Unit 25

Recent Trends in Physics

This unit online, with its interactives:
science-playground.com/s/12f25

At 11:56 on the morning of Saturday, 25 April 2015 (12 Baisakh 2072), the ground under Barpak, a village in Gorkha, lurched. A crack 150 km long tore eastward under the hills at nearly 3 km a second, and for almost a minute the whole of central Nepal shook. In Kathmandu, 80 km away, the first jolt came about a quarter of a minute later and the shaking grew for nearly a minute, and Dharahara, the city's white tower, fell.

Five months later, on 14 September 2015, two machines in the USA felt a shaking of a very different kind: a squeeze and stretch of space itself, a few thousandths of the width of a proton, from two black holes that had collided 1.3 billion years before. Both were waves carrying energy from a sudden event far away. This unit is about such recent work in physics: earthquakes and the waves they send, the 2015 Gorkha earthquake, gravitational waves, the Higgs boson, and nanotechnology, the science of the very small.

A STORY FROM SCIENCE

Peter Higgs and the missing particle

Peter Higgs (1929–2024) was a British theoretical physicist at the University of Edinburgh. In 1964 he, and independently François Englert and Robert Brout in Brussels and three others in London, worked out how the particles of nature could get their mass from a field filling all of space. Higgs pointed out that the field should also show itself as a new particle. His paper was at first turned down by a journal as of no obvious relevance to physics.

The particle, the **Higgs boson**, became the last missing piece of the **Standard Model** of particle physics, the theory of all known fundamental particles and the forces between them (except gravity). It was found 48 years later, in 2012, at CERN's Large Hadron Collider, and in 2013 Higgs and Englert shared the Nobel Prize in Physics. Higgs, a shy man who disliked fame, heard the news from a neighbor in the street, having gone out to avoid the reporters. He died on 8 April 2024.



Figure 25.1 *Peter Higgs in Stockholm in December 2013, the week he received the Nobel Prize.*
Photo: Bengt Nyman from Vaxholm, Sweden, CC BY 2.0

DID YOU KNOW?

Do you know?

- Nanotechnology gives us stronger materials, faster electronics, and medicines that are carried straight to the cells that need them.
- The Gorkha earthquake of 12 Baisakh 2072 had a moment magnitude of **7.8**.
- Gravitational waves were detected for the first time in 2015, by LIGO, the Laser Interferometer Gravitational-Wave Observatory.

25.1 Earthquake

An **earthquake** is a sudden shaking of the ground, when energy stored in the rocks below is suddenly let go. The energy travels out as **seismic waves**, spreading in every direction from the point underground where the earthquake starts.

Most earthquakes start on a **fault**: a break in the crust where the rock on one side can move against the rock on the other. When two blocks try to move past each other but are held by friction, stress builds up in the rock year after year, bending it like a stick bent between your hands. When the stress becomes greater than the friction, the rocks suddenly slip, the bent rock springs back, and the stored energy is released as an earthquake.

Faults are named by the way the blocks move (Figure 25.2). Where a fault slopes, the block above it is the **hanging wall** and the block below it the **footwall** (a miner in a sloping tunnel along the fault would hang a lamp on the one and stand on the other).

Check 12

10. Nanomaterials are materials with at least one dimension measuring less than:

a 1 nm
b 10 nm
c 100 nm
d 1000 nm

15. Define nanotechnology. Briefly explain its history, and name any four major fields where nanotechnology is used.

A companion to your textbook, not a replacement for it: study from the book your school uses, and where the two differ, follow your teacher. Found a mistake? Please tell us.

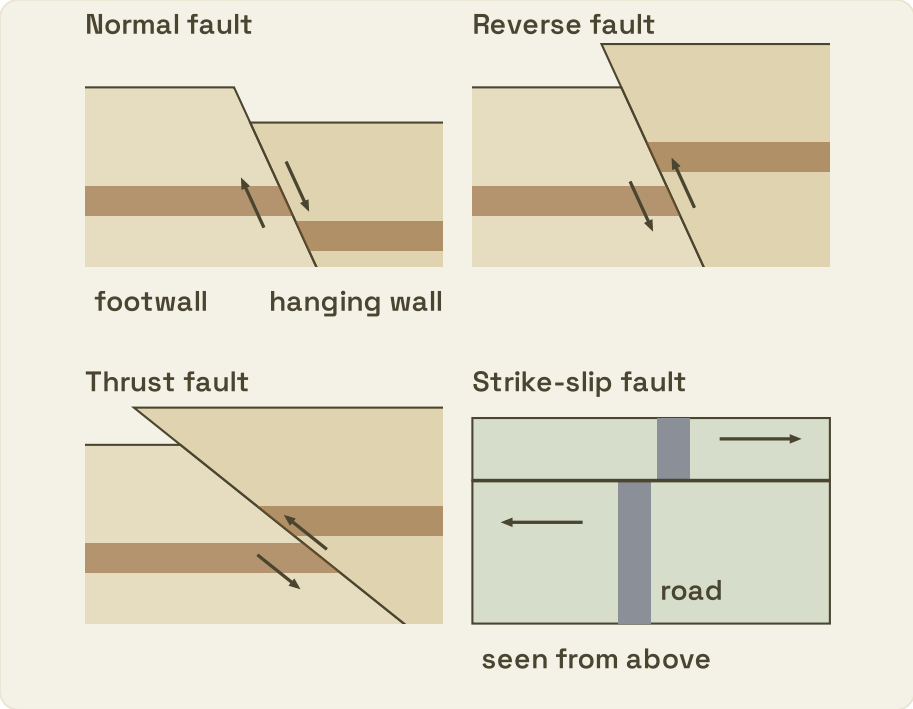


Figure 25.2 *The four kinds of fault.* ***Normal:*** *the hanging wall slides down, where the crust is pulled apart.* ***Reverse:*** *the hanging wall is pushed up, where it is squeezed.* ***Thrust:*** *a reverse fault at a low angle, under 45°: the faults under Nepal are thrusts.* ***Strike-slip:*** *the blocks slide past each other sideways (seen from above), as on California's San Andreas Fault. Not to scale.*

Key terms to know

- **Focus** or **hypocenter:** the point inside the Earth where the rock first slips and the earthquake begins.
- **Epicenter:** the point on the Earth's surface directly above the focus. The shaking is usually strongest near it.
- **Foreshocks:** smaller tremors that sometimes come before the main shock. They can be recognized only afterwards, once the main shock has come.
- **Aftershocks:** smaller earthquakes that follow the main shock, as the rock around the slipped fault settles, becoming smaller and less frequent with time.

