travels — but the water doesn't. (The same is true of other kinds of waves. A sound wave is a disturbance that travels through air; a light wave is a disturbance in the electromagnetic field. Best we don't get into all that just now — water waves are strange enough!)

Scientists have found that as a wave goes by, the water moves in a vertical circle. As the crest of the wave passes, water moves forward at the top of its circle. When the trough of the wave comes by, water moves back, returning to its original location.

When the wave starts to break, things change. Seaweed, foam, and surfboards move forward with the breaking wave. (Seagulls, quite sensibly, take off before all this happens.) We'll get to breaking waves presently (about the same time we get back to Paul, floating happily off the beach at Santa Cruz, putting in a hard day's work). But first, let's finish our examination of the waves before they break.

Chucking a Rock in a Pond

One thing that preoccupies both physicists and surfers is wave speed. Today, surfers who surf the World Wide Web as well as the waves can read up-to-date satellite and ocean buoy data about waves hundreds of miles from their beaches. By knowing the distance the waves are from shore and the correct velocity of the waves, a surfer can compute when the waves will arrive.

You might think that all you need to do to figure out the speed of a wave is calculate how fast that wave is moving. But figuring out wave speed, like so many things, is trickier that it might first appear.

When you are watching waves at the beach, you may notice that waves arrive in groups — what surfers call "sets." Several waves come one after another, then there's a lull. It's when you look at groups that the trickiness of calculating wave speed becomes apparent.

A group of waves travels at one speed while the individual wave crests that make up the group move at a different, faster speed. If you think this sounds pretty screwy, Pat agrees with you. How can a group move at a different speed than the parts of that group? To convince Pat, Paul (in true Exploratorium style) suggested an experiment that you might want to try.

Go out and find a calm pond, preferably one where there are no rules about throwing rocks. Toss a tiny pebble in the pond. Small waves will form around the impact point and spread out in concentric circles.

The distance between the crests of two of those waves is the wavelength. The waves you make by tossing a pebble usually have a wavelength shorter than a finger width. These small waves are pulled downward more by the surface tension of water (a force created by the attraction of water molecules for each other) than they are by gravity. In this column we're going to ignore surface tension waves. (They're too small to surf.)

So you've got to make some bigger waves. Toss in a rock that's larger than your fist. The resulting "ploosh" is followed by higher waves with longer wavelengths. The piles of water thrown up by the rock's impact are mainly pulled down by gravity. These, like ocean waves, are called gravity waves. As these waves move outward, their height decreases as they spread over larger and larger circles.

Watch these waves closely and you'll see that the waves with a longer wavelength take the lead, moving ahead of the waves with a shorter wavelength. The same thing happens with waves made by the wind on the deep ocean. The waves with the longest wavelength travel fastest.

Physicists call the speed of the wave crest the "phase velocity" of the wave. Let's take a look at gravity waves in water that's deeper than the wavelength — that is, waves before they start breaking. The wave's speed is proportional to the square root of its wavelength. So if you quadruple the wavelength, the speed of the wave doubles.

Incidentally, the speed is also proportional to the square root of the acceleration of gravity — which makes a difference to surfers and physicists on other planets, but doesn't affect your experiments here on Earth. High gravity planets will have faster wave speeds than low gravity planets.

That's how physicists talk

about waves. Surfers, on the other hand, usually talk about the period of the waves, rather than their wavelength. The period of the wave is the time it takes a wave to roll from one crest to the next. If you are watching a seagull in the waves, the period is the time from the moment that the gull is at the top of one wave crest to the moment when the bird is at the top of the next crest.

Periods of surfable waves tend to run from five seconds to over twenty seconds. The speed of a wave is linearly proportional to the wave's period. If you double the period, the speed doubles. (You can see why surfers prefer talking about periods — you don't have to calculate the square root to figure out the speed!)

Nautical people measure speeds in nautical miles per hour or knots. A knot is fifteen percent faster than a mile per hour. The speed in knots of a wave crest in deep water is about 3.2 times its period in seconds. So a wave with a period of ten seconds travels at thirty-two knots.

