The Science *of* Ocean Waves

Ripples, Tsunamis, and Stormy Seas

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To Frances Cleveland,
whose critical judgment
helped to make this a better book

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Preface

Some of my best memories of Hawaii are of watching the surfers at the Banzai Pipeline, on the north shore of Oahu. In the months between November and January, waves 10 meters (m) high or more roll in majestically, curl, and break with awesome power. These waves draw a dedicated band of top-fligh surfers, who come to compete or just to test their skills.

But come back during a gale and see the power of the ocean when it is fully aroused by strong winds. Then the surf is really spectacular, with breakers that crash with a sonic boom and flood up th beach, carrying everything before them. In a hurricane, it is not worth your life to remain too near the shore.

Powerful ocean waves fascinate the public, and they have made a lot of news lately. We all remember the terrible loss of life and property that Hurricane Katrina caused in 2005. Much of the damage on the Gulf Coast was caused by battering waves that rode up a storm surge to a height of 9 m

Then there was the tsunami launched by the great Sumatran earthquake in December 2004. At Aceh, near the epicenter, a wave of 30m (98ft) crashed onshore and obliterated the town. This impulsive wave crossed the Indian Ocean and killed over 200,000 people in 14 countries.

But the great tsunami that crushed the shore of Japan in March 2011 and inundated the Fukushima nuclear power plant was in some ways the scariest of recent events. The combination of a magnitude 9.0 earthquake, a 10-m tsunami, and the prospect of a core meltdown was a scenario usually seen onl in science fiction.

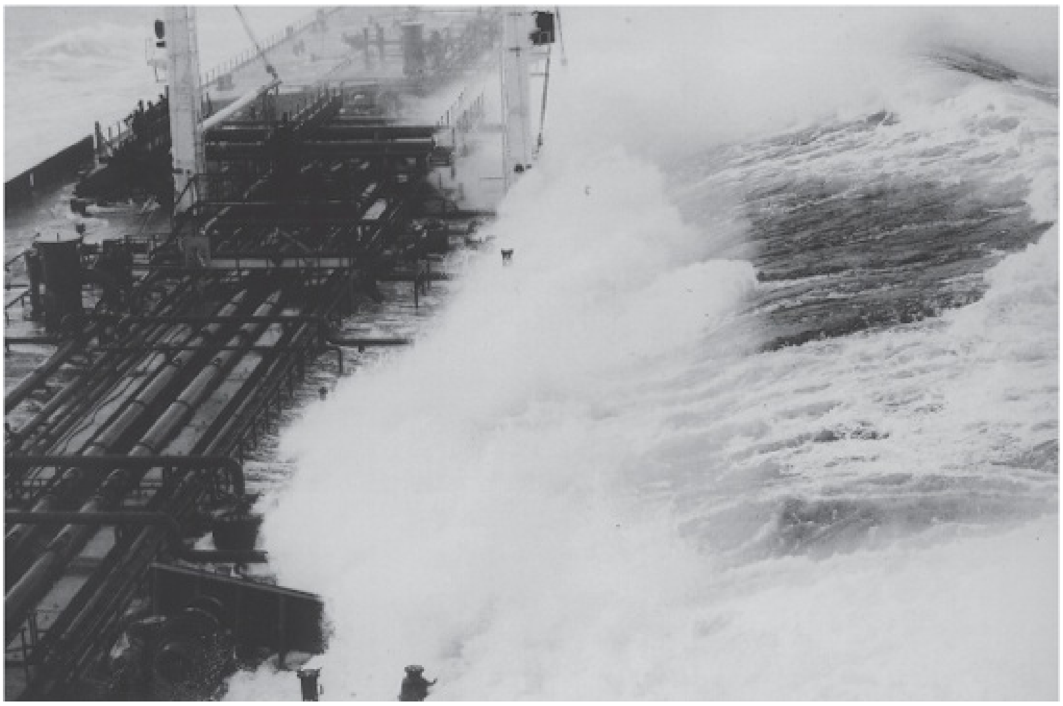
Perhaps the most awesome waves are the so-called rogues or freaks that can rise up out of a moderate sea to heights of 20m or more. In 1942, for example, the giant passenger ship *Queen Mary* was carrying 16,000 troops to England. The ship was hit by a 28-m-high rogue wave that rolled the huge liner to an angle of 52 degrees. A few degrees more might have capsized the vessel. Such freak waves were thought to be extremely rare events, but radar-equipped satellites have since disproved that comfortable assumption.

Surfing at the north shore of Oahu. (Photo 13438619, dreamstime.com.)

Most ships lost at sea are wrecked by “ordinary” storm waves, however. The North Atlantic in ~~winter is notorious for 10-m seas that persist for days. In the Drake Passage, between South America~~ and Antarctica, waves commonly reach heights of 10m and more, bedeviling the ships that try to round Cape Horn.

Powerful waves like these pose a real threat to shipping, and the maritime nations of the world ha organized to cope with them. First and foremost they have sponsored research programs aimed at improving wave forecasting methods. Several forecasting centers now produce hourly or daily maps of wave heights to guide mariners at sea. In addition, satellite radars are deployed to monitor storm conditions.

In this book we’ll look at all sorts of topics having to do with waves. I begin by introducing the properties of waves (without equations) and the physics that control them (chapters 1–4). Along the way we’ll learn how a blustery wind generates ocean waves, how storm waves propagate, and how weak waves differ from stronger waves.



Rogue wave hitting oil tanker *Overseas Chicago*, headed south from Valdez, Alaska, 1993. The ship was running in about 25-foot seas when the 60-foot wave struck it broadside on the starboard side. Photo by Captain Roger Wilson. (Courtesy of National Oceanic and Atmospheric Administration/Department of Commerce)

In Chapter 5, I describe some of the massive experiments oceanographers have carried out at sea and in laboratories to test their theories. Chapter 6 recalls the progress oceanographers have made in forecasting wave heights and directions. We’ll see how radar works and how satellites are used to monitor great storms.

In the second half of the book, I discuss the beauty and power of breaking waves, the origins of those unpredictable rogue waves, the devastating tsunamis, and the ocean-wide El Niño phenomenon The ocean tides are less dramatic than storms, but they are essential to the maritime industry. We’ll recall how tides are generated and how daily forecasts are made (chapter 11). I discuss the amazing symmetry of ship wakes, and we’ll learn how the hull of a racing yacht is designed to reduce the resistance of the waves they produce (chapter 13). Finally in chapter 14, we’ll look into the development of clever machines that could capture the energy of ocean waves and tides and produce electricity on an industrial scale.