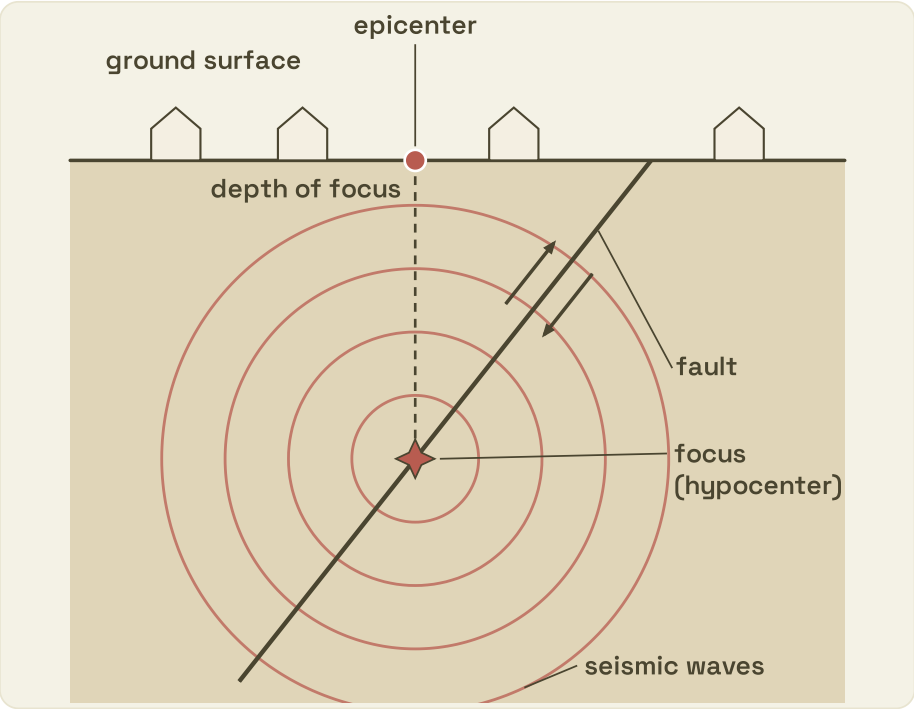


Figure 25.3 *A slice through the ground across a fault. The rock slips at the focus (hypocenter), and seismic waves spread out from it in every direction. The epicenter is the point on the surface straight above the focus. Not to scale.*

Causes of earthquakes

Earthquakes can be caused by sudden movements along faults, volcanic eruptions, large landslides, and bomb blasts or underground explosions. By the nature of their source, earthquakes are of two kinds.

- **Natural earthquakes** are caused by the movement of tectonic plates or by volcanic activity. The Earth's outer shell, the **lithosphere**, is broken into large plates that move a few centimeters a year. Where they grind past each other or collide, at plate boundaries, energy builds up in the rock and is released in earthquakes. Nepal sits on such a boundary: the Indian Plate pushes north under the Eurasian Plate at about 2 cm a year, raising the Himalaya.
- **Artificial earthquakes** are triggered by human activities: blasting during construction, mining, filling large reservoirs behind dams, pumping fluids deep underground, and nuclear or bomb explosions.

Check 5

3. What kind of motion does a Love wave produce?

a elliptical rolling motion
b horizontal side-to-side motion
c vertical shaking
d back-and-forth compression

Check 6

4. The Higgs boson was confirmed through experiments at:

a NASA
b ISRO
c CERN (LHC)
d MIT

Check 7

5. Which of the following waves can travel through solids, liquids and gases?

a S wave
b P wave
c Rayleigh wave
d Love wave

Check 8

6. What is the speed of gravitational waves?

a 10,000 km/s
b the speed of light
c half the speed of light
d different for different sources

Check 9

7. What does the Higgs field do?

a binds electrons and protons
b causes gravitational attraction
c gives particles their mass
d generates dark energy

Check 10

8. The point within the Earth where an earthquake's seismic energy is first released is called the:

a epicenter
b hypocenter
c area of greatest building damage
d area of least building damage

