
A Fragile System?

## OVERVIEW

Natural cataclysmic events affect the Earth every day, and are a normal part of the Earth-ocean-atmosphere system. However, these same events (landslides, earthquakes, hurricanes, tsunami, etc.) can kill people or reduce the quality of life. This dichotomy motivates the title for this Module: Is the Earth a fragile system?

To address this question, you start by reviewing the metrics used to describe our world. You next look at the materials that make up the Earth, ocean, and atmosphere. Natural processes can be disasters because of their tremendous energy release, so you will review the types of energy. Some disasters such as earthquakes and tsunami propagate as waves, which you will study. With this background, you will examine the relationship between population growth and the societal impact of natural disasters, and make your own decisions about whether the Earth is a fragile system.

**INSTRUCTIONS and QUIZ**

Study and make notes based on the following Course Notes and the textbook reading assignments. The Learning Goals will allow you to assess your understanding of the key concepts.

This Module will be covered in the Fragile Systems (FS) Quiz. Consult the FAQs for information on taking the Quizzes.

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## LEARNING GOALS

The goal of this Module is to prepare you for the Modules that follow; namely, to help you understand the basic concepts used to describe different disasters, and to help you put disasters into perspective.

Use the following learning goals as a self-assessment tool to help you gauge your understanding of the course material presented in this Module.

After you complete this Module you will be able to:

1. Explain what density is and how it relates to stratification.
2. Explain why disaster scales are based on the Order-of-Magnitude concept and interpret graphs with logarithmic scales.
3. Relate natural-disaster risk and intensity to frequency, return period, and consequences (costs).
4. Explain how recent disasters were associated with the concentration or dilution of energy.
5. Get the disaster info you need from reliable sources.
6. List the 1st and 2nd most common elements in the Earth, ocean, and atmosphere.
7. Describe how viscosity and compressibility relate to the phase of matter.
8. Be able to diagnose the type of strain by the way a material deforms.
9. Explain why gravity affects motion and energy.
10. List the 5 types of energy, and describe what causes them to vary.
11. Explain (with examples) how energy conservation applies to natural disasters.
12. Describe relationships between force, pressure, stress, strain, energy, and power.

13. Describe population growth and explain why it is important for natural disasters.
14. Explain how Earth's carrying capacity and overpopulation are related to the fate of the human race, and anticipate your role in it.

## ORGANIZATION

A Fragile System? contains five units (A - E) that span the objectives listed above.

| UNIT | TOPIC |
|---|---|
| A | Natural Disasters are Rare Events |
| B | Materials |
| C | Energy |
| D | Waves and Turbulence |
| E | Is the Earth a Fragile System? |

## READINGS: A Fragile System?

Read all of **Chapter 1. A Global and Canadian Outlook on Natural Disasters**
Read the following sections of **Chapter 2. Energy Flows**:

- Energy sources of natural hazards (page 24)
- In Greater Depth: Energy, force, work, power, and heat (page 25)
- In Greater Depth: Material deformation (pages 30-31)
- Isostasy (pages 31-32)
- Internal sources of energy (pages 32-33)
- External sources of energy (pages 33-34)
- The rock cycle (pages 45-46)

Important Notes:
a) Don't memorize any Tables but understand the main points that the Tables illustrate.
b) Figures contain very important information, too! Read the captions and understand the ideas being illustrated

| UNIT | TOPIC |
|---|---|
| A | Natural Disasters are Rare Events |

## OUTLINE

Recall that the goal of this Module is to prepare you for the Modules that follow; namely, to help you understand the basic concepts used to describe different disasters, and to help you put disasters into perspective. So lets jump right in and review some of the metrics used to measure our world, and how to quantify the intensity of disasters and their frequency of occurrence.

1. SI magnitude prefixes

2. Time measures
3. Distance (space) measures
4. Mass (matter) measures
5. Density
6. Stratification
7. Quantifying Rare Events
8. Disaster Scales
9. Intensity vs. Frequency

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## 1. Magnitude Prefixes

The **International System of Units (SI)** specifies the following prefixes to represent various multiples or magnitudes:

| | | | | |
|---|---|---|---|---|
| k | = kilo | = thousand | = 1,000 | = $1 \times 10^{3}$ |
| M | = mega | = million | = 1,000,000 | = $1 \times 10^{6}$ |
| G | = giga | = billion | = 1,000,000,000 | = $1 \times 10^{9}$ |
| T | = tera | = trillion | = 1,000,000,000,000 | = $1 \times 10^{12}$ |
| | | | | |
| c | = centi | = hundredth | = 0.01 | = $1 \times 10^{-2}$ |
| m | = milli | = thousandth | = 0.001 | = $1 \times 10^{-3}$ |
| μ | = micro | = millionth | = 0.000001 | = $1 \times 10^{-6}$ |
| n | = nano | = billionth | = 0.000000001 | = $1 \times 10^{-9}$ |

***FAMILIAR EXAMPLES INCLUDE***:

- 1 kilometre = a thousand metres
- 1 gigabyte = a billion bytes

To learn more about prefixes and SI units, see http://en.wikipedia.org/wiki/SI

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## 2. Time

The **SI** standard for time is the **second** (s).

Other non-SI time units (but accepted for use with SI) derived from this standard include:

- 1 **minute** (min) = 60 s
- 1 **hour** (h) = 60 min
- 1 **day** (d) = 24 h

We also frequently use other time units that are not standard (i.e., can vary):

- 1 **year** (yr) = 365.25 d (approximately; consider year and leap years.) (Note: often we use the word **annum** with its abbreviation (**a**) in place of **year**.)

- 1 **millennium** = 1000 yr = 1000 a

We can use these time units and prefixes to describe some important events in the Earth's evolution:

- Age of Earth = 4.57 billion years = 4.57 Ga
- Age of oceans = 4.3 Ga
- Age of present ocean basins = 200 million years = 200 Ma (when supercontinent **Pangaea** broke-up into the present-day continents)
- Time before present when life begins = 3.8 Ga

Time can also be used to quantify how many disasters involve a sudden release of large amounts of energy, even though the energy supply is initially very slow. Thus the energy must first be concentrated, but this takes time. In the examples in the table below, the build-up time is greater than the release time.

**Table FS.1 Time scale of build up and release of energy during natural disasters**

| DISASTER | BUILD-UP | RELEASE |
|---|---|---|
| Earthquakes | years | minutes |
| Volcanoes | decades | days |
| Hurricanes | months | days |
| Thunderstorms | hours | minutes |
| Rogue waves | hours | seconds |
| Landslides | days | seconds |
| Meteor Impact | millennia | seconds |

Some of the disasters above inject so much energy in a short time, that subsequent events are triggered over longer times that can still be devastating. Namely, even after spreading or dilution of the initial energy release, the effects can still threaten lives and property:

**Table FS.2 Timescale of build up and release of energy during disaster events**

| INITIAL CAUSE | DISASTER | BUILD-UP | RELEASE |
|---|---|---|---|
| Earthquake | Tsunami | minutes | hours |
| Thunderstorm | Floods | hours | days |

Namely, for these cases the build-up time is less than the release time.

Later in the course, we will study some other disasters such as:

- Storm surges
- Lahars

After you study these, think about the relevant time scales.

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## 3. Space or Distance

The SI standard unit of distance is the **metre** (m).

Although there are no derived units with special names, we commonly use metres prefixed with a magnitude:

| | | | |
|---|---|---|---|
| 1 micrometre | = 1 μm | = 1 m / 1 million | = $10^{-6}$ m |
| 1 millimetre | = 1 mm | = 1 m / 1 thousand | = $10^{-3}$ m |
| 1 kilometre | = 1 km | = 1,000 m | = $10^{3}$ m |

We can use distance units to describe some typical scales of features on Earth:

- Earth radius: 6357 km
- Atmospheric thickness:
    - The bottom portion (**troposphere**) that has the storms: 11 km
    - To the top of the atmosphere (**exosphere**): 550 km
- Ocean depth:
    - Average depth: 4 km
    - Deepest portions, such as the Mariana Trench: 11 km
- Air molecule: 0.001 μm = $10^{-9}$ m

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## 4. Mass

Mass is what things are made of. It is **matter**.

The SI standard unit of mass is the **kilogram** (kg). Derived units include:

- 1 **gram** (g) = 0.001 kg (this is the only SI unit where the prefix "kilo" is on the standard)

A non-SI mass unit that is accepted for use with SI is:

- 1 **tonne** (t) = 1000 kg (also sometimes called a metric ton).

A range of typical mass scales is illustrated by:

- mass of Earth: $5.97 \times 10^{24}$ kg
- mass of air molecule: $4.8 \times 10^{-26}$ kg

> ***CAUTION***: Sometimes in science, the same letter or symbol is used to abbreviate two or more different things (due to the limited number of letters and symbols available). For example, sometimes we let the **variable** called mass have the abbreviation "*m*". Other times, we use the abbreviation "m" to represent the **unit** of distance. This can be very confusing, and often can be resolved only from the context in which it is used.
>
> To help distinguish between **variables** and **units**, publishers often use *italic* fonts for

variable names, and normal (roman) fonts for units. For example, the following equation, which we will study later in this course, has both variables and units:

$$F\ (\mathrm{m\ kg\ s^{-2}}) = m\ (\mathrm{kg}) \cdot a\ (\mathrm{m\ s^{-2}})$$

and could be confusing because "m" is used one place as a unit and another place as a variable.

## 5. Density

Density is defined as mass per unit volume. It describes how much mass fits into a space. To help visualize volume, recall that a cubic metre ($m^3$) is roughly the size of a large fish tank or a large cardboard box. This variable is sometimes given the symbol **ρ** or ***d***.

Its units are $kg/m^3$, which is sometimes written as $kg\text{-}m^{-3}$.

For comparison materials with different densities:

| | | |
|---|---|---|
| density of iron | $= \rho_{iron}$ | $= 7870\ kg / m^3$ |
| density of ocean water | $= \rho_{ocean\ water}$ | $= 1025\ kg / m^3$ |
| density of air | $= \rho_{air}$ | $= 1.2\ kg / m^3$ |

***CHECK YOUR UNDERSTANDING***: A solid iron cannon ball will sink when immersed in a fluid.

A) Yes
B) No
C) not enough info to answer

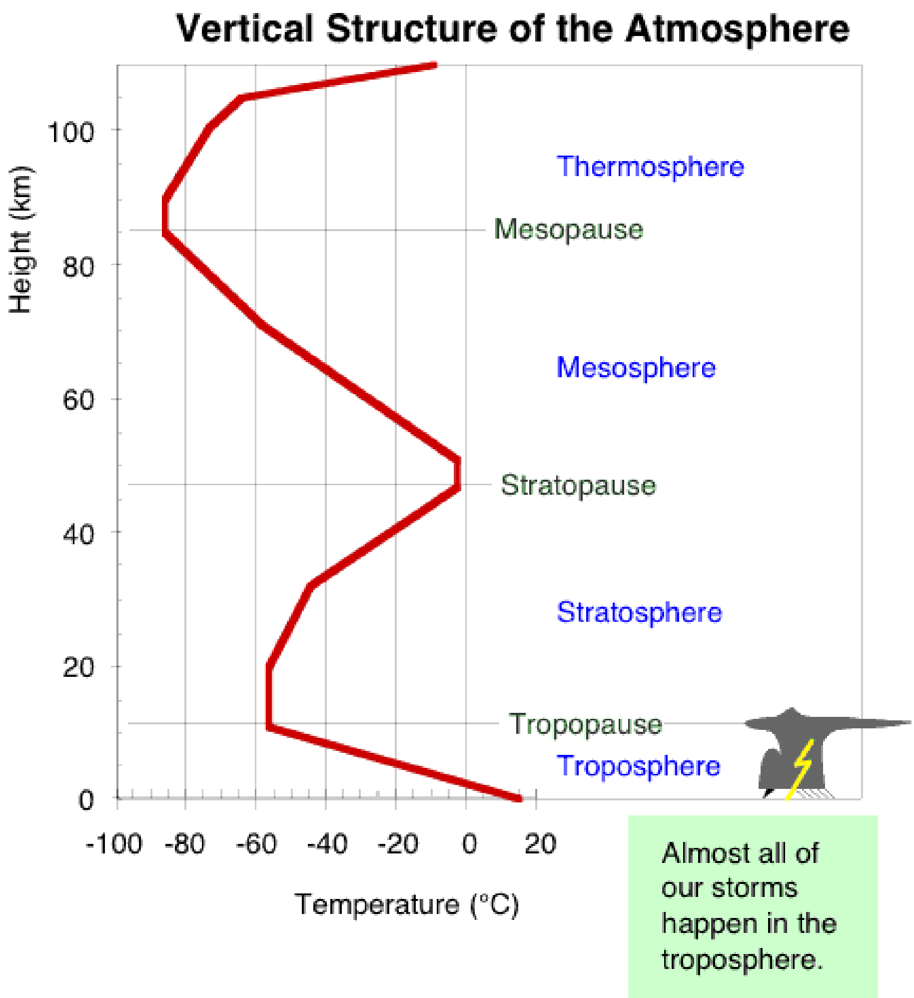
## 6. Stratification

Density is important because less-dense materials float on top of denser materials, in the presence of gravity. For example, cream floats on milk. Oil floats on water. Steel floats on mercury. Fresh river water floats on top of salty ocean water. Continental crust (rocks that make up the continents) floats on top of oceanic crust (rocks that make up the sea floor).

When more than two different materials are mixed together, the least dense floats to the top, the most dense sinks to the bottom, and the other materials form middle layers that are segregated such that density increases as you go downward. The end result is a **layering** of materials. Namely, the materials are **stratified** into layers.

Over the long periods of geologic time, the materials that make up the earth have also become stratified. The most obvious is that the least dense (air) floats to the top, and the most dense (rocks) sinks to the bottom, leaving the middle-density materials (ocean) in the middle. But even within the atmosphere, the ocean, and the Earth, there is also stratification. The resulting layers are given names:

A. ***Atmosphere*** (listed from the top down)




As shown in the figure on the left, the tops of each layer also have names, such as the **tropopause** at the top of the troposphere.