~~We’ll go beyond mere anecdotes and try to understand as much as possible about wave physics~~ without using mathematics. That means we’ll have to review some basic properties of waves and the way winds push waves to great heights. We’ll begin with the simple stuff and build from there. Some topics are more difficult than others, so take your time reading these parts.

It will be an interesting trip, so hop aboard!

CHAPTER ONE

A Walk along the Beach

We can learn a lot about ocean waves just by looking. So before we become immersed in the intricacies of waves, let’s just stroll along the shore and comment on what we see. It’s a nice, sunny day, without much wind: a perfect day for the beach.

As we look out to sea, we see a long train of parallel, equally spaced waves approaching the shore, as is shown in figure 1.1. These waves were probably generated by the winds of the storm that passed far offshore a couple of days ago. The sea is still recovering from the storm.

But what exactly are we looking at? The sea is not pouring steadily up the beach like a broad river If it were, we’d be drowned. Instead, as each wave collapses on the beach, the water sloshes back into the sea. So we realize that these waves are part of a *moving pattern* of humps and hollows that glides over the surface of the sea. This regular pattern is called a *swell*. Swell waves are usually low, only about a meter high or so, and have rounded tops. All the crests we see are nearly parallel to the shore have about the same height, and extend sideways at least six or seven times the distance between crests.

I’d guess that in this swell, the distance between the crest and the trough (which is called the “height” of the wave) is about 1 m. We could estimate the distance between wave crests (which is appropriately called the wavelength) as about 10m, or 33 feet. And if we timed the interval between crests as they pass that buoy out there, we’d find the “period”: about 5 seconds for these waves. Divid one number by the other and we get the speed of the wave, about 2 m/s, or 7km/h, or about 4mph—th pace of a fast walk.

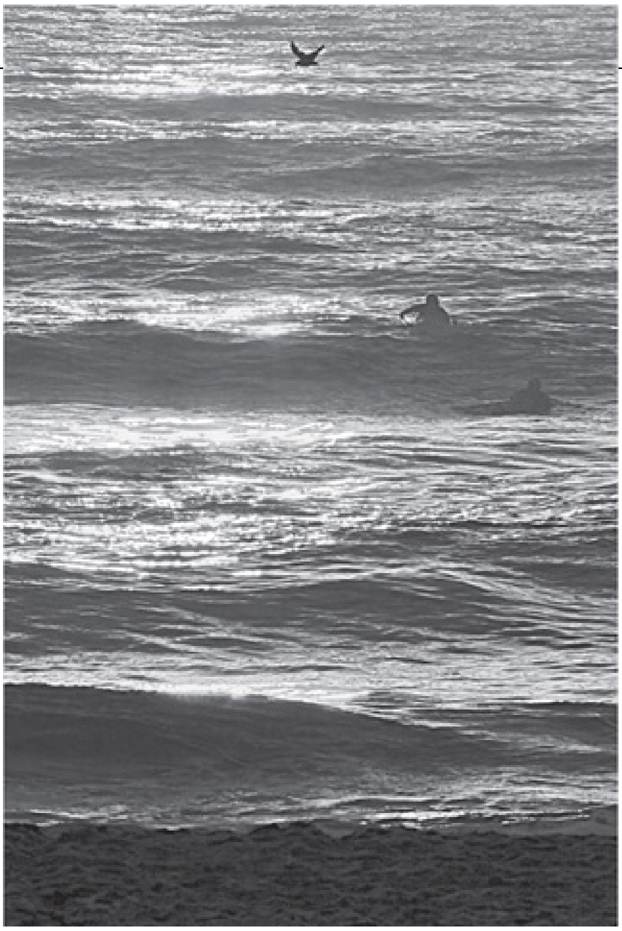


Fig. 1.1 Snapshot of a swell. (Photo 14568824, dreamstime.com.)

The Water under the Wave

There’s a swimmer out there, floating on her back. Notice how she rises and falls rhythmically as eac wave passes her. Although the waves are moving toward shore, she hardly advances shoreward. Her motion follows that of the water beneath her. It may seem surprising, but the water in a wave doesn’t actually travel with the wave toward the shore; it just bobs up and down, practically in place. We’ll talk more about this oscillating motion, and lack of forward motion, later on.

If this swimmer were to dive below the surface, she’d discover that the oscillations of the water gradually become weaker and weaker the deeper she dives. A few meters below the surface she would float in practically still water. Submariners are familiar with this phenomenon; they can escape a violent storm at the surface by diving deep enough to reach calm water.

Surf

Back on our beach, we see some kids playing in the surf zone where the small waves finally break. One little guy ventures out too far and gets knocked over by a wave. He’s all right; he picks himself u and runs back up the beach. His little accident reminds us, however, that a breaking wave carries a punch. Or in more technical terms, a wave carries the energy the wind gave it and releases that energ when it breaks. When a wave breaks, its energy accelerates the water, which then has enough momentum to knock you over. If you’ve ever waded out through the surf to reach quiet water beyond the breaking waves, you’ll understand what I mean.

This beach that we’re walking along is curved in a deep arc, a C shape maybe 2km long. As we walk toward the rocky point at the far end, we keep a sharp eye on the waves offshore. We notice that everywhere along the beach, the waves come rolling in parallel to shoreline. Somehow the waves roll~~ing in from the horizon *turn* so as to face the shore at every point. How is this possible? This~~ effe is called *refraction*, and we'll learn how it works later on. Every type of wave (such as sound, seismi or electromagnetic) exhibits refraction.

As we walk along, we notice that the appearance of the breaking waves changes from place to place. Where we started out, the beach sloped very gently into the water and the waves broke very gently. These were "spilling" waves; you can see an example in figure 1.2 (top).

Fig. 1.2 Top, a spilling wave; *bottom*, a plunging wave. (Photos 12068479, 3918008, dreamstime.com.)

Further along, the beach becomes steeper, and the crest of each wave curls and plunges forward as it reaches the beach (the "plunging" waves in fig. 1.2, bottom). Avid surfers look for a beach with jus the right amount of slope to create a good plunging breaker. Finally, we reach a part of the beach that slopes very steeply away from a cliff, and here the waves barely rise up before smashing against the cliff. These are called "surging" waves.