Check 11

9. Which of the earthquake waves is recorded first on a seismograph?

a P waves
b S waves
c Rayleigh waves
d Love waves

IN SHORT

Key ideas of Unit 25

- An earthquake is the sudden shaking of the ground when stressed rock slips along a fault, releasing energy as seismic waves. Focus (hypocenter): where it begins; epicenter: the point on the surface above it. Faults: normal, reverse, thrust and strike-slip.
- Magnitude is logarithmic: one step up is 10 times the wave height and about 32 times the energy, $E_1/E_2 = 10^{1.5(M_1-M_2)}$. The moment magnitude M_w works for every earthquake.
- Body waves: P (longitudinal, 6–8 km/s, through solids, liquids and gases, first) and S (transverse, 3–4.5 km/s, solids only, second). Surface waves, slowest and most damaging: Rayleigh (rolling ellipses, up and down and back and forth) and Love (side to side, horizontal, a little faster).
- Gorkha, 25 April 2015: M_w 7.8, epicenter Barpak, shallow (about 8 km), a thrust on the Main Himalayan Thrust rupturing about 150 km eastward; aftershock 7.3 on 12 May; nearly 9,000 deaths.
- Gravitational waves: ripples in space-time traveling at the speed of light, predicted by Einstein (1916), first detected by LIGO (2015) from two black holes merging; LIGO is a laser interferometer with 4 km arms. Kinds: continuous, burst, stochastic and compact binary inspiral (the only ones detected by LIGO so far).
- The Higgs boson (predicted 1964, found at CERN's LHC in 2012): the particle of the Higgs field, which gives fundamental particles their mass; it completed the Standard Model.
- Nanotechnology works at 1–100 nm (1 nm = 10^{-9} m), where materials gain new properties. Feynman's lecture (1959), the STM (1981), fullerene C_{60} (1985). Uses in medicine, electronics, energy, water, textiles, food, building and cosmetics.

Exercise

Choose the correct option

Check 3

1. Which type of seismic wave travels fastest?

a surface wave
b Rayleigh wave
c S wave
d P wave

Check 4

2. Who predicted the existence of gravitational waves?

a Newton
b Albert Einstein
c Peter Higgs
d Stephen Hawking

Answer these questions

11. What is seismology? Describe the various types of seismic waves.

DID YOU KNOW?

Nuclear tests and earthquakes

An underground nuclear explosion sends out seismic waves like an earthquake. Seismometers all over the world record every nuclear test, and a network of stations run by the Comprehensive Nuclear-Test-Ban Treaty Organization watches for them. An explosion and an earthquake look different on the record: an explosion pushes outward in every direction at once, so its first P waves are pushes everywhere, while a fault's slip pushes in some directions and pulls in others.

Earthquake magnitude

Magnitude measures the energy released at an earthquake's source. It was first measured on the **Richter scale**, worked out in 1935 by the American seismologist **Charles F. Richter** from how far a seismograph's needle swung. The scale is **logarithmic**: each increase of one in magnitude means

- waves **10 times** taller on a seismograph, and
- about **32 times** as much energy released (more exactly $10^{1.5} \approx 31.6$).

So a magnitude 8 earthquake has waves 10 times taller than a magnitude 7 and 100 times taller than a magnitude 6, and it releases about 32 times as much energy as the 7 and about 1000 times as much as the 6.

$$\frac{E_1}{E_2} = 10^{1.5\,(M_1-M_2)} \qquad (25.1)$$

As more seismograph stations were built, it became clear that Richter's method worked only for certain distances and wave frequencies, and that it gave too small a number for the biggest earthquakes. New scales were made for particular waves, the **body-wave magnitude** M_b and the **surface-wave magnitude** M_s, and finally a scale that works for every earthquake, the **moment magnitude** M_w, worked out from how large an area of the fault slipped and by how much. For most earthquakes the scales give about the same number, so news reports often still say "Richter".

Earthquakes below magnitude 3.0 are usually not felt; those above 7.0 can cause severe destruction. The largest ever recorded, the **1960 Valdivia earthquake in Chile**, had a moment magnitude of 9.5.

CAREFUL

Ten times or thirty-two times?

"A magnitude 8 is 10 times stronger than a magnitude 7" is true only of the **height of the waves** on a seismograph. In **energy**, the thing that does the damage, each step is about 32 times, and two steps about 1000 times.

Seismology and seismic waves

Seismology is the study of earthquakes and of the seismic waves that move through and around the Earth. A **seismograph** records the ground's shaking; its record is a **seismogram**.

Seismic waves are **elastic waves** made by earthquakes or explosions: as they pass, they deform the rock, which springs back, so they carry the earthquake's energy away from the focus. They are

mechanical waves (Unit 6, Types of waves), of two families: **body waves**, which travel through the inside of the Earth, and **surface waves**, which travel along its surface.

Body waves

P waves (primary, or pressure, waves) are **longitudinal**: the rock is pushed and pulled along the direction the wave travels, in compressions and rarefactions, like sound in air. They are the fastest seismic waves, about **6 to 8 km/s** in the crust, so they arrive first, and they travel through solids, liquids and gases. They are also called compression waves.

S waves (secondary, or shear, waves) are **transverse**: the rock is shaken at right angles to the direction of travel, up and down or side to side. They are slower, about **3 to 4.5 km/s**, so they arrive second, and they travel **only through solids**: a liquid has no stiffness against being sheared, so it can't pass a shear wave on. That S waves never cross the Earth's outer core is how we know it is liquid.

Surface waves

Surface waves form when body waves reach the Earth's surface layers. They travel along the surface, more slowly than body waves but with larger swings that last longer, and they do most of the damage in an earthquake. There are two kinds.

- **Rayleigh waves**, predicted by Lord Rayleigh in 1885, roll along the surface like waves on the sea: each bit of ground goes round an upright ellipse, moving **up and down and back and forth** along the direction of travel. They are made where P waves and up-and-down S waves meet the surface, and their motion dies away with depth. Of all seismic waves they are usually the slowest, and they carry much of the ground shaking.
- **Love waves**, described by the British mathematician A. E. H. Love in 1911, shake the ground **from side to side**, horizontally, at right angles to the direction of travel, with no up-and-down motion. They are made by side-to-side S waves trapped in the surface layers, so they need a solid whose properties change with depth (soft layers over hard rock). They are a little faster than Rayleigh waves and shake the bases of buildings sideways.

The four waves compared:

YOUR TURN

25.2 Nanotechnology in modern life

State any two practical uses of nanotechnology in modern life.