It's More Complicated than That

That's not so difficult — but then, we aren't done yet! Chuck another big rock into your pond and watch those waves again. After a while, you'll see a ring of spreading waves with calm water inside and outside the ring. Now if you carefully watch the crests of the waves, you'll notice something odd going on.

A wave crest will move from the inside of the ring toward the outside where it will vanish. Then another wave will be born inside the ring and race forward through the ring of waves to disappear in turn. That's because the phase velocity of the wave crests is greater than the speed of a group of waves. In fact, the group velocity for water waves is exactly half the phase velocity.

So consider the situation of a surfer calculating how long it will take waves from a storm hundreds of miles off the coast to send some fabulous waves to the beach by her house. She needs to know that the groups of waves travel at half the speed of individual wave crests or she'll get to the beach way too early. The speed at which a group of deep water waves travels in knots is 1.6 times the period of its constituent waves in seconds.

Big Waves, Shallow Water

Now that you have a detailed understanding of waves, let's get

back to the beach, where Paul has been hard at work.

On the day in question, Paul knew that waves from a huge Pacific storm hundreds of miles out at sea should just be reaching that particular beach. At the right time he lay on his surfboard looking over his shoulder searching for what he calls a "Goldilocks wave," one that is just right. Waves rolled in with sinusoidal purity under a sunny blue California sky. (We told you this was a tough job!)

When waves hit a place where the water is shallower than a wavelength, they begin to interact with the bottom of the ocean and slow down. As they slow down, the water piles up and the waves get higher. The higher waves then break. They rise up and their fronts become steeper.

When a wave is breaking, the water moves with the wave, rather than just moving in a circle. Seaweed, foam, and surfboards move forward with the wave.

A surfer who successfully catches a breaking wave slides down the wall of water at the front of the wave. It is interesting to note that the water on the front face of the wave is rising up the steep face, so that riding a surfboard down the wall of rising water is kind of like running down an up escalator.

Propelled by the pull of gravity, the surfboard and surfer can go faster than the wave itself. A researcher in Australia put a speedometer on a surfboard and found that it traveled ten to twenty knots relative to the water under average conditions.

Paul watched to determine where the waves were breaking. Then, at just the right time, Paul paddled hard to catch a wave. He remembers catching the wave. "I timed it just right and could feel the acceleration as I caught the wave. I got up on my long board. The wave was breaking on my left side so I changed my balance and turned the board right to keep ahead of the break. It was great to race along the face of the wave, turning up and down, playing with gravity and the kinetic energy of motion."

The wave Paul caught was bigger than the waves he usually rode. "Everything was going great at first," he says, "but then the higher wave began to interact with the bottom in ways I had never felt before. The crest began to curl over ahead of me, behind me and then...over me. Pretty soon I was interacting with the bottom myself!"

Surfers don't like a wave that breaks all at once, like the one that

caught Paul. They look for a wave that starts to break at one place. That breaking point then moves along the front of the wave. The surfer works to keep just in front of the break. So the surfer travels along the face of the wave while sliding down the wave.

Paul emerged from his encounter with the ocean bottom in fine shape. The wave he caught was a big wave, but not a really big wave.

Near the Exploratorium is a surf spot named Mavericks. Paul doesn't surf there. At Mavericks, long-period, wind-created waves run into shallow water in a way that makes huge waves — reaching heights of thirty feet or more.

When a wave hits water that's shallower than its wavelength, the wave speed changes. The speed of a wave in shallow water is proportional to the square root of the average depth of the water. The wave speed doesn't depend on the wave's period anymore but rather on the height of the wave. Bigger waves travel faster. Quadruple the height of the wave in water so shallow that the trough is licking the bottom, and the wave speed will double.

As far as surfers are concerned, the problem with these giant waves is not that they can be lethal (though they can be). Rather, the difficulty is their speed. To catch a wave, you have to paddle your surfboard up to a speed close to the speed of the wave. Bigger waves break in deeper water and travel too fast for a surfer to catch them. Some surfers have had friends on jet skis tow them up to speed so that they can catch the biggest waves, but traditionalists regard that as cheating.

BUT WHAT ABOUT THE DINOSAURS?