Later on we'll examine this connection between the shape of breakers and the slope of the beach i more detail.

Playing with Waves

We pass two little girls who are dropping pebbles into a circular pool of water they’ve dug in the san As a pebble falls in the water, it creates a circular ripple that spreads out and *reflects* from the edge o the pool toward the center, as can be seen in figure 1.3A. This event is a small version of a tsunami! The pebble represents the undersea earthquake that launches a group of waves across the water. The waves cross the ocean and reflect back from a coast. This effect was seen in the Indonesian tsunami o 2004. It crossed the Pacific Ocean basin at 750km/h and bounced off the east coast of Africa. Incidentally, *reflection* is another universal property of waves.

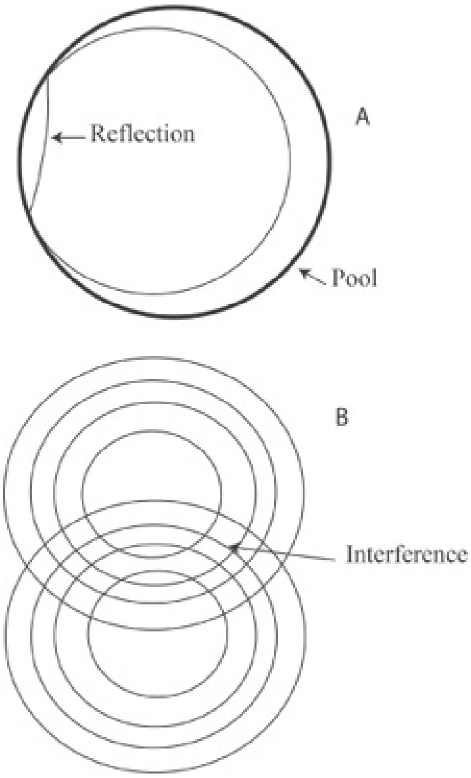


Fig. 1.3 A, circular waves arise when we drop a pebble into a pool. When they reach a border they are reflected. *B*, the cross-hatched interference pattern that arises after dropping two pebbles at the same time.

Before we leave the girls playing by the pool, watch what happens when they drop two pebbles at the same time. Now we have two circular patterns that expand outward and cross each other, as show in figure 1.3B. When two crests overlap, the result is a taller crest; when a crest and a trough overlap they cancel each other and the result is a draw. This *interference* of water waves is remarkable: they can pass over and through each other without disruption, but only if the waves have small heights compared with their wavelengths. Tall, steep waves can behave quite differently, as we shall see later on. Once again, interference is a behavior common to all types of waves.

Navigation by Wave Patterns

Let me digress from our stroll on the beach to note that interference patterns in the ocean have been used in a very practical application: navigation. The natives of Micronesia and Polynesia were famou for the long voyages they made in open canoes across hundreds and thousands of miles of empty ocean. They could be out of sight of land for many weeks, and yet they could locate a tiny island in th midst of the vast ocean.

To navigate they used a variety of aids, such as the stars, cloud formations, winds, currents, and th flight of birds. In addition, the natives of the Marshall Islands in the western Pacific developed a ~~special skill. They learned to read the interference patterns of swells that were driven by the prevailin~~ northeast trade winds. Swells bend around islands and spread out in the channels between them. The overlap of swells from different directions produces a distinctive interference pattern that can help t fix your location.

The Marshall Islanders preserved their knowledge of the sea in so-called stick charts, which were passed down through the generations. The charts were made of strips of coconut leaf midrib and woo Small cowrie shells were attached to the framework to represent individual islands. Curved strips represented the zones where interference patterns could be found. Other strips represented currents. skilled navigator would orient the chart with the sun or stars and look for a particular interference pattern to guide his voyage. A simple but effective scheme!

A Bird’s Eye View

Now let’s climb to the top of the high cliff that looks down on the shore. From there we can see how swell interacts with itself and with a small island offshore. In figure 1.4 a swell is traveling from the lower right to the upper left. As it brushes against the mainland, the right ends of its wave turn slight (*refract*) to face the cliff (notice the little bends in the ends). Then these refracted waves *reflect* off t promontory and *interfere* with the oncoming waves.

We can also see a good example of *diffraction* as the swell squeezes between the island and the mainland: a series of spreading circular arcs. Finally we see another swell entering from the left and interfering with the diffracted waves. Once again, reflection, refraction, diffraction, and interference are basic processes that all types of waves exhibit. So not only ocean waves, but also sound waves, light waves, and seismic waves show them.

Ah, but now the wind is picking up. We’re about to see how the sea changes under a rising wind. first we see small waves building on top of the existing swell. These ripples break up almost immediately into small whitecaps because of the force of the wind. This is what’s called a *choppy* se or a *chop* for short.

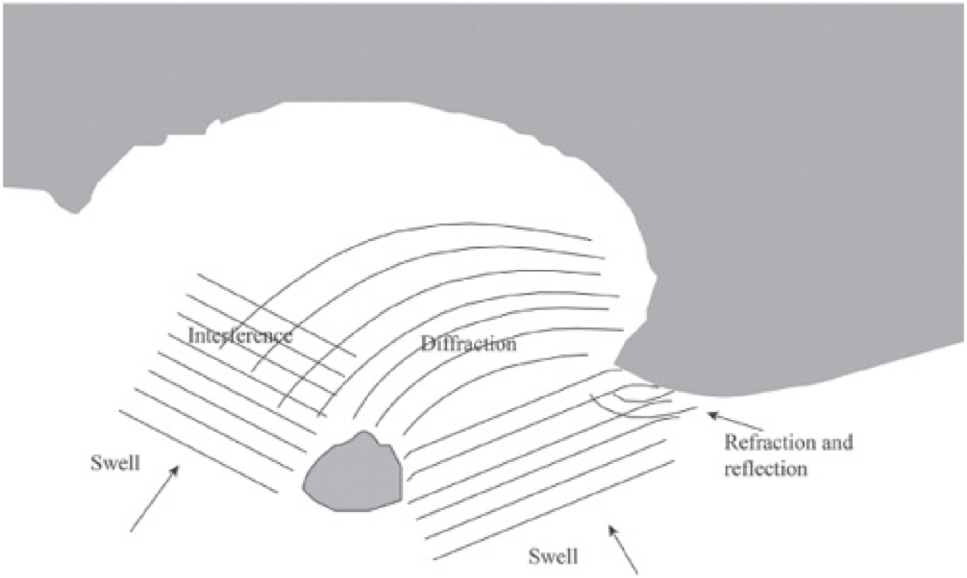


Fig. 1.4 Looking down on the sea from a cliff, we can see several phenomena common to all types of waves: reflection, refraction, interference, and diffraction.