Answer

Any two, for example: drugs carried by nanoparticles straight to cancer cells; chips whose transistors are a few tens of nanometers across; sunscreens with zinc oxide nanoparticles; nano-filters for clean water; stain-resistant, antibacterial clothes; rapid diagnostic tests.

YOUR TURN

25.3 Who and when?

Who proposed the existence of gravitational waves, and in which year?

Answer

Albert Einstein, in **1916**, from his general theory of relativity.

YOUR TURN

25.4 Two surface waves

Name and describe the two types of surface seismic wave.

Answer

- **Rayleigh waves** roll along the surface like waves on the sea: each bit of ground moves round an upright ellipse, up and down and back and forth along the direction of travel. They are the slowest seismic waves.
- **Love waves** shake the ground from side to side, horizontally and at right angles to the direction of travel, with no vertical motion. They are a little faster than Rayleigh waves.

WORKED EXAMPLE

25.5 Nanotechnology

What is nanotechnology, and what size range does it work in?

Answer

Nanotechnology is the science and engineering of controlling matter at the scale of atoms and molecules. It works in the range **1 to 100 nanometers**, where 1 nanometer is a billionth of a meter (10^{-9} m).

WORKED EXAMPLE

25.6 Why surface waves do the damage

Explain what makes surface waves more destructive than body waves.

Answer

Surface waves (Rayleigh and Love waves) travel along the Earth's surface, where the buildings are, instead of spreading through the Earth's whole volume, so their energy weakens less with distance. They have **larger amplitudes** and **last longer** than body waves, and they heave the ground up and down (Rayleigh) and shake it sideways (Love), so they do the most damage, especially near the epicenter.

WORKED EXAMPLE

25.7 Half a step of magnitude

The Gorkha earthquake had a magnitude of 7.8, and its largest aftershock 7.3. How many times as much energy did the main shock release?

Answer

By Equation 25.1:

$$\frac{E_1}{E_2} = 10^{1.5\,(7.8-7.3)} = 10^{0.75} \approx 5.6$$

The main shock released **about 5.6 times** as much energy. Half a step of magnitude is more than five times the energy.

YOUR TURN

25.1 The Higgs field

What is the Higgs field, and how does it relate to mass?

Answer

The **Higgs field** is an invisible field that fills the whole universe. Fundamental particles get their mass by interacting with it: the more strongly a particle interacts with the field, the greater its mass. Particles that don't interact with it, such as the photon, have no mass.

Property	P wave (primary)	S wave (secondary)	Rayleigh wave	Love wave
Type	longitudinal (compression)	transverse (shear)	surface wave, rolling	surface wave, horizontal transverse
Speed	fastest, about 6–8 km/s	about 3–4.5 km/s	slowest	a little faster than Rayleigh
Motion of the ground	along the direction of travel	at right angles to the direction of travel	elliptical rolling: up and down and back and forth	side to side, horizontal
Travels through	solids, liquids and gases	solids only	along the Earth's surface (solids only)	along the Earth's surface (solids only)
Arrives	first	second	after P and S waves, last	after P and S waves, before Rayleigh
Damage	least	more than P waves	heavy: most of the ground's heaving	heavy: strong sideways shaking of foundations
Felt as	a sharp jolt	stronger shaking, up and down and sideways	the ground rolling, like a boat	the ground jerking sideways

Check 1

At a seismograph 300 km from an earthquake, which arrive first?

a. the P waves, then the S waves, then the surface waves
b. the S waves, then the P waves, then the surface waves
c. the surface waves, because they travel along the shortest path
d. all of them at once, since they leave the focus together

25.2 Gorkha earthquake 2015

On **25 April 2015**, at 11:56 Nepal time, an earthquake of **moment magnitude 7.8** struck under **Barpak** in Gorkha district, about 80 km northwest of Kathmandu. It began at a shallow depth, about 8 km by the U.S. Geological Survey's estimate (other estimates put it nearer 15 km), and a **shallow-focus earthquake** shakes the surface above it hard.

It ruptured about **150 km** of the **Main Himalayan Thrust** (MHT), the great fault along which the Indian Plate slides under the Eurasian Plate. The rupture spread mostly **eastward**, under Kathmandu and beyond, and the shaking was felt across Nepal and far into India, Tibet and Bangladesh. The main shock lasted about **50 to 60 seconds**, longer and stronger than any of the aftershocks that followed: more than 400 of magnitude 4 or more in the following months, the largest of magnitude **7.3 on 12 May 2015**, near Dolakha.

The seismic waves arrived as expected for the Himalaya's rocks:

- **P waves** at 5.0–8.0 km/s,
- **S waves** at 3.0–4.5 km/s,
- **surface waves** (Love and Rayleigh), slower, about 2.0–3.5 km/s, but with the largest swings at the surface.

Scientists had long feared that an earthquake this size would flatten much of the Kathmandu Valley. The damage there, though terrible, was less than feared. The rupture slipped smoothly, so it sent out less of the quick, jerky shaking that breaks low brick and stone houses than expected, and the valley's soft lake-bed sediments shook mostly in a slow sway, about once every four to five seconds. That slow sway was hardest on tall structures, which sway slowly themselves, such as the nine-story Dharahara.

Key seismic parameters

1. **Magnitude:** 7.8 (moment magnitude, M_w).
2. **Epicenter:** Barpak, Gorkha district (28.23° N, 84.73° E).
3. **Depth of the focus:** about 8 km (shallow); estimates range up to 15 km.
4. **Fault type:** a thrust fault, the Main Himalayan Thrust.
5. **Duration of shaking:** 50–60 seconds.

Pattern of energy release and aftershocks

1. The earthquake occurred on the Main Himalayan Thrust, the collision zone between the Indian Plate and the Eurasian Plate.
2. The rupture spread eastward from Gorkha, under Kathmandu and beyond.
3. A strong aftershock of magnitude 7.3 struck on 12 May 2015, near Dolakha.
4. More than 400 aftershocks of magnitude 4.0 and above were recorded over the following months.