- Exosphere (where hydrogen and helium escape to space; NOT shown in Figure)
- Thermosphere
- Mesosphere
- Stratosphere
- Troposphere (the layer containing storms)

**Figure FS.1 The vertical temperature profile of the Earth's Atmosphere and its layers.**

B. ***Ocean*** (listed from the top down)

- Surface zone / mixed layer
- Intermediate layer(s)
- Deep / abyssal / bottom layer

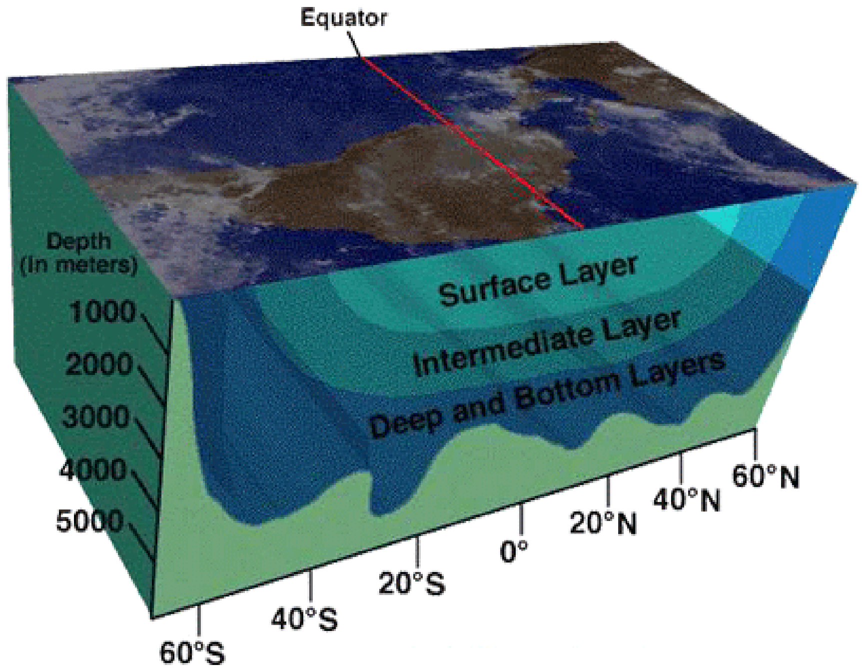



**Figure FS.2 Stratification in the oceans is driven by changes in temperature and salinity, which determine seawater density.**

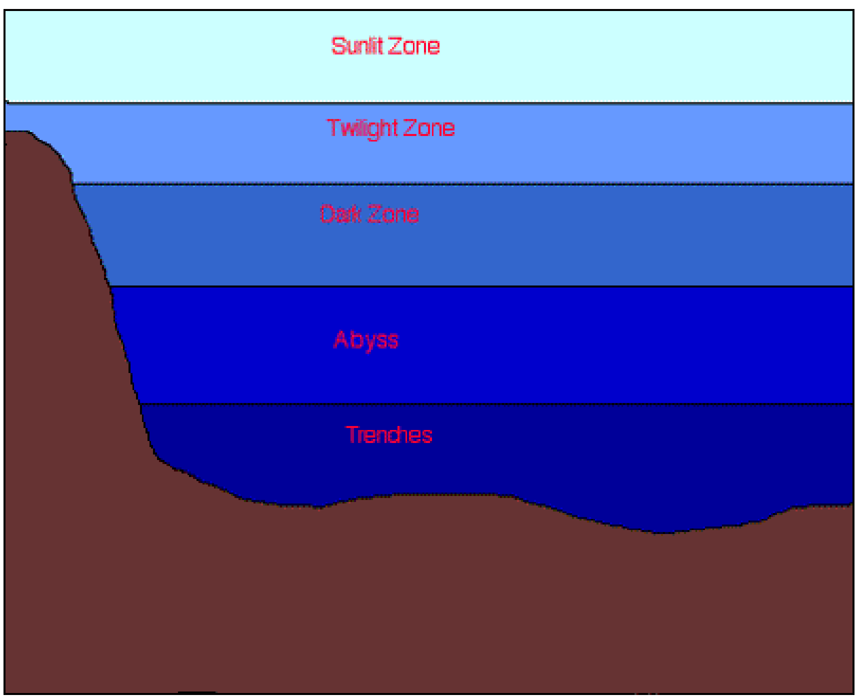



**Figure FS.3 Ocean layers based on availability of light.**

There are many other names for layers in the ocean. One series is based on the amount of light that reaches different layers (Figure on the left). The amount of available light determines the ecological layering.

- Sunlit zone
- Twilight zone
- Dark zone
- Abyss
- Trenches

and another based on their ecological characteristics (Figure on the right).

- Epipelagic zone

- Mesopelagic zone
- Bathypelagic zone
- Abyssopelagic zone
- Hadalpelagic zone

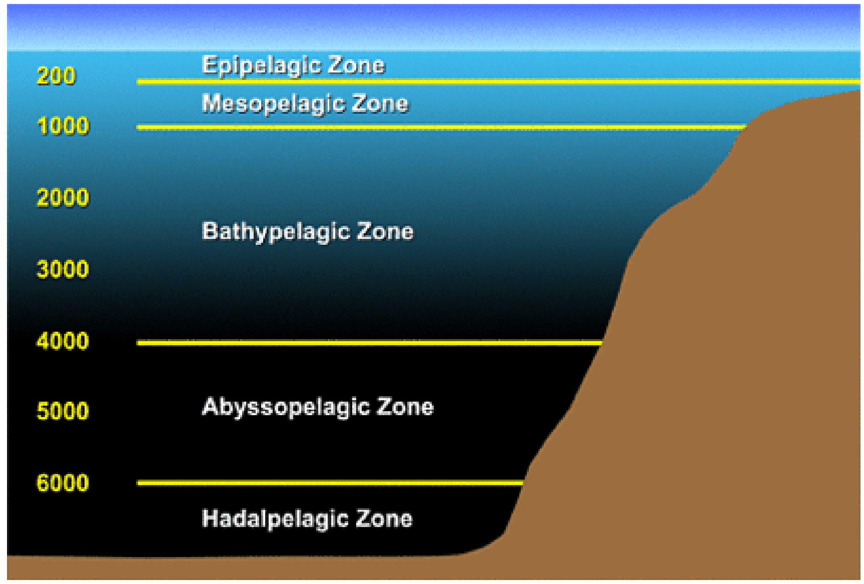



Figure FS.4 Ocean layers based on ecological parameters.

C. ***Earth*** (listed from the top down)

- Lithosphere (solid, crust)
- Asthenosphere (plastic rock)
- Mesosphere (solid rock)
- Outer core (liquid metal)
- Inner core (solid metal)

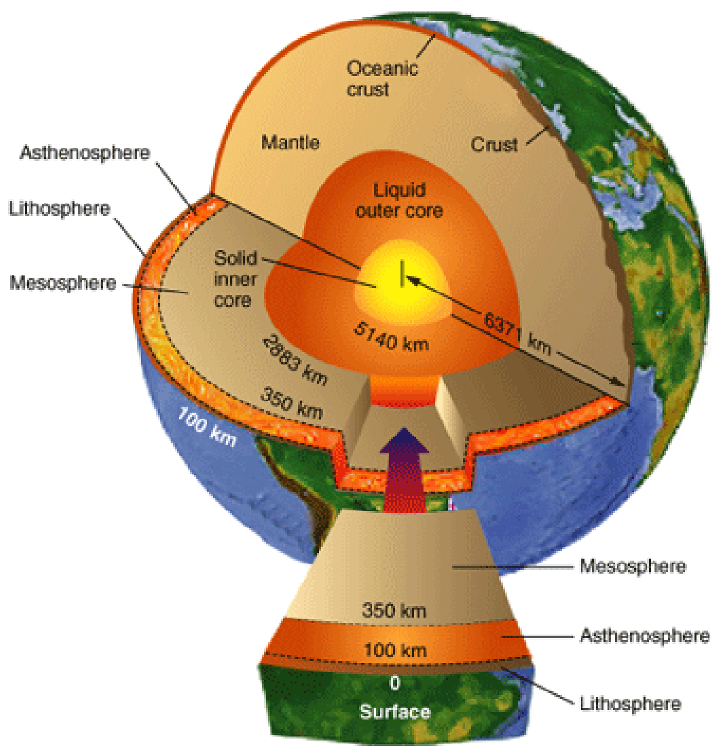



Figure FS.5 Earth's internal layers based on chemical and physical characteristics.

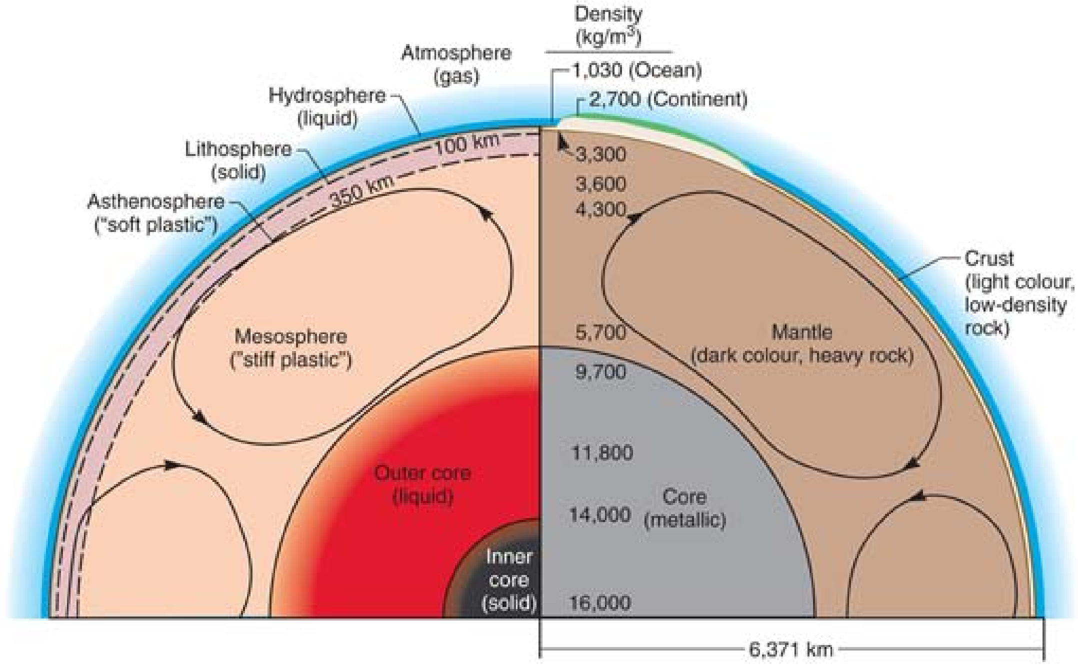



**Figure 2.6**

Density stratification within the Earth, that is, lower-density materials float atop higher-density materials. Pressure and temperature both decrease from the centre of the Earth to the surface. Layers illustrated on the left show the differences in physical properties and strengths. Layers on the right emphasize different mineral and chemical compositions. Arrows indicate large convection cells.

There are also other names for Earth layers as shown in *Figure 2.6 of Abbott and Samson, 2012* (above):

- Crust
- Mantle
- Core

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## 7a. Quantifying Rare Events: Intensity

The phrase "**order of magnitude**" means something very specific in science. It means "power of ten". For example, if the number of students on the UBC-Vancouver campus is an **order of magnitude greater** than the number of students on the UBC-Okanagan campus, it means that the Vancouver campus has ten times as many students as at the Okanagan campus. Namely, if there are 4,000 students at the Okanagan campus, then there are 40,000 students at the Vancouver campus.

We could also say that the Okanagan campus has an **order of magnitude smaller** enrolment than the Vancouver campus. Namely, it has one tenth the enrolment.

Consider the following list of numbers:

$10^0$ = 1

$10^1$ = 10

$10^2$ = 10x10 = 100

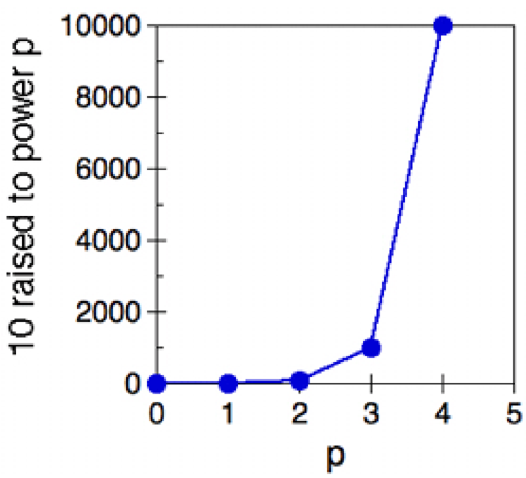
$10^3$ = 10x10x10 = 1,000

$10^4$ = 10x10x10x10 = 10,000

We can generalize the above correlations as $10^P$ , where *P* is the power or exponent. Namely, *P* is a count of the number of zeros in the number.

> ***Aside***: If you are afraid of common **logarithms**, don't be. The logarithm of 10 is just 1. The log of 100 is 2. Log(1000) = 3. ..and so forth. Namely, the log of a number is just a count of the number of zeros after the 1. Namely, *P* is just the logarithm of $10^P$.
>
> But what is the logarithm of any other number, such as 500. Well, we can guesstimate it fairly easily. 500 is between 100 and 1000. We already know that the log(100) = 2 , and the log(1000) = 3. Therefore, I would guess that the log(500) is somewhere between 2 and 3, let's guess 2.5. (When I use my calculator, I get log(500) = 2.7 , so I wasn't too far off.) Not too scary.

We can plot these numbers on a graph, as a function of *P*:




This shape of curve, which starts rising very slowly at first for small values of P, but increases faster and faster as P gets larger, is called an **exponential curve**.

But notice that much of the graph is off scale (too small, or too large). For *P* = 0, 1 and 2, the values of $10^P$ are all plotted along the very bottom of this graph, so it is difficult to distinguish any differences. Also, for very large *P* such as *P* = 5, the curve is way off the top of the graph – again useless.