Fig. 1.5 An example of a “sea,” a jumble of short, high, pointed crests. (Photo 19376143, dreamstime.com.)

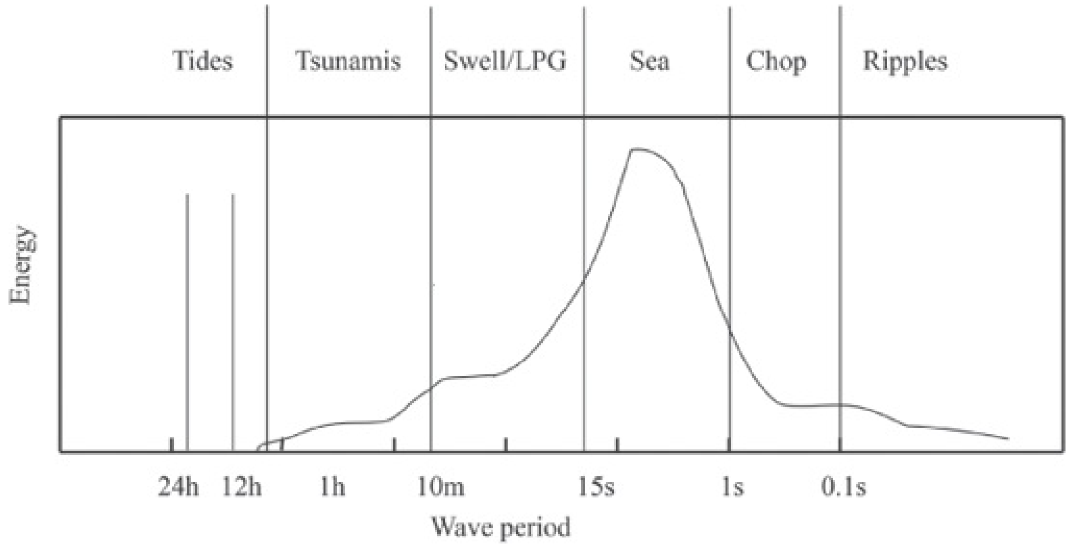


Fig. 1.6 Types of waves, arranged by period. (*LPG* refers to long-period gravity waves.) The curve indicates the amount of energy each type possesses.

Now the wind is rising very quickly; we are having a fierce squall. After a short while the sea is churned into chaos, with tall waves running in directions away from the wind and breaking into whitecaps. Sailors would call this a “sea” (fig. 1.5). Finally, in a gale or hurricane the ocean becomes “fully developed sea.” Now the wave crests have sharp pointed tops, are irregular in height, and exte sideways only a few wavelengths. Short waves are piled on top of long waves, and the sea surface is bouncing up and down erratically. A small boat could easily be swamped in such a sea.

This is a good place to summarize the basic properties of ripples, chop, seas, swells, tsunamis, tides, and other types of waves. In figure 1.6 we see these waves arranged in order of period. The curve indicates the amount of energy each type possesses in the sea.

Well, the wind has turned cold. We’ll meet all these waves again, along with some scientists who have studied them, but for now it’s time to move on.

CHAPTER TWO

What Exactly Is a Wave?

Everybody knows what a wave is. At least, we recognize one when we see it. When asked to imagine wave, most people think of ocean waves, those majestic waves that roll steadily toward the shore or the chaotic waves in a stormy sea. Most people also know that other kinds of waves exist: light wave sound waves, and earthquake (seismic) waves, for example. But when asked to describe what they se most people are a little vague. Obviously something is moving but what exactly? Let’s try a few thought experiments to answer the question.

Remember the game we used to play with dominoes as children? We’d stand them up on their sho sides in a long row, taking care to space them apart by the same small distance. Then we’d touch the first in line and watch them all fall over, one after the other. We’d see a wave of some sort moving rapidly down the line. Very exciting! But what was moving? Each domino slumped on its neighbor and came to rest. On the other hand, the wave traveled very quickly to the end of the line.

Therefore we could say, in a general sense, that a wave is a traveling disturbance in some medium The medium in this case was the line of dominoes; the disturbance was the tipping of each domino. That’s not a bad definition. But we could also say that the wave was carrying a message from one domino to the next: “Lean away from me!” So in some sense it was the angle of leaning that was traveling down the line. Notice that no domino traveled with the wave down to the end of the line: each domino just tipped over and stopped. It is the message that moves, not the medium.

Strictly speaking, I would call this single domino wave a pulse, not a genuine wave. Genuine waves, in my opinion, involve some type of oscillation. A good example is provided by a child’s toy, Slinky.

The Slinky

A Slinky is simply a long, loosely coiled spring (see the image at the top of fig. 2.1). If we push and pull one end of the spring rhythmically in and out, we send waves of compression and rarefaction down the coil, a good analogy to pressure waves in a sound wave.

In figure 2.1 we see a time sequence of such a compression wave in the Slinky. Initially the Slinky is at rest, and each loop is in its rest position, equally spaced from its neighbors. Then at time T_1 we push in our end, creating a region of compressed loops. The compression moves down the spring. If we look carefully, we’ll see why: each loop of the spring moves forward a small distance and pushes the next loop in line, and so the compression advances.