Effects of the earthquake

1. Nearly 9,000 people died, and about 22,000 were injured.
2. Hundreds of thousands of homes, and thousands of schools and health posts, were destroyed or damaged, worst in Gorkha, Sindhupalchowk, Nuwakot, Dhading, Rasuwa, Dolakha and the Kathmandu Valley.
3. The earthquake set off an avalanche from Pumori onto Everest Base Camp, killing at least 22 people, and an avalanche of ice and rock that buried the village of Langtang.
4. Historic landmarks, Dharahara and many temples and monuments in the Durbar Squares of Kathmandu, Patan and Bhaktapur, were damaged or reduced to rubble.

The Gorkha earthquake showed how powerful the tectonic forces under the Himalaya are, and how shallow thrust earthquakes put the whole region at risk. It also showed the resilience of Nepal's people, and the importance of being prepared: earthquake-resistant buildings, safe schools, drills, and early warning systems. (Going Further, Can you design an earthquake-safe house?, shows how buildings are made to survive.)

Worked examples

WORKED EXAMPLE

25.1 Gravitational waves

Define gravitational waves and list two major events that can produce them.

Answer

Gravitational waves are ripples in space-time caused by violent events in space, such as massive objects accelerating. They travel at the speed of light. Two major sources: a) **collisions of black holes** (or neutron stars), and b) **explosions of stars** (supernovae).

WORKED EXAMPLE

25.2 The Gorkha earthquake

What were the magnitude and the epicenter of the Gorkha earthquake of 2015?

Answer

It had a **moment magnitude of 7.8**. Its epicenter was **Barpak, in Gorkha district**, about 80 km northwest of Kathmandu.

WORKED EXAMPLE

25.3 P waves and S waves

Distinguish between P waves and S waves in their motion and speed.

Answer

	P waves (primary)	S waves (secondary)
Type	longitudinal	transverse
Motion of the rock	along the direction of travel	at right angles to the direction of travel
Speed in the crust	fastest, 6–8 km/s	slower, 3–4.5 km/s
Travel through	solids, liquids and gases	solids only

WORKED EXAMPLE

25.4 The Higgs boson

What is the Higgs boson, and why is it important in physics?

Answer

The **Higgs boson** is a fundamental particle that goes with the Higgs field, which fills all space. It was proposed by Peter Higgs and others in 1964. It matters because the Higgs field explains how fundamental particles get their mass, and its discovery at CERN in 2012 confirmed the last missing piece of the Standard Model of particle physics.

Test yourself

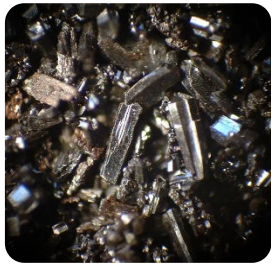


Figure 25.10 *Crystals of fullerene, C_{60}. Each molecule is a ball of 60 carbon atoms about 0.7 nm across.*

Photo: Fotograf: Jochen Gschnaller, CC BY-SA 3.0

Uses of nanotechnology

1. **Medicine:** nanoparticles carry drugs straight to the cells that need them, especially in cancer treatment, so less of the drug harms healthy cells.
2. **Diagnosis:** faster and more accurate tests for disease. The lines on a rapid test (for pregnancy or COVID-19) are made red by gold nanoparticles.
3. **Electronics:** the transistors in a modern chip are a few tens of nanometers across, so billions fit on a chip, making devices faster, more efficient and smaller.
4. **Solar panels** made more efficient at turning sunlight into electricity.
5. **Batteries** that charge faster and last longer.
6. **Water purification:** nano-filters remove bacteria and harmful substances.
7. **Textiles:** clothes made waterproof, stain-resistant and antibacterial.
8. **Food packaging** that keeps food fresh longer and detects spoiling.
9. **Construction materials** made stronger and lighter.
10. **Cosmetics:** nanoparticles of zinc oxide and titanium dioxide in sunscreens block ultraviolet light while looking clear on the skin, and are used in creams for better absorption.

Like any new technology, it needs care: particles so small can get into the lungs and cells, so the safety of each nanomaterial has to be tested.

Check 2

Which of these is about 1 nm across?

a a bacterium
b a red blood cell
c a buckyball, a molecule of 60 carbon atoms
d the width of a human hair



Figure 25.4 *All that was left of Dharahara, Kathmandu, after the earthquake of 25 April 2015. A new Dharahara was built beside the stump and inaugurated in 2021.*

Photo: Parazlaure, CC BY-SA 3.0

DID YOU KNOW?

Why Kathmandu shook for so long

The rupture started under Barpak and ran east at about 3 km/s: the slipping fault itself took about 25 seconds to come under the Kathmandu Valley, sending out waves all the way. So people in Kathmandu felt the shaking grow for a long time, rather than a single jolt from far away.

YOUR TURN

The gap between the waves

A seismograph in Kathmandu is about 80 km from the focus of an earthquake. Taking the P waves' speed as 6 km/s and the S waves' as 3.5 km/s, how long after the P waves do the S waves arrive?

Hint

Find each wave's travel time, $t = \dfrac{d}{v}$, and subtract.

Answer

P waves: $t_P = \dfrac{80}{6} = 13.3$ s. S waves: $t_S = \dfrac{80}{3.5} = 22.9$ s.
The S waves arrive **about 9.5 s** after the P waves. That gap is what an earthquake warning on a phone uses: the P waves are recorded near the focus, and a radio warning, at the speed of light, can reach a city before its S and surface waves do.