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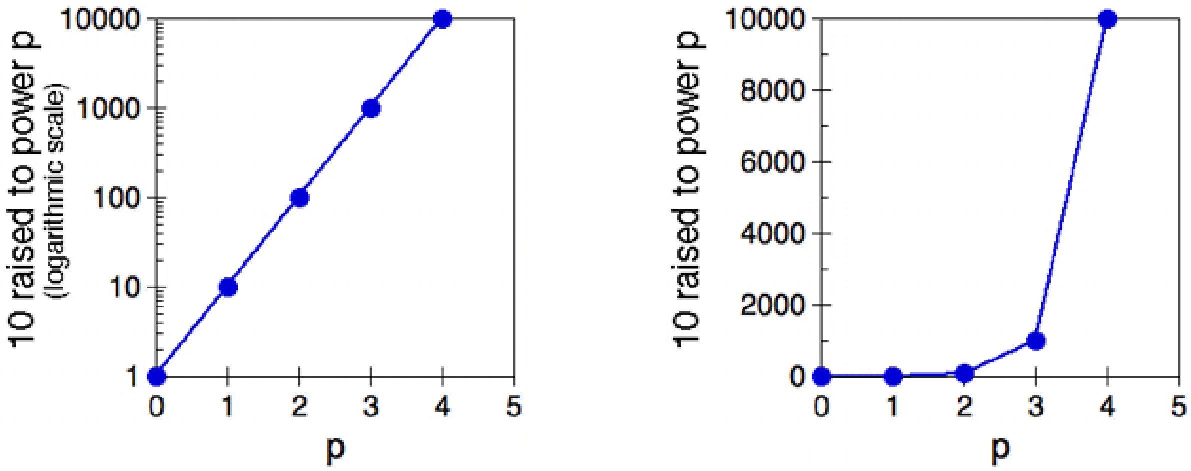
## 7b. Quantifying Rare Events: Intensity Using Logarithmic Scales

To avoid the graphic difficulty mentioned in the previous page, we can use a **logarithmic graph**, where the **ordinate** (the vertical axis of the graph) steps by powers of 10. Namely, the **abscissa** (horizontal axis) is linear, but the ordinate steps by orders of magnitude. See graph on left below:




This graph looks nice! Compare with the the graph on right presented previously. For each value of *P*, we can see the value of $10^P$ from the graph. And we would have to extend this graph only a little along the ordinate to capture $10^5$. So why not use the power (to which 10 is raised) as a surrogate measure of the number?

Namely, use power 3 as a surrogate measure for the number 1,000. Use power 4 as a surrogate for 10,000 and so forth.

In fact, many disaster scales use just such a "power" surrogate to indicate intensity. For example, an earthquake of magnitude 6 is roughly an order of magnitude more violent than an earthquake of magnitude 5. Most disaster scales are this way.

***CHECK YOUR UNDERSTANDING***: A disaster of intensity 6 is how much stronger than a disaster of intensity 4? (Assume these are order-of-magnitude scales.)

A) 2
B) 10
C) 100
D) $10^4$
E) $10^6$

---

## 8. Disaster Scales

Disaster scales are often named after the person who developed it. Here is a list of disaster scales for the disasters that we will study in this course. The details of each disaster scale will be explained in the other Modules of this course, when you learn about each type of disaster.

A. **Earth**

  - Richter Scale (earthquakes)
  - Modified Mercalli Scale (earthquakes)
  - Moment Magnitude Scale (earthquakes)
  - Volcano Explosivity Index (volcanoes)

B. **Ocean**

- Beaufort Scale (wind and waves)
- Saffir-Simpson Scale (hurricanes)

C. **Atmosphere**

- dBZ (radar echo intensity of precipitation)
- Fujita Scale (tornadoes)
- Torro Scale (tornadoes)

D. **Impacts from Space**

- Torino Scale (meteor strikes)

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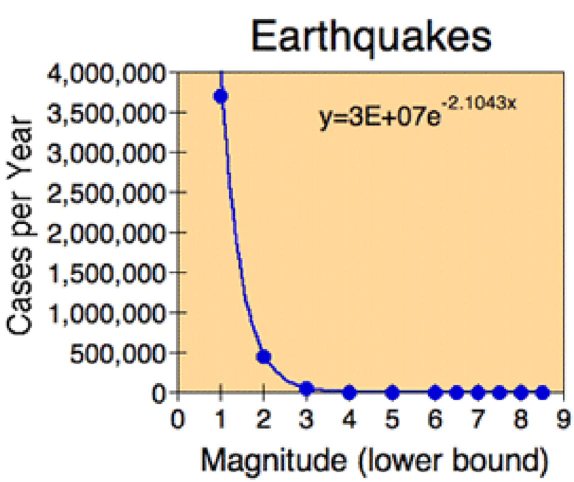
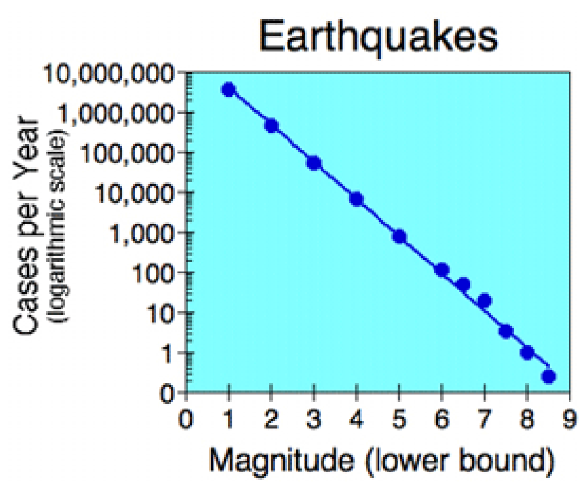
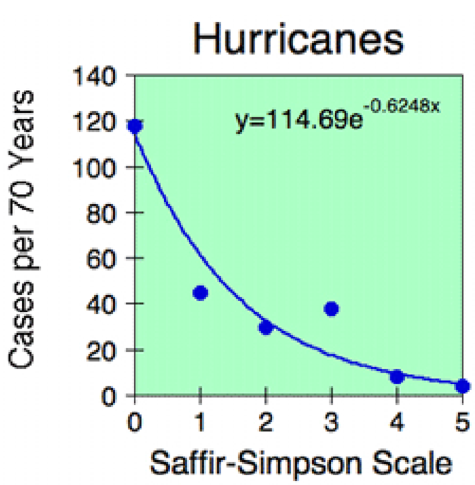
## 9a. Intensity vs. Frequency: Examples

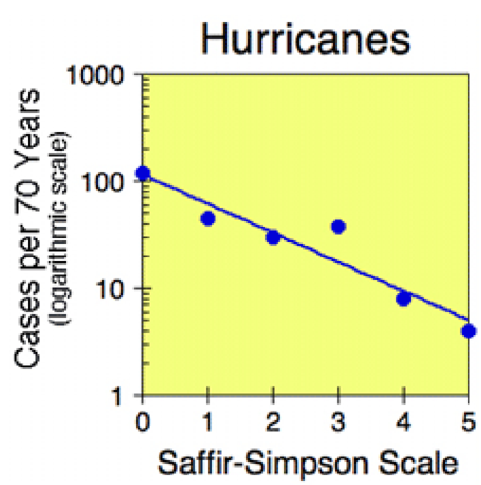
More-intense disasters occur less frequently. Namely, intense disasters are relatively rare.

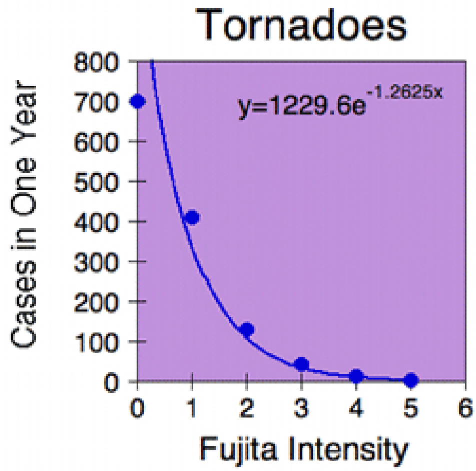
The following graphs are from actual data of disaster occurrence vs. intensity. They are plotted on both normal graphs (linear vs. linear) on the left, and semi-log graphs (power-of-ten ordinate vs. linear abscissa) on the right.

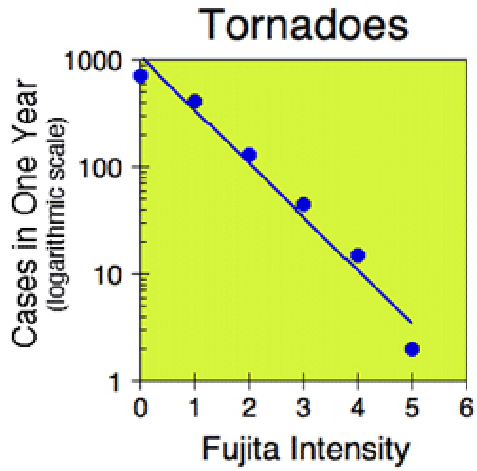





Thankfully, each graph indeed shows that more-intense disasters happen less frequently. One way to quantify how often a disaster has occurred in the past is the "**Return Period**". This will be discussed next.

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## 9b. Intensity vs. Frequency: Return Period

**Return period (*RP*)** is the average number of years between disaster events of the same magnitude (*M*).

When you hear phrases such as "a 50-year storm", or "a 100-year flood", these refer to a storm of such intensity that its return period averages once every 50 years, or a flood of such intensity that it occurs once every 100 years on average.

Calculate it by:

$$RP_M = \frac{(\text{time span of data record})}{(\text{number of cases of magnitude M})}$$

For example, if we have been recording hurricane damage for the past 70 years in the USA, and if a hurricane of intensity 5 on the Saffir-Simpson Scale has happened only twice in that period, then:

$$RP_5 = \frac{(70\ years)}{(2\ cases)} = 35\,years$$

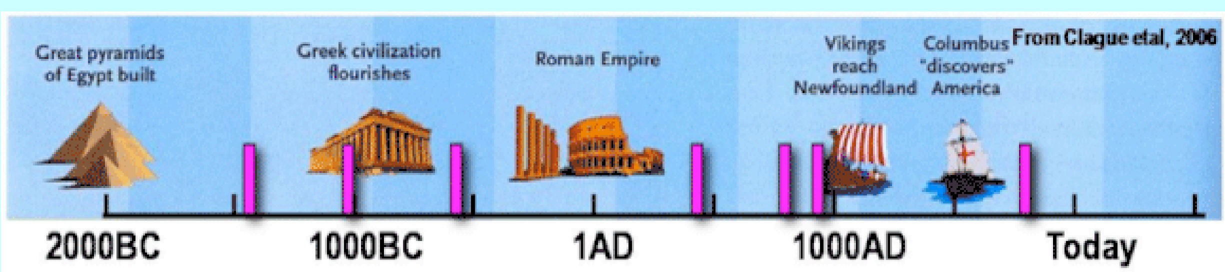
The above calculation means that intense hurricanes (of magnitude 5) strike the USA only once every 35 years, on average. Why does this matter?

Below is a map that shows what wind speed (km/h) in a given location has a return period of 50 years. For example, near the Great Lakes, winds of 90 km/h or faster occur only once every 50 years. However, over the Queen Charlotte Islands of British Columbia, much stronger winds, that of 140 km/h or faster occur once every 50 years. Thus, if you design a house that won't blow down during your remaining lifetime, you would want it to be able to withstand winds of 140 km/h if you built it on the Queen Charlottes. However, if you build you house near the Great Lakes, you would need it to withstand only winds of about 90 km/h.


**Figure FS.6 A map of Canada showing contours of wind speed (in km per hour) with 50-year Return Periods. Map from Environment Canada.**

You must be very careful when you interpret and utilize return-period data. First, they are average statistics of PAST weather, not certainties of what will happen in the FUTURE. Second, although winds of 140 km/h happened once every 50 years on average, the actual time period between any two events could have been less or more than 50 years.

Third, even though you might live for another 50 years in the Queen Charlottes, it is possible for you to experience a 160 km/h wind. Even if 160 km/h winds might have a return period of say 75 years, that does not prevent it from happening during the 50 years that you live there. Lastly, all the caveats above ignore the additional possibility that the climate might change between the past measurements and your future period of interest.




***CHECK YOUR UNDERSTANDING***:

1. For SW Canada, extremely destructive earthquakes have occurred as plotted above with magenta bars. Estimate the return period (in years)?

A) 155 years
B) 286 years
C) 572 years

D) 2000 years
E) not enough info to answer

2. Predict the year of the next earthquake.

A) THIS year
B) approximately in the year 2065
C) approximately in the year 2295
D) approximately in the year 2581
E) not enough info to answer

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## Summary

At this point, you should have a good understanding of metrics used to measure our world, and how to quantify the intensity of disasters and their frequency of occurrence. In particular, we covered:

1. SI magnitude prefixes
2. Time measures
3. Distance (space) measures
4. Mass (matter) measures
5. Density
6. Stratification
7. Quantifying Rare Events
8. Disaster Scales
9. Intensity vs. Frequency

The important points are that:

- We must use common metrics in order to share information efficiently
- In physical sciences, the metric "value" always includes numbers *and* units.

These concepts will be used in all of the remaining Modules of this course, so feel free to refer back to this unit if you can't recall some of these basic information.

The next unit will discuss the materials that make up our Earth, ocean, and atmosphere.

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| UNIT | TOPIC |
|---|---|
| B | Materials |

## OUTLINE

Many disasters involve the movement or transport of, or change in, materials. For example, rocks break in earthquakes, water oscillates in tsunami, and air rises in thunderstorms. In this section, we examine the nature of materials.

1. Elements and Atoms

nucleus
- atomic number
- atomic mass number
- isotopes

2. Key Elements Used in this Course
3. Molecules and Ions
4. Minerals
5. Crystals

    - crystal structure
    - cleavage
    - structural failure
    - some examples

6. Phases of Matter
7. Properties of Materials

    - compressibility
    - viscosity
    - strain

---

## 1. Elements and Atoms

a. **Elements** are the building blocks of our world. A chemical **element** consists of identical atoms. Thus, an atom is the smallest piece of an element.
b. **Atoms** are made of

    - **protons**, which have a (+) charge
    - **neutrons**, which are neutral
    - **electrons**, which have a (–) charge

    Normally, the number of electrons and protons in an atom are equal, causing the atom to have no net charge (i.e., to be neutral).

    In modern physics, even these particles can be further subdivided. But we need not be concerned with such smaller subatomic particles for this course.

    i. **Nucleus**. The nucleus is the center of an atom. It holds the protons and neutrons. Swarming around the nucleus is the cloud of electrons.
    ii. **Atomic Number**. Atoms (and the elements formed from them) are identified by the number of protons. This number is the atomic number.
    iii. **Atomic Mass Number**. But because two or more versions of one element can have different numbers of neutrons, we define the atomic mass number to differentiate between these versions. The atomic mass number is the sum of:protons + neutrons = **atomic mass number**
    iv. **Isotopes**. Isotopes are different versions of an element that have the same number of protons, but different numbers of neutrons. Namely, they have the same atomic number, but different atomic mass numbers.