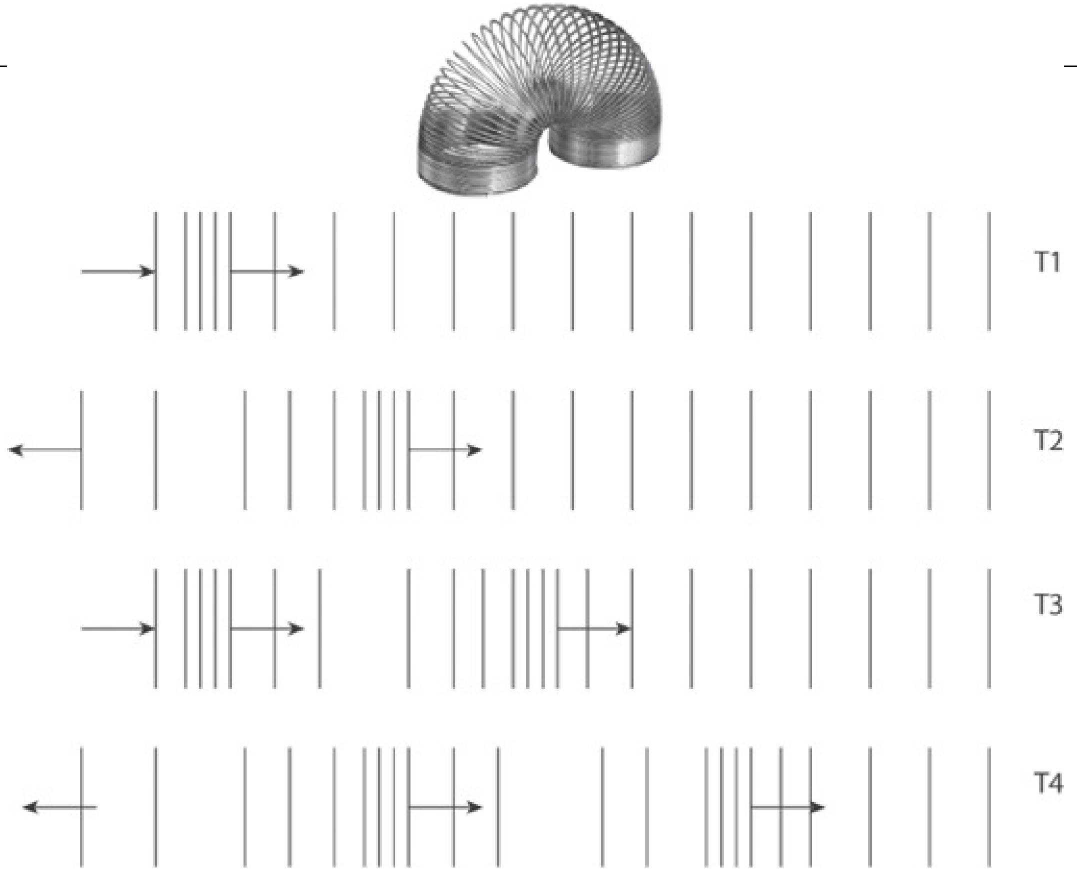


Fig. 2.1 A wave of compressions and rarefactions on a Slinky. At time T1 a compression is formed. I moves down the coil at time T2. At time T3, a rarefaction is formed and moves down the coil. These oscillations of loops about their rest position generate the wave we see.

In this forward motion, each loop overshoots its rest position: its momentum has carried it too far forward. But then the tension in the spring acts as a restoring force on the loop and causes it to rebound from its furthest advance. Once again the loop overshoots its rest position, and tension pulls forward. Each loop therefore oscillates back and forth, along the direction of wave propagation.

A half period later (T_2) we pull back on our end of the spring and create a rarefaction, a region of low loop density. This time each loop *pulls* on its neighbor in the direction opposite to the direction o propagation. The rarefaction also propagates down the spring (T_3). Notice that although the loops are moving backward in their oscillation, the rarefaction is moving forward. The cycle repeats at time T_4 No loop travels from one end to the other. Only the wave energy travels that far.

The main point here is that the wave propagates because each element of the medium (the loops o the spring) communicates its oscillations to its neighbor downstream after a short delay. The speed o the wave, it turns out, is controlled by the stiffness of the spring: the harder it is to push or pull the loops, the faster is the wave.

Incidentally, the Slinky waves are *longitudinal* waves, meaning that the displacement of an eleme (a loop) was along the direction of propagation. The Slinky wave is a good model of a sound wave in air, a series of compressions and rarefactions. But we need a better model for water waves. A child’s jump rope is a simple example.

A Jump Rope

Let’s imagine two girls pulling gently on opposite ends of a long rope. Now let’s watch as the girl at the left end, Louise, snaps her end up and down sharply, just once. We see a kink in the rope travel ~~quickly along the rope to Rachel, at the other end (fig. 2.2A). When the kink arrives, Rachel's hand~~ i snapped up and down, just once.

This kink was a *pulse*, a single isolated disturbance in the rope, not a true wave. But it served to show that that the pulse carried *energy* from Louise to Rachel, sufficient to shake Rachel's hand up and down. Her hand absorbed the energy, so that no pulse was reflected back to Louise. The speed of the pulse depends on how much tension the girls have put on the rope: the greater the tension, the faster the pulse. It also depends on how heavy the rope is: the heavier the weight, the slower the spee

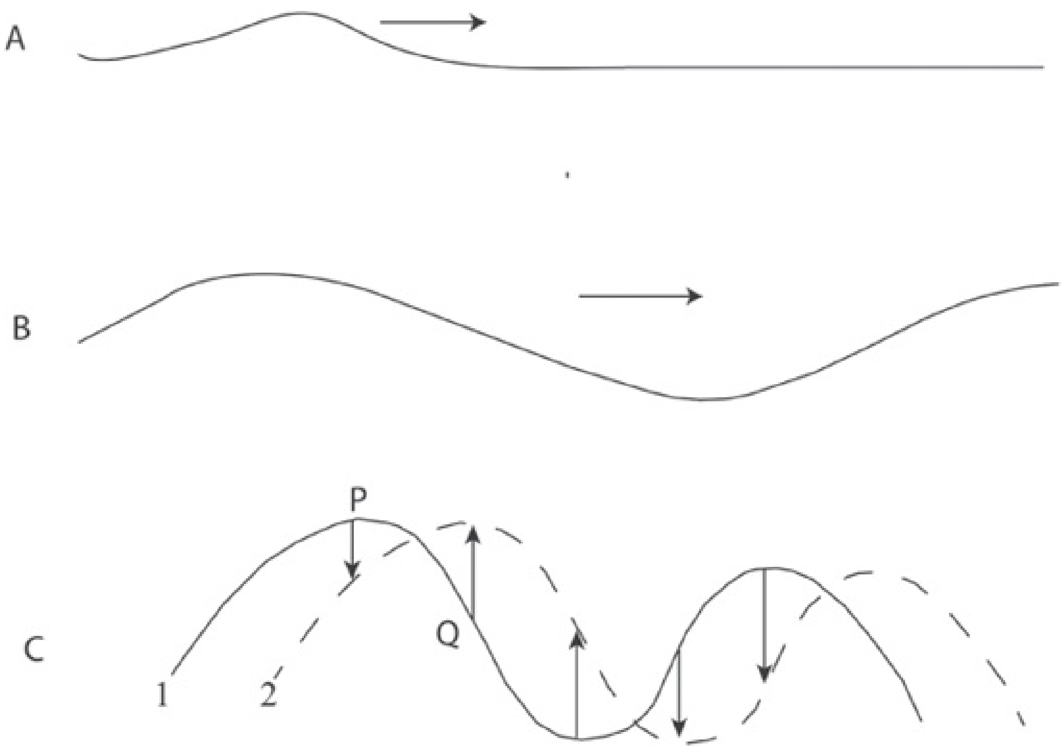


Fig. 2.2 Waves on a rope. *A*, a pulse; *B*, a true wave; *C*, a crest shifting rightward to the next part of the rope.