25.3 Gravitational waves

Gravitational waves are tiny ripples of space and time themselves, made by some of the most violent events in the universe, such as black holes or neutron stars colliding, or a star exploding. They spread out from their source in all directions at the **speed of light**, carrying information about what made them.

The idea was first put forward by **Albert Einstein** in **1916**, from his general theory of relativity: space and time together, **space-time**, are bent by mass, and massive objects accelerating should disturb it so that ripples spread out, like ripples from a stone thrown into water. A passing wave

stretches space in one direction and squeezes it in the direction at right angles, back and forth (Grade 11, Gravitational waves).

For almost a century they stayed a prediction, because by the time they reach us they are unbelievably weak. Then, on **14 September 2015**, the two detectors of **LIGO**, the Laser Interferometer Gravitational-Wave Observatory in the USA, detected one for the first time. It came from two black holes, of about 36 and 29 times the Sun's mass, merging about **1.3 billion light years** away. **Rainer Weiss, Barry Barish and Kip Thorne** won the 2017 Nobel Prize in Physics for the detection.

How LIGO hears a wave

LIGO is a giant **interferometer**, the same idea as Michelson's in Interference of Light. A laser beam is split in two, and the halves travel along two arms, each **4 km** long, at right angles, bounce off mirrors and come back to be recombined (Figure 25.5). The arms are set so that the two returning waves cancel: no light reaches the detector. A passing gravitational wave stretches one arm while it squeezes the other, so the two light waves no longer arrive exactly out of step, and light flickers onto the detector.

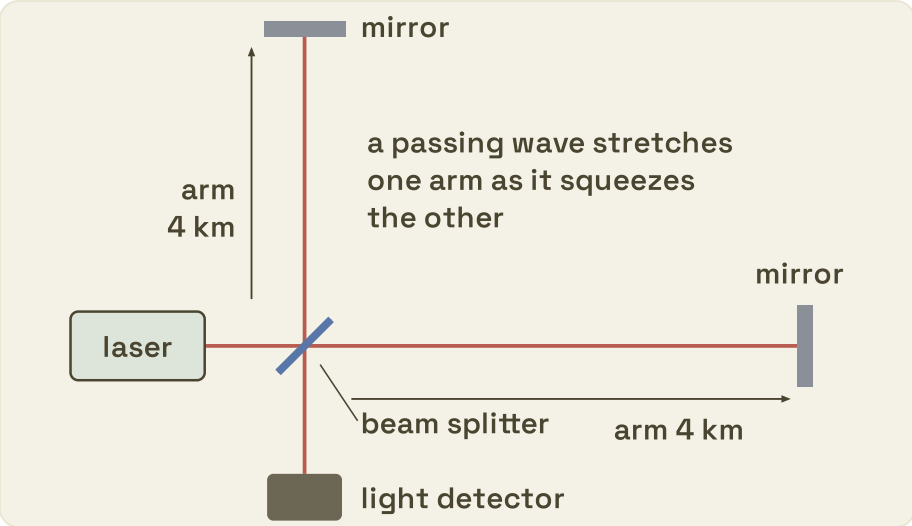


Figure 25.5 *LIGO seen from above. The laser beam is split in two, sent down two 4 km arms at right angles and back, and recombined at the detector. A passing gravitational wave changes the arms' lengths in opposite directions. Not to scale; in the real detector the light also bounces back and forth about 300 times in each arm.*

The change is tiny: the first wave changed each 4 km arm by a few times 10^{-18} m, a few thousandths of the width of a proton. To be sure a signal is real, LIGO has two detectors 3000 km apart, in Hanford, Washington, and Livingston, Louisiana; a real wave reaches both within 10 milliseconds (the time light takes to cross the distance), while a passing truck shakes only one.