We said we'd get back to science fiction — and at last we have. When Larry Niven and Jerry Pournelle wrote about that giant wave in *Lucifer's Hammer*, they were, as is traditional with science fiction writers, basing their extrapolation on fact. They got the surfer behavior right. When hurricanes send huge waves slamming into Florida, some surfers head toward the beaches while everyone else heads away.

The results of their comet impact are also very believable. You throw pebbles into ponds; the Universe throws rocks the diameter of the city of San Francisco into oceans. Sixty-five million years ago, a rock measuring about fifteen kilometers across slammed into the ocean, in a region that is now Mexico's Yucatan Peninsula. The impact of that rock,

now known as the Chicxulub Impact Crater, excavated a hole more than two hundred kilometers across and threw material into space that eventually fell back over the entire Earth. The incandescent re-entry of the excavated rock started fires all over the Earth, covered the Earth with dust for over a year, and led to the death of seventy percent of the species alive at that time including every species of dinosaur and everything else that weighed more than fifty pounds.

The impact also sent a wave of water over five hundred feet high washing over the bit of land that is now Florida. The wave traveled across the Gulf of Mexico in less than ten hours and then rushed 300 kilometers inland over the continent that would later be called North America. Imagine a dinosaur that had never seen an ocean, hundreds of miles from the coast watching a wall of water hundreds of feet high coming toward him! Scientists know that the wave from this impact washed entirely over Florida because they have found multi-ton blocks of Gulf of Mexico limestone that have been transported to the Atlantic Ocean bottom.

A wave produced by a meteorite is known as a tsunami. These giant waves can also be caused by earthquakes and underwater landslides. Scientists have found evidence that huge landslides occur on the underwater slopes of the Big Island of Hawaii every few hundred thousand years or so. Huge blocks of limestone have been found a thousand feet up the side of Hawaii's Mauna Loa volcano, carried there by a tsunami. These waves from Hawaii cross the Pacific Ocean and impact the shore all around the Ring of Fire.

Unlike the normal wind-created waves with periods measured in seconds, tsunamis have periods ranging from twenty minutes to over two hours. They have wavelengths of hundreds of miles.

And remember: whether a wave is a shallow water wave or not depends on how many wavelengths deep the pond is. Even though the ocean is many miles deep, the wavelength of a tsunami can be hundreds of miles — so a tsunami crossing the ocean is a shallow water wave. Using the shallow water equation to calculate the speed, we find that tsunamis in the deepest oceans travel through the water at over 600 miles an hour, nearly the speed of sound in air. They can cross the Pacific Ocean in half a day, and circle the world in less than two days.

In the open ocean, you wouldn't even realize that a tsunami was passing under you. Tsunamis have a height of half a meter or so and a wavelength of hundreds of miles. Space satellites can see them, but a ship floating on the surface would have a hard time detecting them. But when these undetectable open-ocean tsunamis move into shallower water, the water piles up into high waves.

We use the plural there on purpose. Tsunamis, like the waves you made by tossing a rock in a pond, come in sets. In 1964, a birthday party at an oceanside pub in Crescent City, California, disbanded before the arrival of the first wave of a tsunami created by an earthquake in Alaska. After the first wave, the partygoers returned to the pub. Since everything appeared normal, they continued their party. The second and subsequent waves killed five of them.

Stranger than Fiction

It's only to be expected that big waves generate big stories — some of them true. In the desert north of Arica, Chile, many miles from the ocean, Paul once came across the ruins of the *Watree*, a nineteenth-century American Naval Paddlewheel steamer. This steamer had been visiting the port of Arica in 1868 when an earthquake near the Peru-Chile Trench generated a set of tsunamis.

The first big wave came and receded, leaving the ships sitting on the bottom of the waterless harbor. When a ninety-foot-high second wave came in, it picked up the *Watree* and washed it deep into the Atacama Desert.

That's strange enough, but stranger still, after it landed, the captain kept the ship operating in the desert, coming and going by mule instead of by ship's boat. Some real stories are stranger than even science fiction.

To learn more about Pat Murphy's science fiction writing, visit her web site at *www.brazen hussies.net/murphy*. For more on Paul Doherty's work and his latest adventures, visit *www.exo.net/ ~pauld*.