Next, we watch Louise shake her end of the rope rhythmically. She generates a true wave, a sequence of kinks that travel steadily to Rachel (fig. 2.2B). Rachel's hand is shaken as before; she is absorbing the energy that Louise is pumping into the rope. If Louise shakes the rope more frequently the distance between the kinks (the wavelength) becomes shorter, but the kinks travel the same spee as before. That's because the speed depends only on the rope's tension and weight.

While Louise is shaking her end of the rope, we should look carefully at the motion of kinks in th middle of the rope. In figure 2.2C we see the rope at two instants, 1 and 2. The arrows indicate the directions of the motion. The pieces of rope are definitely not moving bodily toward Rachel. They ar merely oscillating up and down a short distance from their rest positions. And yet their vertical motions help to produce the horizontally traveling wave that we seem to see. How does this happen?

First let's agree that what we interpret as a wave is an apparent movement of the high spots in the undulating rope. The rope is not streaming toward Rachel as a whole; only the locations of the high spots are streaming.

We notice that during its oscillation, point *Q* exactly repeats each of point *P*'s vertical motions, bu with a short time delay. For example, when *P* is at the top of its rise and moving down (see the arrows), *Q* is still rising toward its top (fig. 2.2c). That means that *Q* will reach its top a short time after *P* has. The location of the high spot in this part of the rope will have moved from *P* to *Q*. We would interpret this shift as a forward movement of a wave.

~~It is exactly this time delay in the motion of neighboring segments that generates the wave that~~ we find so eye-catching. Each segment lags the segment behind it, in Louise’s direction, by the same delay. Therefore, we see that the closer a segment is to Rachel, the later it reaches the top of its rise. Basically, the wave is *a horizontally moving pattern* that arises from the motion of *vertically oscillating* elements.

Incidentally, this is an example of a *transverse* wave, in which the displacements of the medium (the rope) are perpendicular to the direction of wave propagation. Light is also a transverse wave. So are the vibrations of a guitar string and an ocean wave.

We now have the tools we need to talk about water waves, so let’s move on.

The Construction of a Water Wave

Watching gentle ocean waves roll onto a shore can be hypnotic. It’s a very restful pastime that I’ve enjoyed occasionally. But after you’ve been watching for some time, you may begin to wonder why the waves are so regular (as in fig. 1.1). The crests are spaced apart by a constant distance (the wavelength), they move toward shore at a constant speed, and they arrive at a constant interval (the period). Moreover, each wave has very nearly the same shape. It may remind us of the sine waves we studied in high school, except that the crests seem a bit sharper and the troughs a bit broader.

How is this regular pattern maintained, especially with no wind? What is happening under the surface of the water? And how are the different characteristics of the waves related? We can get a clu to the mystery by watching that swimmer offshore, who is floating on her back. As a crest approache her, she rises at first and moves forward a bit, then sinks, and finally moves backward, in what looks like a circular motion. She’s not surfing, not being carried forward with the surface wave; she and the water under her are just oscillating in place.

Clearly these incoming waves have some connection with oscillations of the water. To learn what the connection is we need to look under the surface. Fortunately, two clever brothers did this for us almost 200 years ago and reported what they saw.

Under the Surface

Wilhelm Eduard Weber (1804–91) and his older brother Ernst Heinrich Weber were the first scientis to investigate water waves experimentally in a lab. In 1825 Wilhelm was a 20-year-old graduate student in physics at the University of Halle in Saxony, Germany, and an avid believer in experimenting. Ernst was already a professor of physiology at the University of Leipzig, interested in how blood flows through arteries, and he decided to draw on Wil-helm’s proven experimental skills.

Wilhelm was easily persuaded. He set up several glass tubes with different diameters, pumped various fluids through a tube under precise pressures, and measured the rates of flow. In a long series of trials he and Ernst determined the viscosity (stickiness) of such fluids as mercury, water, and brandy. These simple experiments were so successful that the brothers probably celebrated by drinking the brandy. Then, in the flush of victory, they decided to tackle a more difficult problem, the motion of water waves.

So they set up a rectangular wave tank, a narrow channel 2m long and 2cm wide, filled 0.5m deep with water. They could launch a train of small waves by dropping precise amounts of water into the tank at regular intervals (the “period”). Then they could measure the separation of the crests (the wavelength) and the speed of the crests. They could also observe the shapes of the waves through the glass sides of the tank.

~~The first thing they noticed was that the profile of the wave train resembled the familiar sine~~ wave one learns about in high school, but with some differences: the peaks were a little sharper and the troughs were broader. Ocean waves are like that too. Second, the longer the period of the wave, the longer was its wavelength and the faster its speed, although they were unable to determine precise relationships. Third, the height of a typical wave (the vertical distance from crest to trough) could be made larger or smaller without changing the period or wavelength.

Their most interesting results concerned the motions of the water under the surface. To make thes more visible, the Webers added small particles of flour to the water. Figure 2.3A shows a reconstruction of what they could have observed through the glass sides of the tank, a snapshot of a wave traveling to the right.