***FOR EXAMPLE***: We sometimes hear of "carbon dating" old materials.

The most abundant form of carbon (atomic number = 6) on Earth is carbon-12 or $^{12}C$; namely, it is the isotope of carbon having an atomic mass number of 12 (= 6 protons +

6 neutrons). It is a very stable isotope (luckily for us, because we humans are carbon-based life forms).

Carbon-14 or $^{14}C$ is an isotope having an atomic mass number of 14 (= 6 protons + 8 neutrons). Carbon-14 is less prevalent on Earth, and is not stable; namely, it gradually decays with time.

By comparing the relative amounts of $^{12}C$ to $^{14}C$, and knowing the half-life (i.e., the decay rate) of $^{14}C$, one can determine the age of the material.

## 2. Key Elements used in this Course

Elements are often listed in the periodic table. However, in this course, we are concerned with only a portion of known elements. Thus, instead of presenting the whole periodic table, we will list only the elements that are important for us.

In Table FS.3 below, the first column refers to the name of each element. The next column shows the symbol or abbreviation used to represent the element.

The last column gives a brief description of how these elements touch our lives. In this description, some elements are identified as being the (*Gco*) "greatest component of" a portion of the Earth/ocean/atmosphere system, while others are identified as being (*Aco*) "a component of" something. These descriptions, along with the element names and abbreviations, are important to remember. (You might be tested on which elements are the greatest, second greatest, etc. elements in a particular system.)

**Table FS.3 Key elements and their properties**

| ELEMENT | SYMBOL | DESCRIPTION |
|---|---|---|
| Hydrogen | H | Smallest atom; *Aco* water |
| Helium | He | Non-reactive (noble gas); made by fusion in sun |
| Carbon | C | *Aco* most life forms on Earth; *Aco* coal, graphite, diamonds (yes, diamonds burn; it is not true that "diamonds are forever") |
| Nitrogen | N | *Gco* air; *Aco* nitric-acid rain |
| Oxygen | O | *Gco* Earth's crust, 2nd *Gco* atmosphere; *Aco* water; very reactive, such as oxygen-based bleaches, and in combustion of the oxygen in air with other flammable materials |
| Sodium | Na | A very reactive metal; *Aco* salt in oceans |
| Magnesium | Mg | A light metal; reactive; *Aco* the mineral called dolomite; *Aco* salt in oceans |
| Aluminum | Al | A light metal used in cans, foil, aircraft; reactive; 3rd *Gco* Earth's crust |
| Silicon | Si | A shiny silver-coloured semiconductor; 2nd *Gco* Earth's crust |
| Phosphorus | P | *Aco* phosphate fertilizers |
| Sulphur | S | Yellow; burnt match smell; *Aco* sulfuric-acid rain; *Aco* salt in oceans |
| Chlorine | Cl | Very reactive (bleaches); *Aco* salt in oceans |

| | | |
|---|---|---|
| Argon | Ar | Argon is the third most common gas in the Earth's atmosphere |
| Potassium | K | Very reactive metal; *Aco* salt in oceans |
| Calcium | Ca | *Aco* limestone, bones, sea shells, salt in ocean |
| Titanium | Ti | A strong, light metal, often used in military aircraft and some computer cases and eyeglass frames |
| Manganese | Mn | A metal like iron |
| Iron | Fe | A strong metal that is often combined with carbon to make steel; used in cars and in the steel beams and rebar of structures; *Gco* Earth's core; *Aco* meteorites; can become magnetic; 4th *Gco* Earth's crust |
| Iridium | Ir | rare element, found in meteorites |

***SURVEY QUESTION***: Which single element do you feel you could NOT live without?

A) Oxygen
B) Carbon
C) Hydrogen
D) Silicon
E) Other

***RECALL***: Complete the summary table. A few cells have been filled to get you started.

| ABUNDANCE | EARTH'S CORE | EARTH'S CRUST | OCEAN | ATMOSPHERE |
|---|---|---|---|---|
| **Most abundant** | iron, Fe | | | |
| **2nd abundant** | | | hydrogen, H | |
| **3rd abundant** | (unknown) | aluminum, Al | | argon, Ar |

## 3. Molecules and Ions

**Molecules**. Atoms can combine to make molecules (compounds). The subscript in a chemical formula indicates number of atoms in a molecule. Normally, molecules have neutral overall charge (namely, the number of protons equals the number of electrons).

Some molecules are held together by ionic bonds, where valences sum to zero. For this type of bond, one atom such as a metal loses one or more electrons (to leave itself positively charged) and gives them to another atom in the molecule (which becomes negatively charged). One common example is table salt, *halite*.

Other types of bonds are covalent bonds where electrons are shared between different atoms in a molecule. In the examples given in Table FS.4 below, the bonds between the atoms in a molecule are indicated with a single line for a single bond (–), a double line for two bonds (=), and a triple line for three bonds. Each bond represents one pair of electrons being shared. The superscripts indicate the valences (as listed earlier in the list of important elements), and the subscript tells how many of the atoms are grouped to form a molecule. Normally, the valences, when multiplied by the number of atoms, sums to zero in a molecule.

| **Table FS.4 Selected compounds and their properties** | | |
|---|---|---|
| MOLECULE | FORMULA (ABBREVIATION) | NOTATION SHOWING BONDS |
| Salt (halite) | NaCl | (ionic bond) |
| Water | $H_2O$ | H – O – H |
| Carbon dioxide | $CO_2$ | O = C = O |
| Diamonds | C | each C is bonded to four others |
| Hydrogen gas | $H_2$ | H – H |
| Nitrogen gas | $N_2$ | N {triple bond} N |
| Oxygen gas | $O_2$ | O = O |

**Ions (also known as Radicals)**. Tightly bonded groups of atoms that act as single units in molecules, but which are not complete molecules themselves because they carry a nonzero charge (sum of valences of all atoms). The net charge is indicated with the superscript.

| **Table FS.5 Selected radicals and their properties** | | |
|---|---|---|
| RADICAL | FORMULA (ABBREVIATION) | RECIPE |
| Carbonate | $(CO_3)^{-2}$ | $1\ C^{+4} + 3\ O^{-2}$ |
| Sulfate | $(SO_4)^{-2}$ | $1\ S^{+6} + 4\ O^{-2}$ |
| Silicate | $(SiO_4)^{-4}$ | $1\ Si^{+4} + 4\ O^{-2}$ |
| Hydroxyl | $(OH)^{-1}$ | $1\ O^{-2} + 1\ H^{+1}$ |

***FOR EXAMPLE***: Seashells are made of the molecule "calcium carbonate". Namely, they have 1 calcium atom (which has a +2 valence) combined with a carbonate ion (the carbon and 3 atoms of oxygen, which taken together have a net valance of –2), yielding a molecule $CaCO_3$ with neutral charge.

## 4. Minerals

A mineral is naturally occurring solid element or molecule having a characteristic crystal structure and chemical composition. Some examples of minerals used in this course are:

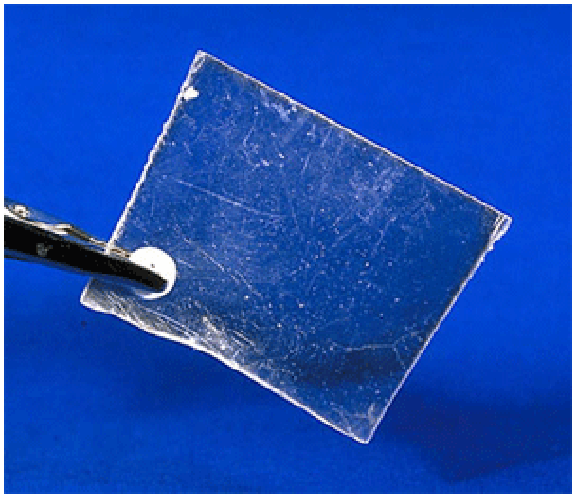
| Table FS.6 Selected minerals and their properties | | | |
|---|---|---|---|
| MINERAL NAME | CHEMICAL NAME | FORMULA | IMAGE |
| Silica (quartz) | Silicon Dioxide | $SiO_2$ |  |
| Calcite (limestone) | Calcium Carbonate | $CaCO_3$ |  |
| Hematite | Iron Oxide | $Fe_2O_3$ |  |
| Magnetite | Iron Oxide | $Fe_3O_4$ |  |
| Pyrite (fools gold) | Iron Disulfide | $FeS_2$ |  |

## 5. Crystals

a. **Crystal Structures**. When atoms in molecules line up in a **regular lattice**, the result is a crystal as shown in the images below. This alignment is caused by the various **bonds**.

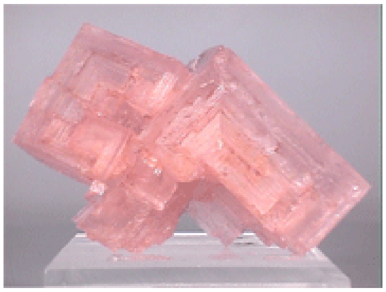

b. **Cleavage**. Crystals often have directions of weakness through them, allowing the crystals to split along smooth planes. These **cleavage planes** follow the **weakest** bonds in the lattice.

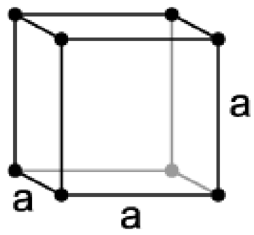
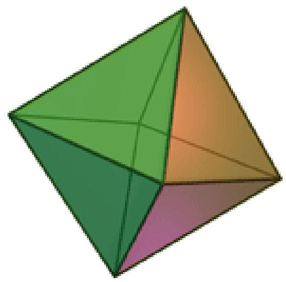
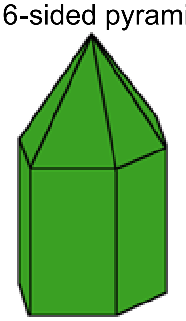
For example, the mineral mica easily separates along its cleavage planes into thin sheets of semi-transparent rock:



c. **Structural Failure**. This is important for failure (**fracture**) of the material, such as in earthquakes.

d. **Selected Crystal Shapes**.

| Table FS.7 Selected crystal shapes | | |
|---|---|---|
| CRYSTAL SHAPE | EXAMPLE | IMAGE |
| **Cubic**<br>shaped line a box; has 6 sides | halite (NaCl)<br>galena (PbS)<br>pyrite ($FeS_2$) |  |

| | | |
|---|---|---|
|   | | Note: in this photo, three separate cubic crystals grew together at an odd angle |
| **Octahedral**<br>shaped like two square pyramids stacked bottom to bottom; has 8 sides<br> | diamond (C)<br>fluorite ($CaF_2$) |  |
| **Hexagonal Column with Pyramid**<br>shaped like a pencil; namely, a 6-sided shaft capped on the end with a 6-sided pyramid<br> | quartz ($SiO_2$)<br>ice ($H_2O$) |  |

## 6. Phases of Matter

The three phases of matter are solid, liquid, gas (vapour). One way to define them is by their physical characteristics of fluidity and compressibility. These will be defined in the next page.

**Solids:**

- not very fluid
- not very compressible

**Liquids:**

- very fluid
- not very compressible

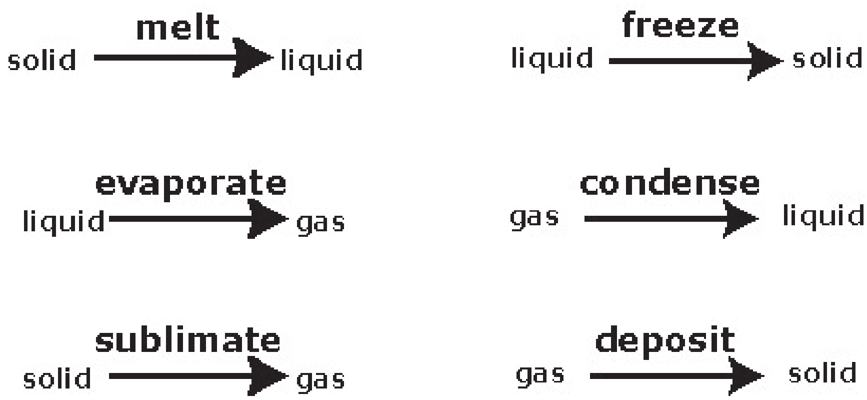
**Gases:**

- very fluid
- very compressible

You might wonder why solids are defined as "not very fluid", instead of as "not fluid". The reason is that over geological time scales, some solids behave like fluids.

> ***FOR EXAMPLE***: We consider ice as a solid form of water, but ice deforms and flows slowly in glaciers. Even some rocks can gradually deform and flow deep in the Earth, given enough pressure and a long enough period of time.

Changes between phases have special names, most of which you will recognize:




> ***CHECK YOUR UNDERSTANDING***: If a material is very compressible and not very fluid, then you would classify it as a ______.
>
> A) gas
> B) liquid
> C) solid
> D) crystal
> E) none of the above

---

## 7. Properties of Materials

a. **Compressibility** is the ability of a material to be squeezed or expanded, so that the mass fills less or more space. Compression results in a change in density (mass / volume) of the object, because of the volume change. A material that is very compressible can be squeezed into a very small space.

b. **Fluidity** is the ability of a material to flow; a material that is "very fluid" flows very easily. Fluids include:

   - Liquids, for example, water
   - Gases, for example, air; Yes, liquids are not the only fluids; gases are too.

c. **Viscosity** is a measure of how much fluids resist flowing or changing their shape. The greater the viscosity, the more it resists change, and the more force must be applied to make it change. Namely, higher-viscosity fluids are thicker, gooier, or less runny.

Viscosity depends on temperature and chemical structure. Examples are:

- High viscosity, for example, magma (molten rock in the Earth)
- Medium viscosity, for example, water
- Low viscosity, for example, air

d. **Strain**. Strain is the change in shape or size (i.e., the **deformation**) of a solid object. Types of strain are:

- **Elastic**. The ability of an object to change shape (i.e., deform) when forced, but to spring back to its original shape when the force is released. For example: rubber band, spring
- **Plastic**. The ability to permanently change shape or deform when forced. For example: ice in glaciers, soft metals, even some rocks

Properties of materials based on their ability to strain:

- **Ductile**. Very plastic (bends and deforms easily). For example: gold
- **Brittle**. Not plastic; fractures (breaks) instead of bending. For example: ceramic dishes

---

| UNIT | TOPIC |
|---|---|
| C | Energy |

## OUTLINE

Recall that last time we learned about materials. But to make materials move and changes, we need energy. It is the **energy release** in natural disasters that causes death and destruction.