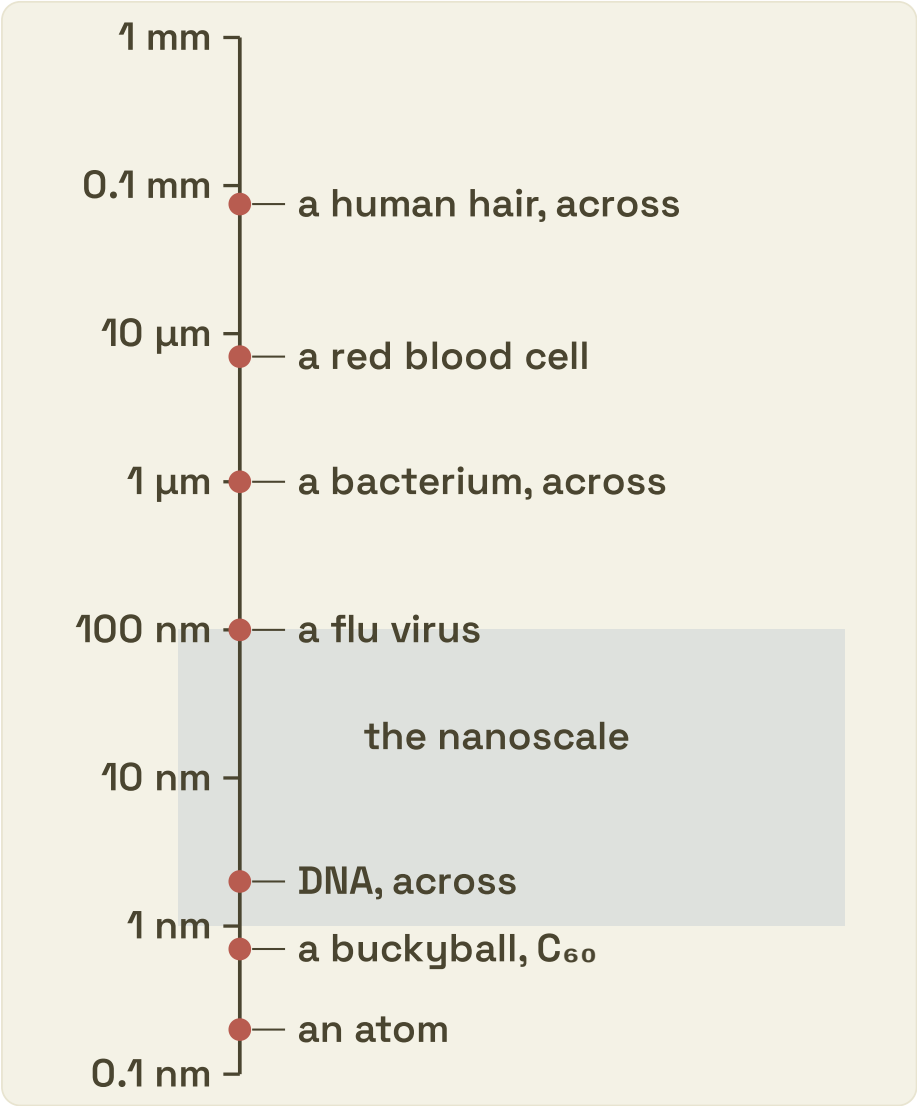


Figure 25.9 *Sizes from a millimeter down to an atom. Each step down the scale is ten times smaller. Nanotechnology works in the shaded band, from 1 to 100 nm.*

25.5 Nanotechnology

Nanotechnology is science and engineering with matter on an extremely small scale, between **1 and 100 nanometers** (nm). One nanometer is a billionth of a meter, $1\ \text{nm} = 10^{-9}$ m: a strand of human hair is about 50,000 to 100,000 nm wide, and a row of five to ten atoms is 1 nm long (Figure 25.9). At this scale scientists work with individual atoms and molecules to make new materials, tools and devices.

Nanotechnology lets us build structures and machines thousands of times narrower than a hair, with properties ordinary pieces of the same material don't have. Two things change at that scale. A tiny particle has a very large surface for its volume, so more of its atoms are at the surface, where reactions happen: nanoparticles make far better catalysts. And for a particle only a few nanometers across, quantum effects change how it absorbs and gives out light: gold nanoparticles are red, and particles of a semiconductor glow in different colors just by their size. This is changing medicine (drugs carried to a tumor, sensitive tests), electronics (smaller, faster chips), energy (better solar cells and batteries), food safety and environmental science.

History of nanotechnology

- **1959:** the American physicist **Richard Feynman** gave a famous lecture, "There's Plenty of Room at the Bottom", imagining machines that place atoms and molecules one by one, and writing a whole encyclopedia on the head of a pin. (The word *nanotechnology* was coined in 1974 by the Japanese engineer Norio Taniguchi.)
- **1981:** Gerd Binnig and Heinrich Rohrer, at IBM in Zurich, built the **scanning tunneling microscope** (STM), which feels a surface with a needle so sharp it ends in a single atom, and shows the individual atoms. It won the 1986 Nobel Prize in Physics. In 1989, IBM scientists used one to move 35 xenon atoms on a nickel surface to spell "IBM".
- **1985:** Harold Kroto, Robert Curl and Richard Smalley discovered **fullerene**, C_{60}, a hollow ball of 60 carbon atoms joined in hexagons and pentagons like a football (Nobel Prize in Chemistry 1996). It opened up new forms of carbon nanomaterials: carbon nanotubes (1991) and graphene, a sheet of carbon one atom thick (Nobel Prize in Physics 2010).



Figure 25.6 *The LIGO detector at Livingston, Louisiana, from the air. Each arm is 4 km long.*
Photo: Caltech/MIT/LIGO Laboratory, Public domain

Causes of gravitational waves

Gravitational waves are produced whenever huge masses accelerate. The ones strong enough to detect come from:

1. a **supernova**, an exploding star, if it explodes unevenly;
2. two **neutron stars** orbiting each other;
3. two **black holes** spiraling together and merging.

Because these events are so far from the Earth, the waves that reach us are extremely weak, and only very sensitive detectors such as LIGO can notice them.

Key points to remember

1. They are ripples of space-time itself, sent out by violent events far away.
2. They spread out in every direction at the speed of light.
3. Einstein predicted them in 1916; LIGO first caught one in 2015.
4. They give astronomers a new sense, **gravitational-wave astronomy**, for events that give out little or no light, such as black holes merging.

Types of gravitational waves

Scientists sort the waves they look for into four kinds, by their source and the signal it makes.

1. **Continuous gravitational waves** would come from a single spinning, slightly lopsided object, such as a neutron star with a tiny bump on its surface. They would have a steady frequency and go on for years, so a long search can add up a signal too weak to see at once. None had been detected by 2026: they are expected to be far weaker than the waves from collisions.
2. **Burst gravitational waves** come from short, violent events whose signal can't be predicted in detail, such as a supernova. Because their shape isn't known in advance, they are hard to pick out from the detectors' noise. None had been detected by 2026; a supernova in our own galaxy could be heard.
3. **Stochastic gravitational waves** are a random background "hum" from very many sources all over the universe, too many to tell apart, and perhaps also from the first moments after the Big Bang. In 2023, astronomers timing the steady flashes of pulsars found the first evidence of such a background, with waves years long, probably from pairs of giant black holes in the centers of galaxies.

4. **Compact binary inspiral gravitational waves** come from two compact objects, black holes or neutron stars, spiraling toward each other: two neutron stars (BNS, binary neutron stars), two black holes (BBH) or one of each (NSBH). As they come closer they orbit faster, so the waves' frequency and strength rise together into a **chirp**, then stop when the two merge. Each kind of pair gives its own waveform, but they all follow the same pattern. These are the only gravitational waves the detectors had caught by 2026: hundreds of them since 2015.