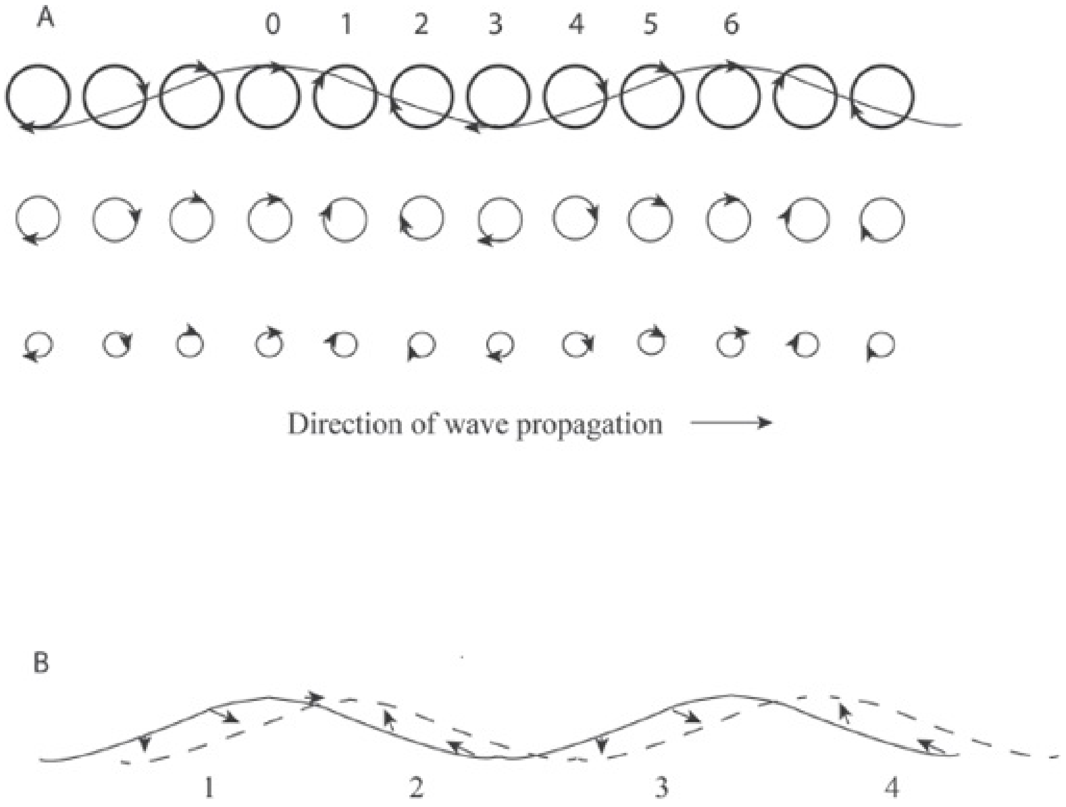


Fig. 2.3 Water blobs under the ocean’s surface rotate in circles as a deep-water wave passes by. See text for description.

Under the surface, a traveling water wave looks like the inside of a fine clock, filled with carefull synchronized “gears.” The gears are actually the vertical circular orbits of small blobs of water (let’s just say the size of a blob is a small fraction of the wavelength). The orbits decrease in size the deepe one looks. Moreover, except for a very small drift in the forward direction, each orbit remains in its place as the crest passes by. (This is the reason the swimmer discussed earlier merely rocks up and down in the water without advancing toward the shore.)

In the illustration each blob revolves in its orbit at a constant angular speed in a clockwise directio and completes a revolution during one period of the wave. Moreover, all the blobs in a vertical colum are at the tops of their orbits (and moving horizontally) at the same instant, just as a crest passes overhead. In fact, a crest is just the visible result of this coordinated rise of all the blobs. Similarly, when all the blobs in a vertical column are at their lowest points, they create a trough.

But there is more to this subtle motion. The blobs in each vertical column reach the tops of their orbits a little later than those in the column to their left (or upstream). So in figure 2.3A, the blobs in ~~column 1 lag those in column 0 by a small amount—in this drawing, a sixth of a period. And the~~ blob in column 2 lag those in column 1 and so on down the line to the right.

When all the blobs in column 1 reach the tops of their orbits at the same moment, they stack up to form a new crest at the surface. You can see this in figure 2.3B. Here, we see the position of the wave (the dashed line) after a sixth of a period has elapsed. The blobs in column 1 are now at the tops of their orbits and have created a new crest. In effect, they have shifted the position of the crest to the right by one-sixth of a wavelength. The small arrows show the paths that blobs on the original wave have taken. And the process repeats: the crest continues to shift from one column to the next one downstream. In this way, the crests and troughs travel from left to right in the figure.

For convenience, I've drawn only seven orbits between two crests in figure 2.3A, but of course there is an orbit of the same size—an infinite number—for every point on the wave's profile. The orbits would overlap, but because of the way the blobs lag each other, they never collide. The motion of the fluid would be perfectly smooth. The same is true for the orbits below the surface of the water.

The Webers made an important discovery with their simple experiments. They revealed that there is a tight connection between the revolution of blobs of water in stationary orbits and the passage of surface wave. Indeed, the wave and the orbits have the same period. The whole train of waves advances by one wavelength in one period of the oscillation. Physicists call this a traveling wave trai We can call it a swell.

The Weber brothers summarized their research in a massive 575-page monograph in which they compared their observations with the laws of fluid flow known at the time. It was the first major advance in the experimental study of waves. But as is often the case, brilliance in one area often carries over to a lifetime of brilliant works. In later life, Wilhelm collaborated with Carl Friedrich Gauss, a brilliant mathematician, in a comprehensive study of magnetism. They also invented the firs telegraph system, but that is another story.

How Energy Propagates

You can watch a swell rolling onto the shore all day without any wind to push it. How is this possible Sailors all know that the waves are created by a storm or a prevailing wind far offshore. The harder th wind blows and the greater the distance it acts on the water (the "fetch"), the higher the waves grow. But once the waves start rolling, there isn't much to slow them down because the internal friction of water (its viscosity) is very weak. So these wind-formed waves roll on until they crash on the beach. There they release the energy that the wind delivered to them.

We can think of a wave train as a conveyor belt that carries energy at a steady rate toward the shore. The basic elements in the conveyor belt are the orbiting blobs of water near the surface. Each blob stores and releases gravitational energy as it rises and falls in its orbit. A blob behaves like a child on a swing, storing gravitational energy as it swings up to its high point, and releasing it as it falls. Each falling blob delivers some of its stored energy to its neighbor downstream, causing it to rise, and so on in a chain reaction. A blob would come to rest after passing along its energy, except that it immediately receives another pulse of energy from its neighbor upstream.