1. Motion and Change
2. Force
    - Basic Concepts
    - Gravity
3. Forms of Energy
    - Work
    - Potential Energy
    - Kinetic Energy
    - Sensible Heat
    - Latent Heat
4. Power
5. Pressure and Stress
6. Stress and Strain
7. Sources of Energy for Disasters
8. Energy Conversions and Conservation
9. Concentration of Energy
10. Natural Disasters thru Earth's History

---

## 1. Motion and Change

**Energy** causes things to move or change. Many disasters release immense amounts of energy, thus causing catastrophic changes. Energy is related to other things like: **force**, **work**, **power**, **pressure**, **stress**, etc., which we will also discuss.

## 2. Basic Concepts of Force

A force **pushes** or **pulls**.

The SI unit of force is the **Newton** (N). A Newton is not a "basic" unit, but is defined as:

$$1\ (N) = 1\ (kg\ m\ /\ s^2)$$

***HOW BIG IS A NEWTON?***: Here are some examples:

- A 15 km/h breeze against your body pushes with a force of about 1 N
- The weight of Mt. Baker volcano (which you can see from Vancouver on a clear day) on the Earth's crust is about $5 \times 10^{14}$ N (500 trillion N)

### Gravity

**Gravity** is a force that attracts matter (i.e., masses) to each other. Objects of mass ***m*** near the Earth's surface are pulled toward the Earth with a force equivalent to:

$$F = m \cdot a$$

where ***a*** is the gravitational acceleration, OR ***g*** = 9.8 (m / $s^2$).

---

## 3. Forms of Energy

There are many forms of energy; the following are important in understanding natural disasters:

- Work
- Potential Energy
- Kinetic Energy
- Sensible Heat
- Latent Heat

We will examine these in detail next.

## 3a. Work

One form of energy is **work**. Work ***W*** depends on the force ***F*** that pushes or pulls an object over the distance ***d*** the object moves.

$$W = F\ d$$

The SI unit of work (and of any form of energy) is the **Joule *J***, which is a derived unit. It is defined as:

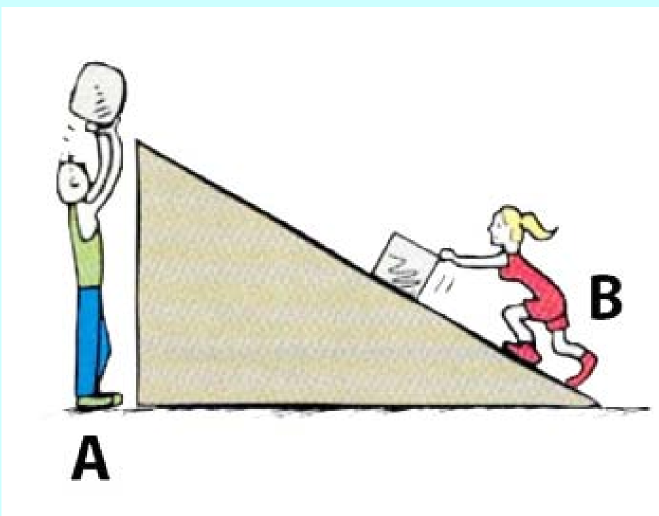
$$1\ (\mathrm{J}) = 1\ (\mathrm{N\text{-}m}) = 1\ (\mathrm{kg\text{-}m^2 / s^2})$$

***FOR EXAMPLE***: You do work of ***W*** = 90 J when you push with 30 N of force to move your refrigerator 3 m across your kitchen.

***CHECK YOUR UNDERSTANDING***: If you push hard (with a strong force) against a wall that does not move, then ______.

A) you've done infinite work
B) you've done zero work
C) the amount of work depends on how much time you spent pushing it
D) the work increases as gravity increases
E) depends on how high above the ground you push against the wall

***CHECK YOUR UNDERSTANDING***: Which requires less work?




A) lifting a 2 kg object vertically
B) sliding a 2 kg object to the same height up a frictionless slope
C) they require the same amount of work

D) not enough info to answer

---

## 3b. Potential Energy

The work needed to raise an object of mass ***m*** a distance ***z*** against the pull of gravity ***g*** is called **potential energy** PE.

$$PE = g\ m\ z$$

***FOR EXAMPLE***: A person with mass 70 kg who walks up from the beach a vertical distance of 50 m to the UBC campus does work against gravity of at least:

**PE = 35,000 J (or 35 kJ)**

---

## 3c. Kinetic Energy

A moving object possesses **kinetic energy** KE:

$$KE = \frac{1}{2} m\ V^2$$

where ***m*** is the object's mass, and ***V*** is its velocity.

***SOME EXAMPLES***:

A typical car of mass 1300 kg moving at speed 50 km/h has a kinetic energy of about:

**KE = 125,000 J (or 125 kJ)**

The 30 m diameter nickel-iron meteor with ***m*** = $10^8$ kg that approached Earth at 20 km/s to form Meteor Crater, AZ, had energy:

**KE = 2 x $10^{16}$ J**

---

## 3d. Sensible Heat

**Heat** is another form of energy. The heat that we can feel (sense) in the form measurable by temperature is called **sensible heat**. We usually care about change of sensible heat $\Delta Q_H$, which is related to change in temperature ΔT by:

$$\Delta Q_H = m\ C\ \Delta T$$

where ***m*** is the mass of the object being heated.

Parameter ***C*** is called the **specific heat**, and depends on the material. It is a measure of the capacity of that substance to store heat. Some examples of specific heat values are:

**Table FS.8 Selected elements and their Specific Heat values**

| MATERIAL | SPECIFIC HEAT, J / kg - K |
|---|---|
| air, typical of Earth's atmosphere | 1005 |
| water, typical of Earth's oceans | 4218 |
| granite, typical of Earth's surface | 801 |

***FOR EXAMPLE***: To heat the water in a typical coffee cup from room temperature to boiling requires:

$$\Delta Q_H = 94{,}500 \text{ J } (= 94.5 \text{ kJ})$$

---

## 3e. Latent Heat

**Latent heat** is *stored* (hidden) when matter changes phase from solid to liquid, or from liquid to vapour. For changes in the opposite direction, namely from liquid to solid, or from vapour to liquid, latent heat is *released*.

The change in latent heat $\Delta Q_E$ associated with a mass $\Delta m$ of matter that changes phase is:

$$\Delta Q_E = L \ \Delta m$$

When solids melt, or liquids evaporate, sensible heat is taken from the surroundings (for example, a stove top) and is stored as latent heat. For opposite changes (freezing or condensation) latent heat is released back to the surroundings as sensible heat.

Parameter ***L*** is called the **latent heat constant**. These parameters have slightly different names depending on the type of phase change:

- **Latent heat of vapourisation** is for change between liquid and vapour. The symbol is $\Delta L_v$.
- **Latent heat of fusion** is for change between liquid and solid. The symbol is $\Delta L_f$.

Different materials have different latent heat constants.

For water:

- $\Delta L_v = 2.5 \times 10^6$ J / kg
- $\Delta L_f = 3.34 \times 10^5$ J / kg

> ***FOR EXAMPLE***: When 1 liter (= 1 kg) of liquid water evaporates from a teapot on a stove, the amount of sensible heat that is taken from the stove top to become heat stored as latent heat is:
>
> $$\Delta Q_E = (2.5\text{x}10^6 \text{ J/kg})\cdot(1 \text{ kg}) = 2.5\text{x}10^6 \text{ J} = 2500 \text{ kJ}$$

---

## 4. Power

**Power** is the rate of doing work, or of consuming energy.

$$P = \frac{\text{Work}}{\text{time}} = \frac{W}{t}$$

It has units of energy per unit time. In fact, a power of 1 Joule per second is defined as 1 Watt.

> ***FOR EXAMPLE***: A 100 W light bulb consumes 100 Joules of energy every second, or 360 kJ/hour.

> ***CHECK YOUR UNDERSTANDING***: Which form of energy does not directly or necessarily depend on mass?
>
> A) kinetic
> B) potential
> C) sensible heat
> D) latent heat
> E) work

---

## 5. Pressure (P) and Stress

- **Pressure *P*** is force per unit surface area, applied **perpendicular** to the surface.
- **Stress τ** is force per unit surface area, applied **parallel** to the surface.

Units for pressure and stress: **1 N / m$^2$ = 1 Pascal (Pa)**

---

## 6. Stress causes Strain

**Stress** tends to **strain** objects. Thus, if you apply a force parallel to the surface of an object, the object (if not brittle) tends to deform.

We can now refine our definitions of different types of strain:

- An object is **elastic** if it deforms easily under stress, but springs back when the stress is removed.
- An object is **plastic** if it deforms easily under stress, but remains deformed after the stress is removed.
- An object that does not deform easily can **fracture** under stress.

Some objects, when subjected to increasing amounts of stress, first deform **elastically**, then deform **plastically** under larger stress, and finally **fracture** when the stress is too great. This is shown in the **Stress vs. Strain Curve** below.

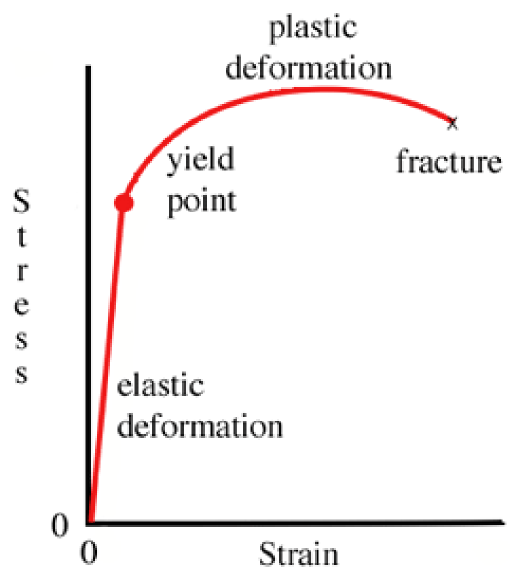



**Figure FS.7 A general relationship between stress imposed on a material and the strain that results.**

How do we "read" the information from the curve shown in the Figure above? When stress is imposed on the material in the region marked as "elastic deformation", strain increases as stress increases, or strain is proportional to stress. This means that when stress is applied, strain will result. Once stress is removed (stress=zero), strain also becomes zero. This is what we know as elastic behaviour.

The boundary between elastic and plastic behaviour is the "Yield Point". In the region beyond the yield point, stress on a material is much greater than in the elastic region. Here, a further increase in stress results in increased strain. However, it only takes a small increment of stress to increase strain by large amounts. As well, when stress is reduced or removed, the material returns to normal very slowly. This is plastic behaviour. Note that a very slow response can sometimes be interpreted as permanent deformation if the response time is too long (thousands to millions of years) relative to standard observation.

## 7. Sources of Energy

The original sources for the energy that drives disasters on Earth are:

- Impacts from space, ***KE***
- Gravitational, ***PE***
- Radioactive decay, nuclear energy
- Solar/Radiative, nuclear energy

Nuclear reactions create energy by converting mass ***m*** into energy ***E*** according to Einstein's famous equation:

$$E = m \times c^2$$

where ***c*** is the speed of light. Much of this energy is released as, or becomes, heat in the Earth / Ocean / Atmosphere system.

In the next section on energy conservation, the energy we refer to is the energy after the nuclear reactions have already converted mass into heat.

---

## 8. Energy Conversions and Conservation

- Energy can **easily change in form** between work, heat, kinetic, and potential energies.
- **Energy is conserved** when it changes from form to form.

All the natural disasters studied in this course involve motion and ***KE***. Some examples of energy conversions associated with natural disasters are:

- Kinetic energy of an asteroid is converted into heat (sensible and latent) when it strikes Earth.
- Heat causes water to expand into steam in the Earth's crust, which does work when it moves magma, some of which rises (increasing PE) in volcanoes.
- Potential energy of rocks high on the slopes of a volcano is converted into kinetic energy when they fall down during a landslide or lahar.

---

## 9. Concentration of Energy

### *a. In Area*

Many of the energy sources are **diffuse** (weak, but covering a wide area). To create natural disasters requires the concentration of this energy into a small area.

> ***FOR EXAMPLE***: Diffuse solar radiation (spread over the surface of the Earth) causes sensible heating of the air and ocean, some of which converts into latent heat by evaporating seawater. This warm, humid air can be concentrated by wind circulations, and drawn into hurricanes where it is released as violent winds, rain, waves, and storm surges.

### *b. In Time*

Other energy sources are **gradual** (weak, but spanning a long time). To create natural disasters requires the energy to continually build-up, allowing sudden release in a short time.

> ***FOR EXAMPLE***: Movements of tectonic plates (large pieces of the Earth's crust) are gradual (in mm/a), but they allow stresses to build to the point where strain causes fracture along the fault lines, allowing the sudden movement that is an earthquake.

---

## 10. Natural Disasters Thru Earth's History

Earth's geological, meteorological, and oceanographic history consists of long periods of calm punctuated by brief, localized disaster events of sheer terror.

In this course, we will study these disaster events and the processes and energy that create them.

---

| UNIT | TOPIC |
|---|---|
| D | Waves and Turbulence |

## OUTLINE

Two of the disasters that we will examine later in this course, earthquakes and tsunami, both involve waves. Seismic waves spread the destructive energy from the initial earthquake fracture point through the material of the solid Earth to many other places on the Earth's surface. Ocean-surface waves spread the destructive energy from an underwater landslide, earthquake or meteor impact to distant coastlines. In this unit, we will learn how waves work, how they transfer energy, and how waves differ from turbulence.

This unit is a general introduction to waves. You will learn more details of waves in the waves and tsunami (The Violent Ocean) and the earthquake (The Shaking Earth) Modules of this course.

1. Waves: Definition and Types
    - Displacement waves
    - Compression wave
2. Wave Metrics
    a. Wavelength
    b. Amplitude
    c. Phase speed
    d. Frequency
    e. Period
3. Energy
    - Propagation
    - Group velocity
4. Turbulence
    - Definition
    - Transport

## 1. Waves

**Waves** are regular oscillations that can propagate (shift) in space.

The two wave types we will study in this course are **displacement** and **compression** waves.

## 1a. Displacement Waves

**Displacement waves** are waves with oscillations perpendicular to propagation direction, as shown in the figure below.

Examples of displacement waves are tsunami, ocean surface waves, some seismic (earthquake) waves, a jump rope.