Together, these four kinds of wave give a new way to explore the most extreme places in the universe.

DID YOU KNOW?

Gold from a collision

On 17 August 2017, LIGO and its European partner Virgo heard two **neutron stars** merge, 130 million light years away. Within two seconds, a space telescope saw a flash of gamma rays from the same part of the sky, and telescopes all over the world then watched the glowing cloud the collision threw out. Its glow, fading over days and reddening as it faded, showed that it was full of freshly made heavy elements; astronomers worked out that the cloud held about ten times the Earth's mass of gold and platinum alone. Much of the gold in the world, perhaps the gold in a necklace, was probably made in collisions like this. And since the waves and the light arrived together after 130 million years, gravitational waves must travel at the speed of light.

25.4 Higgs boson

The **Higgs boson**, nicknamed the "God particle" (after a popular book; most physicists dislike the name), was among the great discoveries of physics in this century. It is the fundamental particle that goes with the **Higgs field**, an invisible field that fills the whole universe. In the Standard Model of particle physics, the Higgs field is what gives the fundamental particles their mass.

Particles that interact with the Higgs field gain mass: the more strongly a particle interacts with it, the more massive it is. The photon doesn't interact with it at all, so it has no mass and travels at the speed of light; the electron interacts weakly, so it is light; the top quark interacts strongly, so it is about as heavy as a gold atom. A picture often used: a famous person crossing a room crowded with admirers is slowed by the crowd that gathers round, and is harder to get moving and to stop, as if heavier; someone unknown crosses easily. (Like every picture of quantum physics, it isn't exact: mass is not a drag that slows a moving particle, but a resistance to changes in its motion.)

The particle was predicted in **1964** by Peter Higgs and others. It was not found until **2012**, because it is heavy, about 125 GeV, 133 times the proton's mass, and lasts less than 10^{-21} s before decaying. Scientists at **CERN** (the European Organization for Nuclear Research) made it in head-on collisions of protons in the **Large Hadron Collider** (LHC), the biggest and most energetic particle accelerator ever built, a ring 27 km round under the border of Switzerland and France. On 4 July 2012, the two great detectors there, ATLAS and CMS, each announced that they had seen it, by the particles it decays into.

The discovery completed the Standard Model and won the 2013 Nobel Prize in Physics for **Peter Higgs and François Englert**. Studying the Higgs boson tells scientists why matter has mass and how nature works at its smallest scale, and it opens the door to physics beyond the Standard Model, such as the nature of dark matter and what happened just after the Big Bang. The LHC is still measuring it, to see whether it behaves exactly as the theory says.

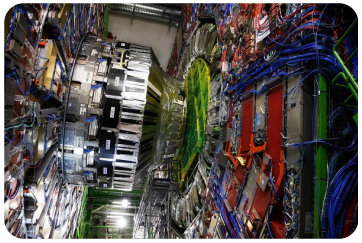


Figure 25.7 *The CMS detector at CERN, one of the two detectors that found the Higgs boson, opened up for work. It is 15 m tall and weighs 14,000 tonnes.*

Photo: Simon Waldherr, CC BY-SA 4.0

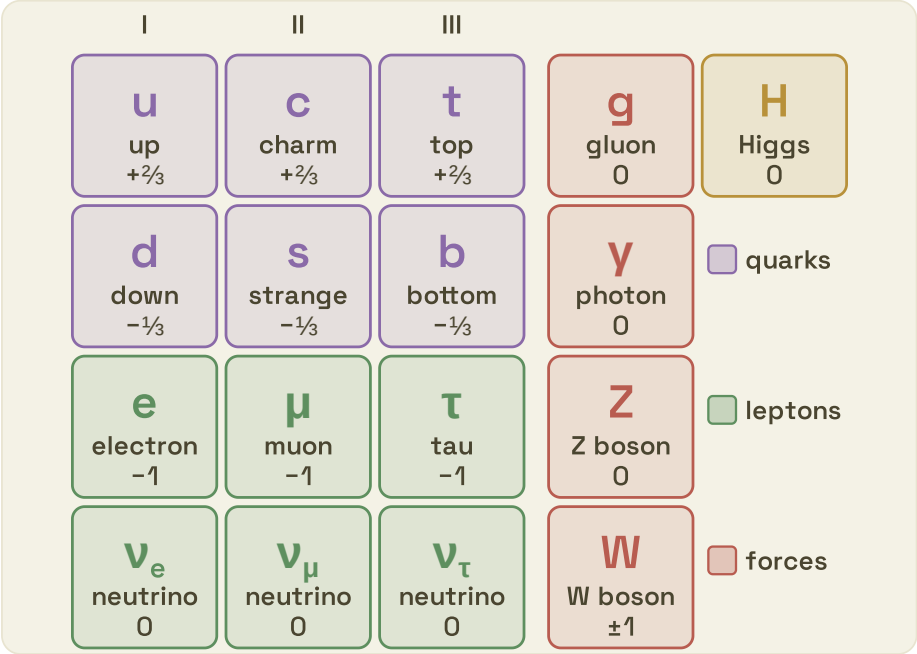


Figure 25.8 *The fundamental particles of the Standard Model: six quarks, six leptons, the force-carrying bosons and the Higgs boson.*

DID YOU KNOW?

Most of your mass isn't from the Higgs

The Higgs field gives mass to electrons and to quarks. But the three quarks in a proton add up to only about 1% of the proton's mass. The other 99% comes from the energy of the quarks and of the gluons that hold them together, by $E = mc^2$. So almost all of your mass comes from the strong force's energy inside protons and neutrons; the Higgs field's share is about 1%. Without it, though, electrons would have no mass, and atoms could not exist.