In effect, the blobs are acting like the workers in a bucket brigade, passing energy down the line without moving far from their normal positions. So the net result is a train of waves that delivers a steady flow of energy to the beach. Because gravity is the key force that enables the water to store energy temporarily, ocean waves are called *surface gravity waves*.

There remains the mystery of how the rotating blobs of water got started, how they became synchronized, and why they don’t propel waves away from the shore. In the next chapter we’ll return to t~~hese questions. There we’ll see how a prevailing wind imparted some of its energy to the water~~ ar also fixed the direction of rotation (clockwise or counterclockwise) of the circular orbits of the blobs But first let’s continue with these blobs.

Restoring Forces

At this point you should have a pretty good idea of how water blobs rotate within a traveling gravity wave. But I really haven’t explained how gravity and pressure drive these motions. As we saw earlie each blob moves both vertically and horizontally as it revolves in a circular orbit. Let’s first conside the forces that control the vertical motions. There are two opposing forces in play: *gravity* (which always acts to pull a crest down and to deepen a trough) and water *pressure* (which builds up under t falling water and pushes against it). Gravity would cause a blob of water to fall indefinitely, but risin pressure from the surrounding water acts as the restoring force in the vertical oscillation of the water

The motion resembles that of a child bouncing on a trampoline. Gravity pulls her down, and she hits the trampoline’s fabric surface hard enough to stretch the coiled springs holding up the fabric. However, as the combined tension from the coiled springs increases, it eventually becomes larger tha the force of gravity, causing the springs to contract sharply and launching her skyward again. In this analogy, the spring tension mimics the rising water pressure in a wave.

In figure 2.3B we can see how this works. We see two snapshots of a sinusoidal wave, taken a sixt of a period apart. The wave (the dashed curve) has moved a sixth of a wavelength to the right in this time. The arrows show the paths that some blobs took during this time. As the back of a crest collapses, the falling water increases the pressure underneath it. At position 1 the pressure increased enough to slow the collapse; at position 2 the excess pressure has reversed the fall and is raising a ne crest to its maximum height. In this way the water oscillates vertically, with gravity pulling it down and the surrounding water pressure pushing it back up.

The *horizontal* oscillation of the water blobs is driven solely by oscillating horizontal pressures. These pressures are less obvious, but they account for the fact that the paths of the water blobs are circles and not merely vertical lines. At position 1 in figure 2.3B, a falling crest creates a horizontal pressure that is larger than the pressure at position 2. That difference of pressure pushes the blobs downstream a short distance and ensures the propagation of the crests.

The Vital Connections

Now let’s get back to the question I posed earlier: what is the relationship between the wavelength ar the period of a wave? For a quick and crude answer we can appeal to an analogy between pendulums and water waves because gravity governs both of their oscillations.

Galileo Galilei was the first to investigate pendulums in a laboratory. He was probably the most famous astronomer of his century but few people today realize that he was also a talented experimentalist. His reputation rests on his stunning astronomical discoveries, which include the moons of Jupiter, the rings of Saturn, and the changes in the shape of Venus’s illuminated disk. But h also made important contributions to our understanding of how bodies move. In particular, he discovered the essential properties of pendulums in series of experiments.

According to a legend, he became fascinated with pendulums after noticing a chandelier in the Pis cathedral swinging with a constant period. Later in his lab he learned that in order to double the perio of a pendulum, you must make the length of the arm four times longer, and to triple the period you must make the arm nine times longer. This led ultimately to the basic equation that correlates the arm’s length with the square of the period: thus, 2 squared is 4, and 3 squared is 9.

~~Now, to the extent that the analogy between gravity waves and pendulums is valid, we could~~ identify the pendulum arm with the wave’s wavelength and guess that the wavelength of a gravity wave increases as the square of the period. I’ll admit that this explanation may seem like sleight of hand. For a sound physical explanation we’ll need to turn to the long line of scientists and mathematicians who investigated water waves.

Sir Isaac Newton

Sir Isaac Newton was probably the first to propose a theory of gravity water waves. (Why isn’t that surprising? He seems to have pioneered everything.) To Newton we are indebted for the law of gravitation and an explanation in terms of physical forces for the movement of the planets. He applie the same methods to water gravity waves.

We will meet his prolific contributions again in later chapters, since he made major contributions to the science of optics and independently invented differential calculus, which allowed future scientists to perform the mathematical calculations needed to truly understand wave dynamics. He was undoubtedly a genius. But he was also an alchemist who tried to convert lead into gold and was well-known in his time as a mystic and a secretive, eccentric person.

In his monumental treatise *Philosophiæ Naturalis Principia Mathematica* (1687) he published an approximate theory that yielded a prime result: the wavelength of a water wave increases as the squa of its period. (Just as we guessed!) So, for example, a gravity wave with twice the period of another wave has a wavelength four times as long.

D’Alembert and Euler

Jean LeRond d’Alembert, a French mathematician born in 1707, shortly before Newton died, was the next in line to study waves. An illegitimate son of a wealthy man, whose mother abandoned him and whose father refused to acknowledge him publicly, he was pressured to become a priest by his father family. Given this start, it would seem unlikely that he would ever have had any connection with the science of waves. But as he grew up, he strongly rejected theology (“rather unsubstantial fodder”) an became a mathematician instead. He helped to build a mathematical theory of music, including the origin of overtones, the concepts of octaves and major and minor chords, and much more.

Eventually, in 1747, he became interested in how the strings on a violin make a specific tone wher plucked. He chose a mental model used earlier by Johann Bernoulli (a Swiss mathematician from the illustrious Bernoulli family of scientists): a chain of beads connected by little springs. Like Bernoull he relied on Robert Hooke’s law (Hooke was a British compatriot of Isaac Newton and a fellow natural philosopher), which says that the restoring force of a stretched spring is proportional to the amount of stretch. Then he imagined shrinking the size of each bead and increasing their number, while keeping the same total mass for the string. He also replaced the springs with a continuous tension in the string. In an important publication, he derived the wave equation that governs the motion of this system and found a general solution. It was the first mathematical analysis of string vibrations ever published.

D’Alembert demonstrated that a wave need not be periodic or have the shape of a sine wave or hav such a thing as a wavelength. Indeed, a wave could consist of a single traveling hump of an arbitrary shape (like the pulse traveling in our domino example). He proved that the shape will remain unchanged as it progresses *only* if each point on it advances the same distance in a given time. With proper modifications, his wave equation would apply to any wave, water waves included. But