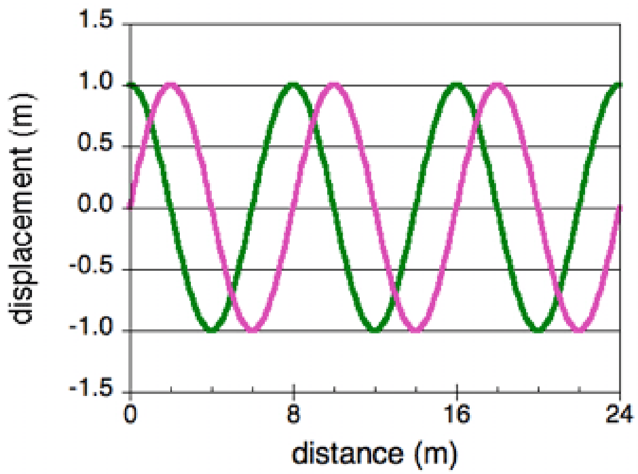



**Figure FS.8 Two displacement waves (green and pink). Read text for a discussion on this wave type.**

Suppose the figure above represents surface waves. In this case, the displacement is just the vertical position of the water surface above or below average sea level. Distance is horizontal distance. Namely, if you are standing on a dock and look straight down, at some instant in time you might see the **crest** (highest point) of a wave directly under you (at distance 0 from your position). You quickly look out across the water, and see the crests of other waves at distances 8 m, 16 m, 24 m, etc. away from the dock. This snapshot of a wave is represented by the green line in the figure.

If you wait a few seconds, the original wave crests all move together, perhaps as shown by the magenta line in the figure above. Namely, the crests have all shifted their positions by a certain distance (2 m in this example) during the few seconds. The magenta line represents the same train of waves, after they have **propagated** (moved or shifted) a little bit. Surfers utilize this propagation to be pushed by the moving wave, and thus to ride the propagating wave toward shore.

So for the wave in this example, the waves are propagating from left to right as shown by the movement of the crests. However, if you were sitting on a boat anchored in the water, you would bob up and down as the waves move past you. Namely, the displacement direction (up and down) is perpendicular to the propagation direction (left to right). Hence, this type of wave is a displacement wave.

Another example of a displacement wave is a jump rope. Try this experiment. Two people hold the ends of the rope, and allow some slack in the rope so it hangs down in a slight arc. The person at one end uses his/her arm to move the rope up and down quickly. The result is waves in the rope that move toward the other end of the rope. Namely, the oscillation direction (vertically) is perpendicular to the direction that the waves move (horizontally from one end of the rope to the other).

---

## 1b. Compression Waves

**Compression waves** are waves with oscillations parallel to the propagation direction, as shown in the figure below.

Examples of compression waves are sound waves, some seismic (earthquake) waves, a slinky toy.

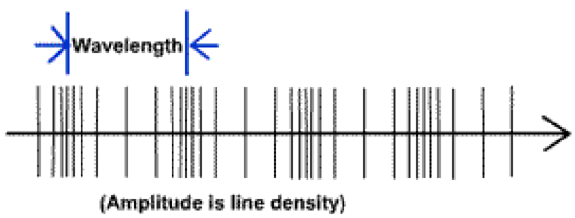



Figure FS.9 A compression wave. The areas of compressed (or most dense) vertical lines indicate the wave crests while the areas of widely-spaced lines are the troughs.

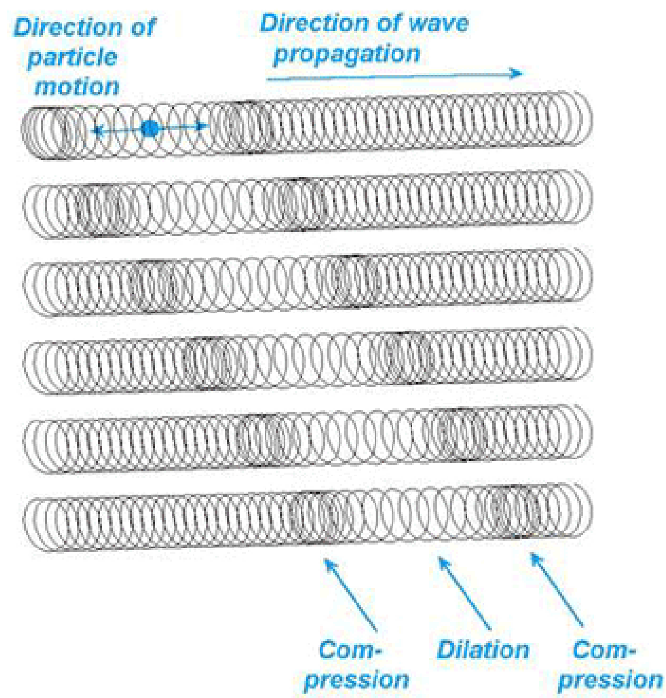



Figure FS.10 Compressional wave propagation in a slinky.

An example of a compression wave is a slinky or spring (refer to Figure FS.10 above). Have a person help you, and stretch the slinky along a tabletop. You hold one end, and the other person holds the other end. In this configuration, the metal coils are roughly evenly distributed along the whole length of the slinky. Namely, they are not bunched up at either end or the middle.

Next, while the other person holds one end of the slinky still, you oscillate your end by pushing and pulling the slinky end in the same direction as the slinky is stretched. Namely, move your end of the slinky so that it moved toward and away from the person at the other end of the slinky. When you do this, you create portions of the slinky where the coils are bunched together (compressed), and other places where they are spread apart (stretched), such as shown in the figure above (where the lines represent the coils of the slinky as viewed from the side or from above.) The regions of compressed coils, as shown in the figure above) represent a series of waves in a wave train.

Also, you will see that as you oscillate your end of the slinky, the regions of the compressed coils quickly moves down the slinky toward the person holding the other end. Namely, you are seeing waves that **propagate** down the slinky. The oscillation direction (you are moving your hand toward and away from the other person), and the propagation direction (the regions of compressed coils are moving toward the other person) are parallel. Hence, these waves are compression waves, NOT displacement waves.

When you talk, your vocal cords make a train of air compressions and expansions that propagate through the air at the speed of sound. When these compression waves reach someone's ears, they move the ear drum, which is connected by a series of small bones to nerves that sense the movement that we hear as sound.

Note that with a slinky, you can also make displacement waves, by moving your end of the slinky left and right instead of pushing it in and out. So with a slinky you can make either kind of wave.

## 2. Wave Metrics

Wave metrics refers to aspects of the wave that can be measured, to help us describe its characteristics. This allows us to answer questions such as: how big is the wave, how strong is it, and how fast is it moving. The figure below illustrates some of these metrics.

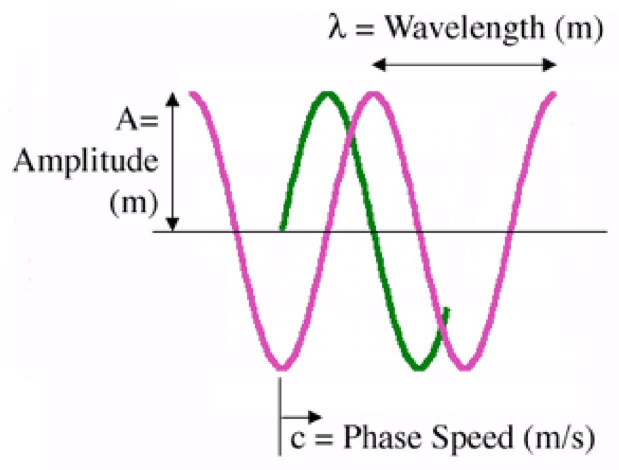



**Figure FS.11 Measurable characteristics of a wave. See next pages for details.**

## 2a. Wavelength (L) or (λ)

**Wavelength** is the distance from crest to crest of a wave train, at one instant in time. For compression waves, the wavelength is the distance from one compressed region to the next. This is one measure of how big a wave is.

It is measured in distance units per each wave cycle (i.e., from crest through trough and back to crest). Namely, the units are m/cycle for normal ocean waves, and km/cycle for tsunami. For short, we often leave out the word “cycle”, and just give the wavelength in distance units (m or km).

We sometimes use the symbol λ or ***L*** to represent wavelength. You get the same measurement if you measure the distance from trough to trough, where the **trough** is the lowest point.

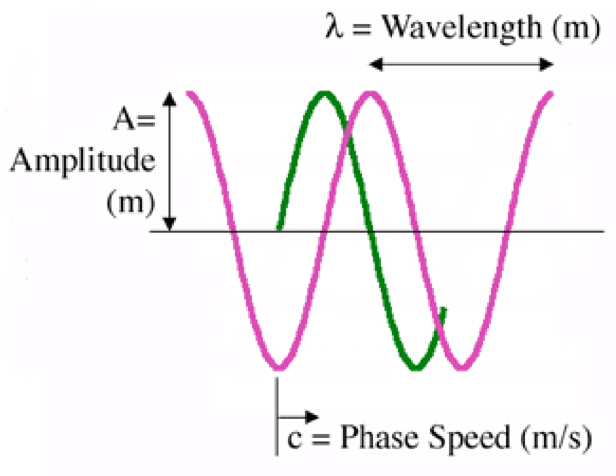



Figure FS.11 Measurable characteristics of a wave.

In the figure of a displacement wave above, the distance between one crest and the neighboring crest of the green displacement wave is 8 m. Therefore, the wavelength of this wave is $\lambda = 8$ m. If we look at the same wave a little later, as shown by the magenta curve we see that the wavelength is still is $\lambda = 8$ m even though all the crests have shifted.

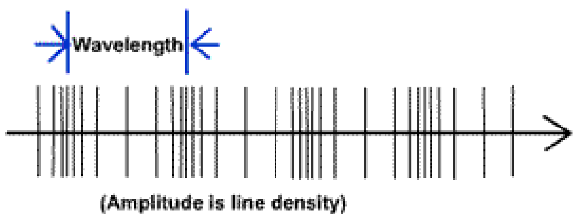


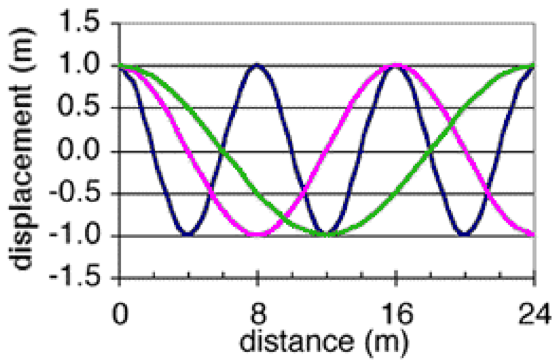

Figure FS.9 A compression wave. The areas of compressed (or most dense) vertical lines indicate the wave crests while the areas of widely-spaced lines are the troughs.

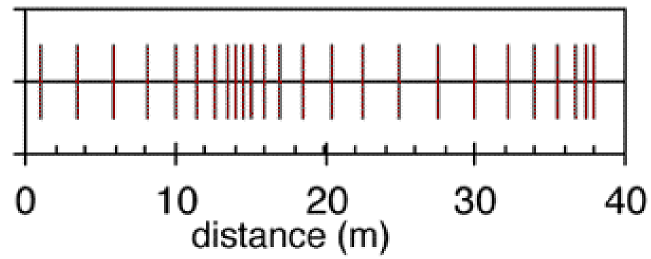
For the compression wave above, the compressed regions are the crests of the wave. Thus, the distance between neighboring compressed regions is its wavelength λ.

***OK, NOW FOR SOME PRACTICE***. Consider the figures below.

a. For the green displacement wave in the figure on the left below, its wavelength is $\lambda = 24$ m. What is the wavelength for the magenta displacement wave?

b. For the compression wave in the figure on the right below, what is its wavelength?




## 2b. Amplitude

The vertical distance from average sea level to the crest of a displacement wave is called the **amplitude**. It is a measure of how strong the wave is, and is measured in distance units (m for displacement waves).

For a compression wave, the amplitude is a measure of how compressed the compressed regions are, compared to the average conditions when there are no waves. For sound waves, the amplitude can be measured by the amount of pressure fluctuations caused by the waves. For example, in sound waves, the wavelength determines the pitch (high note or low note), while the amplitude indicates the loudness.

## 2c. Phase Speed

The **phase speed** is how fast each wave crest or each wave trough moves. It has units of velocity (e.g., m/s or km/h).

> ***FOR EXAMPLE***: If you were surfing on an ocean wave so that you are moving at the same speed as the wave crest, then your speed toward the shore equals the phase speed of the wave. Often, waves of different wavelengths move at different speeds.

## 2d. Frequency (f)

**Frequency** is a measure of how many wave crests pass a stationary point during a fixed time interval. Each wave represents one cycle, going from crest to trough to the next crest. So frequency is measured in **cycles per second**. 1 cycle/s is defined as 1 **Hertz** (Hz).

> ***FOR EXAMPLE***: If you are sitting in an anchored boat, and see that 6 waves pass under your boat in 1 minute, then the frequency is:
>
> *f* = 6 waves / 1 minute
> = 6 cycles / 60 seconds
> = 6 / 60 cycles/s

= 0.1 Hz

Frequency is related to phase speed and wavelength by:

$$f = \frac{c}{\lambda}$$

> ***FOR EXAMPLE***: If an ocean wave moves with phase speed of 2 m/s and has a wavelength of 10 m per cycle, then using the equation above, the frequency is:
>
> *f* = (2 m/s) / (10 m/cycle)
> = 2 / 10 (cycle/s)
> = 0.2 Hz

---

## 2e. Period (P) or (T)

**Wave period** is the elapsed time from the passage of one wave crest to the passage of the next wave crest, as measured from a fixed location. It has units of time per cycle, but is often abbreviated as having units of just time (because the "per cycle" is implied).

> ***FOR EXAMPLE***: Suppose you are sitting in an anchored boat, and find that it takes 10 seconds between when one wave crest passes under your boat and when the next wave crest passes. The period is:
>
> T = 10 s (per cycle)

Frequency and period are related by:

$$P = T = \frac{1}{f}$$

Thus, wavelength and wave speed are related to period by:

$$P = T = \frac{\lambda}{c}$$

---

## 3a. Energy Propagation

For waves, it is **energy that propagates**, not matter.

**FOR EXAMPLE**: Suppose you tie one end of a jump rope to a crankshaft of a small electrical generator. If you hold the other end of the rope and oscillate it up and down, then you are doing work (and getting tired) and are putting this work energy into the waves. The waves carry this energy to the crankshaft, which then generates electrical energy.

A similar concept can be used to generate electricity by having a float on the ocean near shore. As ocean waves carry their energy toward the shore, the float is pushed up and down. This float can be connected to a crankshaft to generate electricity.

But back to the jump-rope example. Suppose you mark the middle of the rope with a colored pen or a piece of tape. As you oscillate the rope and create waves, the mark moves up and down as each wave passes, but the marked portion of rope does NOT move toward the other end of the rope. Namely, the material in the rope is NOT propagating down the rope, only the energy is.

---

## 3b. Group Velocity

The speed of energy propagation by waves is called the **group velocity**. For some waves, the group velocity can be different from the phase velocity. A classic example of these different speeds is the wake behind a moving ship (see figure below).

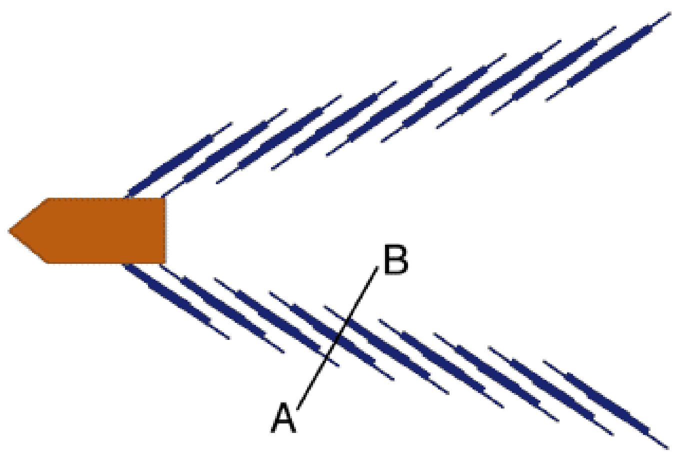



**Figure FS.12 An illustration of the difference between group velocity and phase speed.**

Perhaps you have stood near the stern of a ship, and watched the waves created by the ship as it moves across a nearly calm water surface. In the figure above, individual wave crests are shown with the short blue lines, and the amplitude of each wave is indicated by the line thickness. As shown in the figure, you will often see two regions of waves that gradually spread away from the centerline path of the ship as the ship moves along. Namely, there is a group of waves to the left of the wake centerline, and another group to the right, and the distance between these two groups of waves increases as you look further behind the ship.

The speed that each group of waves moves away from the centerline of the ship path is called the group velocity. For these ocean waves it is fairly slow.

However, if you look at the individual waves in one of the groups, such as the waves in the section A-B in the figure above, then you will notice that the individual wave crests move at a faster phase speed from B toward A than the whole group moves. You can notice this because wave crests seem to appear out of nowhere from B, and grow in amplitude as they move toward the middle of the wave group between B and A, and then diminish and completely disappear as they leave the wave group near location A.

If you haven't had an opportunity to look at this phenomenon from a ship, don't worry about it. The main point to remember about group velocity is that it is the **speed that energy moves due to waves**.

---

## 4a. Turbulence: Definition

**Turbulence** consists of *random* motions in a fluid. Gusty. Irregular. (NOT like waves, which are regular oscillations).

> ***FOR EXAMPLE***, the figure below illustrates the wind speed as might be measured at a fixed point, during a period of a couple minutes. During this time, there are some fast gusts, and some slower lulls in the wind. The wind speed is measured at a weather station, during a time period of a couple minutes.


Due to the irregular nature of this process, there is NOT a well-defined wavelength. Instead, statistics must be used to describe turbulence.

---

## 4b. Turbulence: Transport

There is a very important difference between waves and turbulence:

Turbulence transport both **energy** *and* **matter** but waves transport ONLY **energy**.

> ***EXAMPLES OF TRANSPORT BY TURBULENCE***:
>
> - spreading of smoke or volcanic ash in the air; namely, matter (smoke particles or ash particles) are moved away from their emission source.
> - motions inside thunderstorm; violent turbulence inside thunderstorms can dangerously buffet aircraft, while transporting large amounts of material (air, water droplets) vertically in the atmosphere.

The turbulent motions of the fluid themselves have kinetic energy, associated with the gusty speeds of motion, and the mass of air or water moving.

| UNIT | TOPIC |
| --- | --- |
| E | Is the Earth a Fragile System? |

## OUTLINE

With the background we now have on Earth materials, energy, energy propagation, and return periods, we can now go back to answer the question from the beginning of this Module: *Is the Earth a Fragile System?*

1. Population
    - growth rate
    - doubling time
    - recent growth rate
2. Outcomes
    - holding capacity of Earth
    - alternative futures
3. Transitions
    - infrastructure sensitivity and resilience
    - disaster prediction
    - increasing sensitivity
4. Conclusions

One frame of reference within which we can address this question is **anthropocentric** (centered on humans). Namely, how do Earth, ocean, and atmosphere processes affect our lives, both as individuals and as a population?

To answer this, we must be aware of changes in the Earth's population.

## 1a. Growth Rate

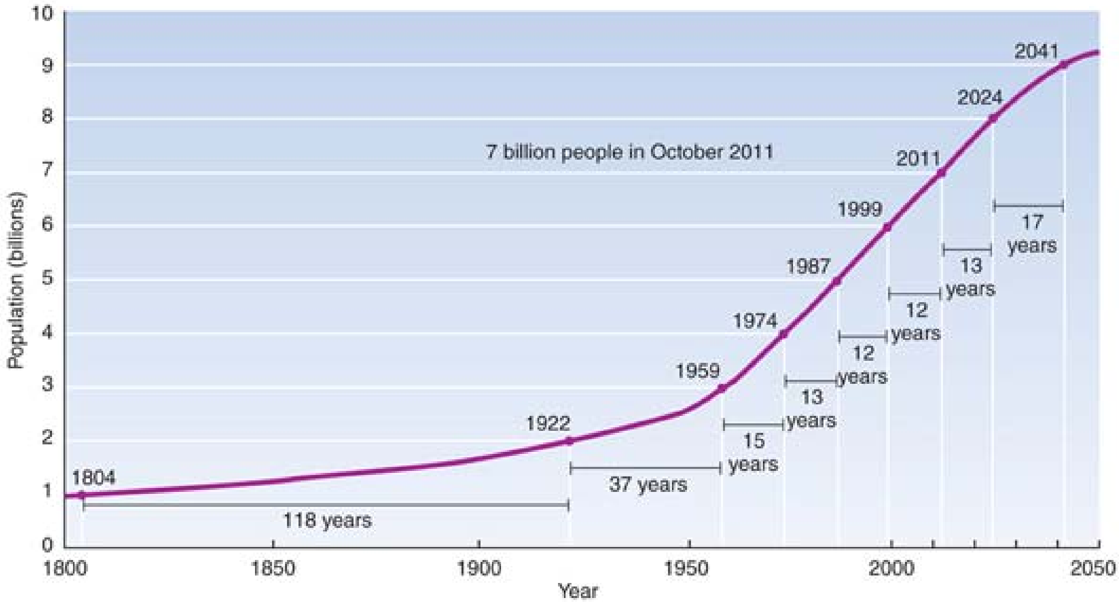



**Figure 1.12**
Growth of the world population of humans. Notice how the time to add another billion people has decreased to date but is projected to start increasing in the future.
Source: © US Census Bureau.

Over the past 8,000 years, world population has been undergoing **exponential growth**! Namely, the population was increasing faster and faster, as shown by figure above, *Figure 1.12 of Abbott and Samson, 2012*.

The world growth rate has been declining from a peak of **2.20 % per year** in 1962 and 1963. Currently, population continuous to grow exponentially at a rate of 1.1 % per year. "But this doesn't sound like much," you might say. But with *exponential growth*, population compounds, like interest in a bank that gets interest on earlier interest. To better picture this growth rate, we can present it as a doubling time, which we will discuss next.

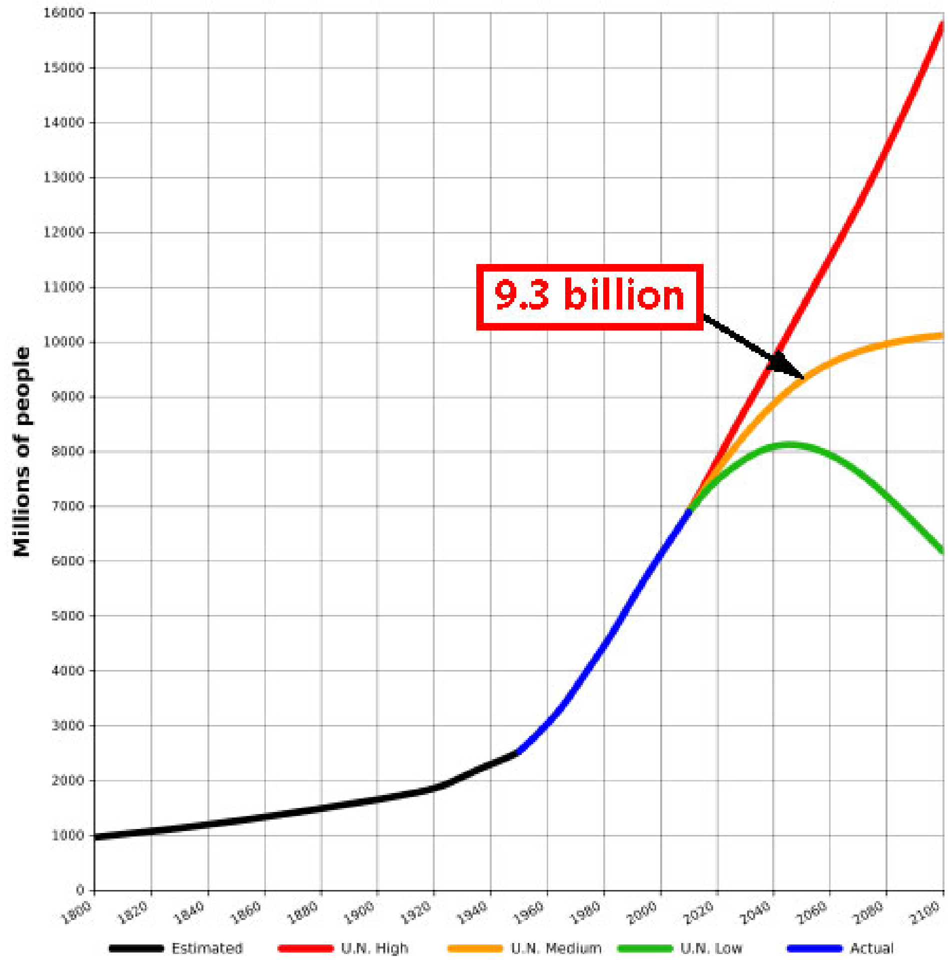



**Figure FS.13 World population estimates from 1800 to 2100, based on UN 2010 projections (red, orange, green) and US Census Bureau historical estimates (black). According to the highest estimate, the world population may rise to 16 billion by 2100; according to the lowest estimate, it may decline to only 6 billion. The projected population for the year 2050 is 9.3 billion. Plot from Wikipedia**

---

## 1b. Doubling Time

**Doubling time** is the number of years for the population to double. There is a simple formula for this:

$$DT\ (\text{years}) = \frac{70}{\%\ \text{growth rate/year}}$$

***FOR EXAMPLE***:

Given a growth rate of 1.16% per year, the doubling time for population is
$\Delta T = 70 / 1.16 =$ **60.3 years**

If the growth rate is 1.14% per year, the doubling time is **61.4 years**.

Most of you will still be alive 60 to 61 years from now. What will it be like? Well, consider the present-day traffic congestion on the highways, crowding on buses, population density in high-rises, waiting lines to check out of grocery stores, air pollution, water and energy shortages, etc. Now, in your mind, double that. Scary.

Different countries and different regions will experience different growth rates, both due to local culture and religion, and due to abundance or lack of food and energy. British Columbia population is projected to increase as shown below over the next two decades or so, based on data from BCStats.

**Table FS.9 Population Trends for British Columbia, 2000-2036**

| YEAR | POPULATION IN B.C. |
|---|---|
| 2000 | 4,039,200 |
| 2005 | 4,196,800 |
| 2010 | 4,531,000 |
| 2020 | 5,175,000 |
| 2030 | 5,816,400 |
| 2036 | 6,155,600 |

Most of this increase will be in the Lower Fraser Valley; namely, the greater Vancouver area.

***IMPORTANT NOTE***:

**Doubling time** applies ONLY to an **exponentially growing population**!

## 1c. Recent Population Growth Rate

Recent (between the years 1970 - 2005) worldwide population growth rate was *almost* linear -- it is still exponential but the rate is quite low.

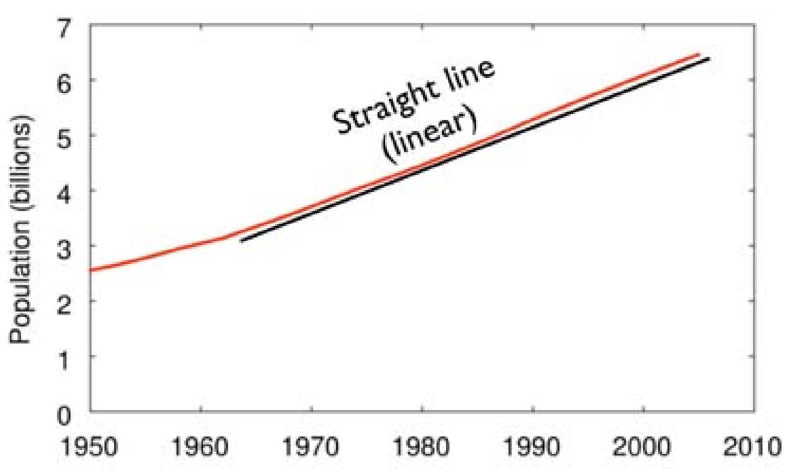


**Figure FS.14 Recent (1950-2005) world population growth (red line). When compared to a straight line (black line representing linear growth rate), note how the population growth rate between 1970-2005 is very close to being linear. At this rate, world population is increasing by 1 billion people every 13 years. Source: Wikipedia, January 2007.**

---

## 2. Outcomes

**Can this exponential population growth continue forever?** Brown, et al. 1991 in "*Saving the Planet*", as quoted in our textbook, explain:

> *Given the variety of cultures, values, and norms in the world today, our greatest hope for controlling population is through improving the well-being of people in developing countries.*

Abbott, 2008 in "*Natural Disasters*" warns:

> *At this current world population growth rate, 529 trillion humans would cover the continents standing shoulder-to-shoulder 900 years from now.*

Of course, this final outcome of 529 trillion humans is impossible, because if people were standing on every square metre of soil, then no crops could be grown, no one could lay down and sleep, etc. So if this end scenario is not possible, then what is?

---

## 2a. Carrying Capacity of the Earth

The **carrying capacity** of the Earth is the population that can be sustainably supported within a given domain (e.g., Earth), given the quantity of food, habitat (living space), natural resources (energy/fuel, water, clean air), sanitation, medical care, etc. In other words, it is the maximum number of humans who can survive given the continued availability of food, clean water, clean air, and energy. Population that exceeds the carrying capacity of an area or environment is said to be overpopulated.

The graph below shows with the extrapolated population based on our high, medium, and low exponential growth rate (red, yellow, and green respectively). Note that the yellow curve projects that the population will be leveling off while the yellow curve predicts that the population will be decreasing. These projected decrease in growth rates are expected as Earth's carrying capacity is approached. Notice the year when the curves start to depart from the exponential growth curve. It is about NOW. Namely, you won't have to wait 900 years to feel the effects of a finite Earth -- you are already starting to feel it!

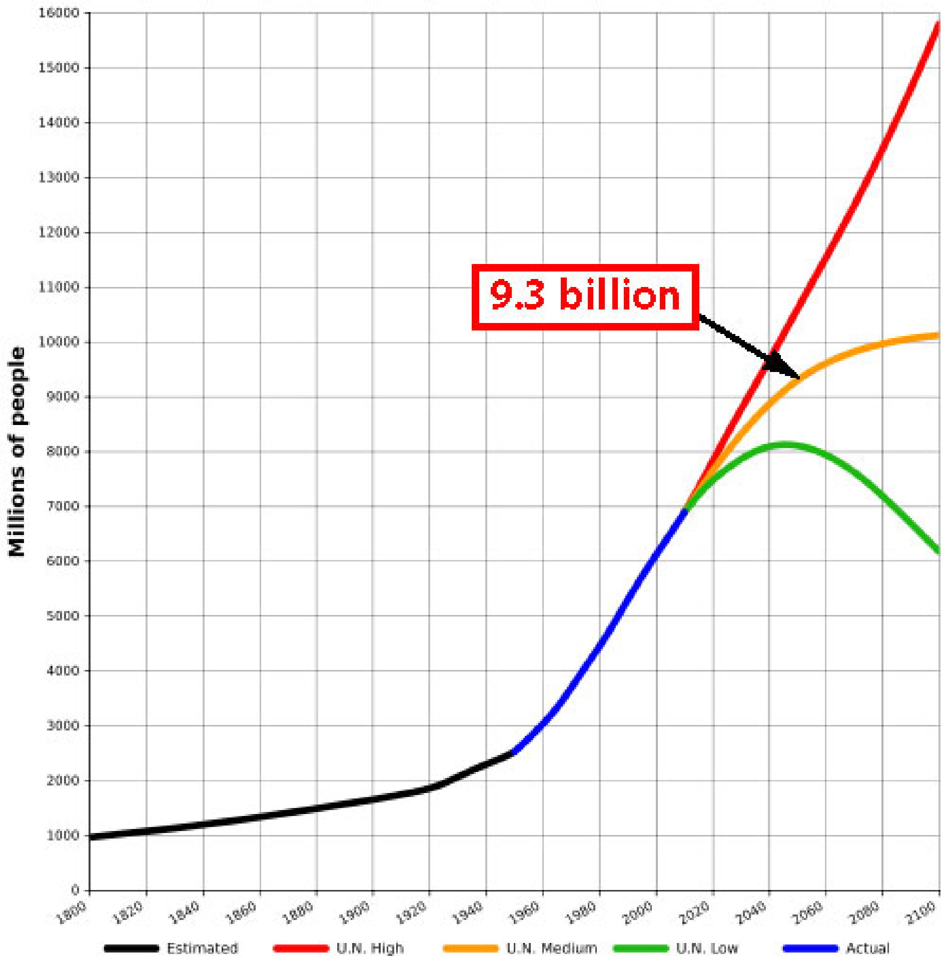
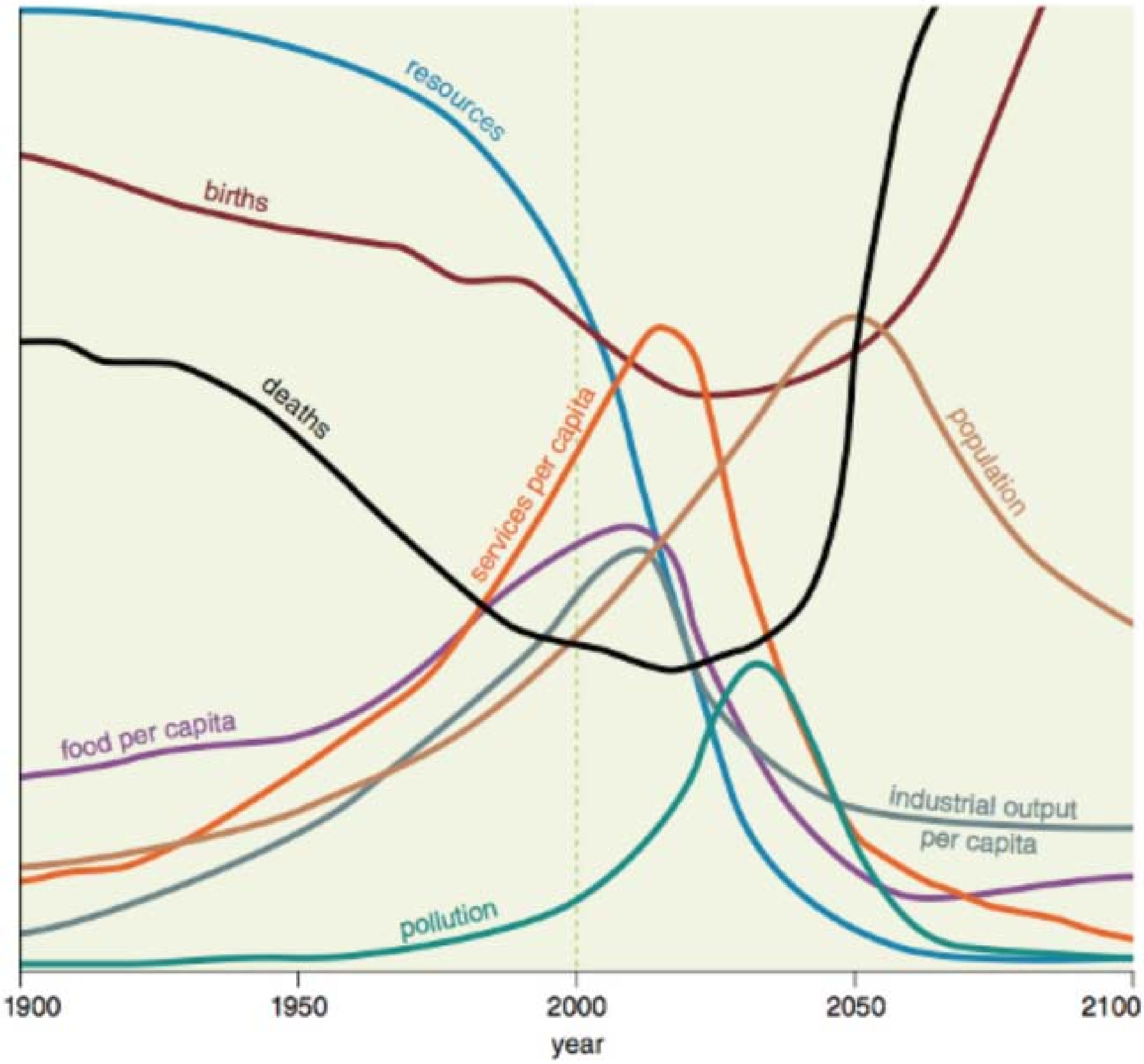



**Figure FS.13 World population estimates from 1800 to 2100, based on UN 2010 projections (red, orange, green) and US Census Bureau historical estimates (black). According to the highest estimate, the world population may rise to 16 billion by 2100; according to the lowest estimate, it may decline to only 6 billion. The projected population for the year 2050 is 9.3 billion. Plot from Wikipedia**

If the carrying-capacity population is reached, the quality of life would be extremely unpleasant. Our survival would be marginal. On average, all of us will be near starvation, receiving the minimum food needed to stay alive. The atmosphere would be so contaminated that life spans would be extremely short. The strong would kill the weak.

Even before we reach this carrying capacity, the stronger countries will wage food wars against their neighbors, to take what they need at the expense of everyone else. They will wage energy wars against their neighbors (for example, the oil wars that we have already seen in the Middle East). Canada is a country rich in natural resources and weak in national defense -- are we next in line for a "benevolent" takeover by a neighboring strong country?

The older generations, including the present generation of governing adults, got us into this mess. However, based on projections as in the figure above, it is ***your generation***, and the generation of your children, will be the ones to suffer the consequences of a finite Earth.




***DISCUSS WITH YOUR PEERS:***

In a paper published in the American Scientist, C.A.S Hall and J.W. Day, Jr. (2009, vol 97, pp 230-237) presented the projections of the limits-to-growth model (figure above). This model examines the relation of a growing population to resources and pollution. Based on the model results, what should we (you, me, and everyone else) do to prevent what is very likely an impending disaster?

A) Canada should hoard its resources and not sell them to the rest of the world
B) The strong countries should bomb the weak countries to reduce the total mouths to feed, so the strong countries stay strong
C) We should colonize other planets or moons to acquire more resources
D) We should genetically engineer crops so we never run out of food
E) We need do nothing, because this disaster will NOT affect us

## 2b. Alternative Futures

The changes needed to limit our population to levels well below the holding capacity of Earth (so that we can all have a reasonably good quality of life) will be extremely difficult ones -- ones that require reconsideration of our basic beliefs, traditions, and cultures. Science, engineering, and medicine will not be able to provide the solutions to these problems, because the critical component is social.

**SO WHAT CAN YOU DO ABOUT IT?** Be proactive. Take a stand. Don't wait. You **can** make a difference.

Start dialogs with others now. Start with your family, your neighbors, your friends, and your classmates. Talk with local government and religious leaders to learn of the roadblocks, the inertia, and the resistance to change, and what can be done to overcome them. National and world governments can do virtually nothing to achieve this change if all their citizens are against it.

So you have to start with the individuals -- especially the ones of your generation. Significant change won't happen until the older people (who currently hold all the power) retire from industry and government, leaving their posts to be filled by bright young people of your generation who have already come around to the new way of thinking. This is how paradigm shifts occur.

The bottom line is:

> **Either we limit our population growth now and retain our humanity, or we savagely compete for scarce resources in the future.**

---

## 3a. Transitions: Infrastructure Sensitivity and Resilience

Before we reach the end of population growth, however, our society is becoming increasingly vulnerable to disruptions such as natural disasters. One aspect is **infrastructure**.

By infrastructure, we mean:

- transportation (including delivery of food and supplies)
- communication (phone and Internet)
- utilities (electricity, water), etc.

These are services and capabilities that we rely on for modern life. Even now, when the electricity fails for half a day, or the Internet is down for a day, we almost put our lives on hold until the services are restored.

---

## 3b. Disaster Prediction

The research we do in the Earth and Ocean Sciences Department at UBC is designed to better understand and predict natural events including disasters.

At present:

- With timely and accurate prediction of natural disasters, some or most people can be evacuated.
- But fixed infrastructure is increasingly destroyed by natural disasters.

This situation is summarized by the illustration below.

A. As we progress from now (on the left side of the graph) toward the near future (on the right), fatalities due to natural disasters are decreasing due to more accurate and timely warnings.

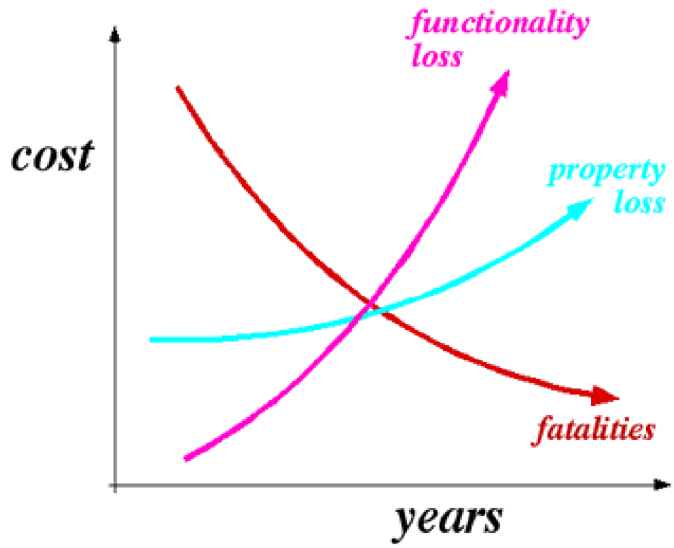



**Figure FS.14 A cost analysis for natural disasters in terms of fatalities and loss of functionality and property.**

B. However, other than some zoning restrictions and improved building codes, property losses will increase simply because of the increasing number and value of property in the world as population expands into ever-more-marginal locations.

C. But the functionality loss of our society due to disruption of our infrastructure is where the greatest expense could lie. This will be where society will likely suffer its greatest losses in the next 20 to 50 years.

---

## 3c. Increasing Sensitivity to Natural Hazards`

Fifty years from now and further in the future, as population continues to grow toward the eventual equilibrium state, we will likely find that:

- Infrastructure becomes even more sensitive, and fails for long periods in large areas.
- People are less likely to be evacuated successfully, so fatalities will increase.
- When all factors are taken together, the *functionality of human society is in jeopardy*. This is primarily due to overpopulation.

An interim goal during this transition period (i.e., in the present century) when the population is still growing but at a reducing rate, is:

**A sustainable society, resilient to natural hazards.**

---

## 4. Conclusions

Earthquakes, volcanoes, lahars, hurricanes, tornadoes, floods, tsunami, asteroid impacts ...

...are NOT disasters to the Earth. They are normal components of Earth's evolution.

Thus, we conclude that:

- the Earth is **NOT** a fragile system
- **Human population is**