# Part IV

# Physics

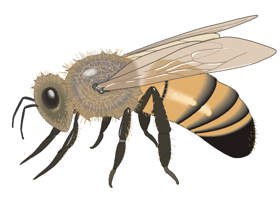
# Chapter 4

## Size and Scale

“Flying bumblebees violate the laws of physics!” Who hasn’t heard someone say this at one time or another? People may marvel that mosquitoes can walk on water, flies stick to the ceiling, or that cats can jump several times their length. Such talents seem supernatural to those who do not understand physics.

The simple explanation for these feats is that physics is *not* the same at all scales. The laws of physics change—or rather, certain physical forces dominate over others—depending on the size of the object and what scale defines its domain.

Most interestingly, some of the problems physicists are now encountering in quantum physics derive from the size and scale issue. Physicists frequently make the mistake of applying imagery from the macro-world to the subatomic world. Difficulties occur when we attempt to measure quantum events at a “classical physics” scale, as we will discover in the “Quantum Physics” section in this chapter.



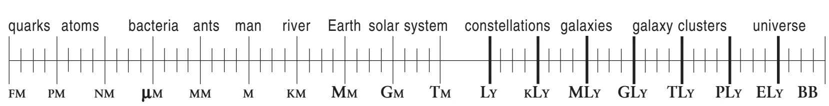
Different forces dominate these two objects.

The table below may help you to understand these size-scale relationships:

**Scale Relationships Table 4.a**

| Size/Scale | Example | Dominant Force |
|---|---|---|
| $10^{25}$ meters | Farthest known galaxy; ~size of the known universe | gravity, inertia |
| $10^{21}$ meters | Galaxy | gravity, inertia |
| $10^{13}$ meters | Planetary system | gravity, inertia |
| $10^{9}$ meters | the moon's orbit around Earth | gravity, inertia |
| $10^{7}$ meters | Earth | gravity, inertia |
| $10^{4}$ meters | An average city | gravity |
| $10^{2}$ meters | Largest buildings, ships, and trees | gravity, drag, friction |
| 1 meter | Human scale | gravity, friction, drag |
| $10^{-2}$ meters | Insects | viscosity |
| $10^{-5}$ meters | Biological cells | molecular forces, viscosity |
| $10^{-8}$ meters | DNA and large protein molecules | molecular forces |
| $10^{-20}$ meters | Atoms | atomic forces |
| $10^{-23}$ meters | Atomic nucleus | strong and weak nuclear |
| $10^{-26}$ meters | Quarks | strong nuclear force |

## Orders of Magnitude

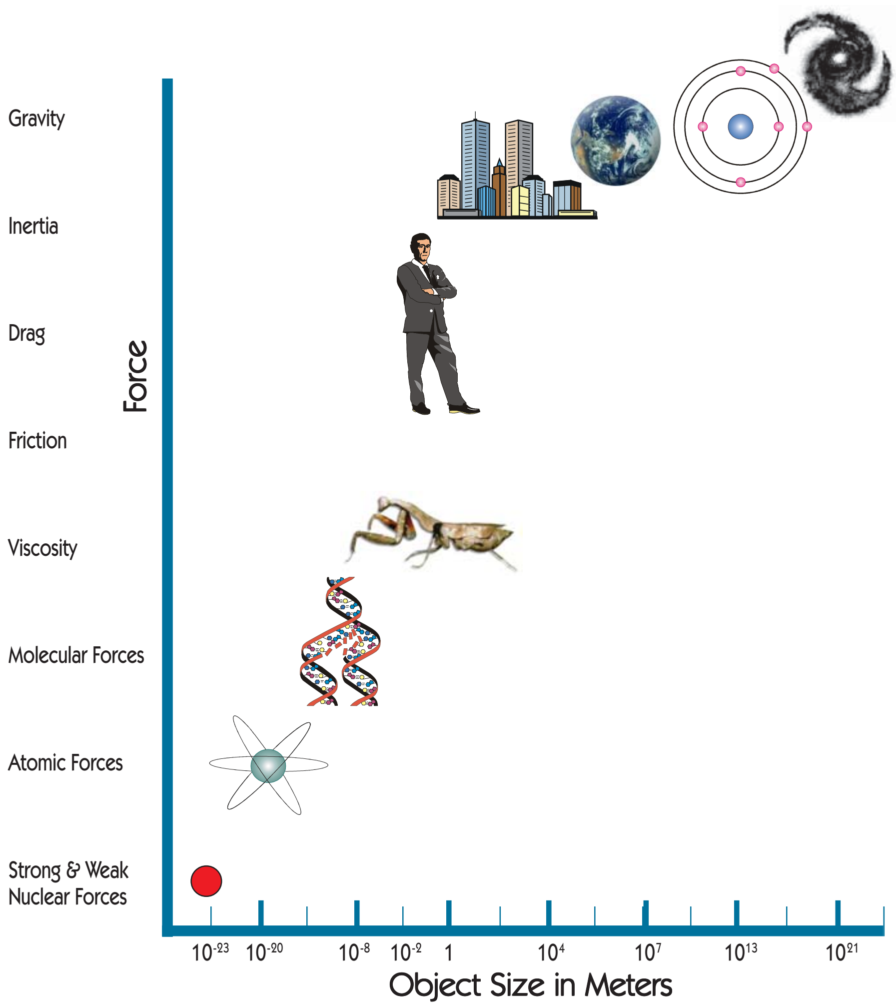


## Forces that Affect Things

- **Molecular forces:** act between molecules. There are two important types—attraction forces (adhesion, cohesion) and repulsion forces. Attraction forces hold molecules together; repulsion forces push molecules apart.
- **Viscosity:** is the thickness of a medium in which the object resides. Viscosity results from the strength of the attraction forces between the molecules that make up the medium. Air has a very low viscosity; water has a higher viscosity; living tissue has an even higher viscosity.
- **Friction and Drag:** the resistance a medium exerts against an object. Air pressure and surface texture cause friction and increase drag.
- **Inertia:** the resistance force of an object as it moves through space. The more massive the object, the more inertia it has.
- **Gravity:** is the force of attraction between objects. The more massive the objects, the stronger the force of gravity.

| Small Things | Large Things |
|---|---|
| • Molecular forces dominate.<br>• Little inertia.<br>• Viscosity of air or water is high compared to the inertia.<br>• Gravity doesn't affect them much. | • Molecular forces don't dominate.<br>• Have a lot of inertia during movement.<br>• The viscosity of air and water are low compared to the inertia.<br>• Gravity dominates. |

## Forces and Objects Table 4.b



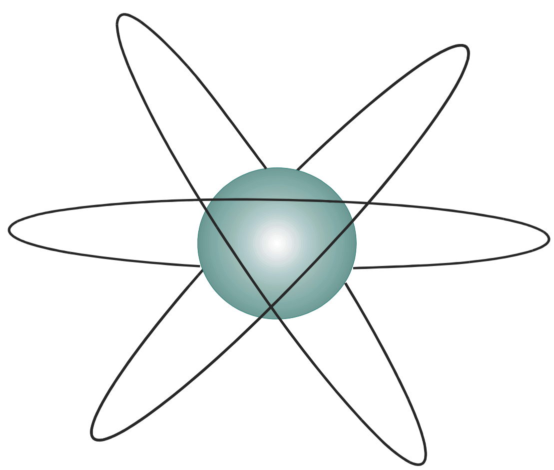
# Chapter 5

## Classical Physics

### Particles and Space: All That Is?

Classical Newtonian "high school" physics describes a universe of mostly empty space, peppered with atoms arranged into mechanistic systems. This "Common Universal Model"—a void containing atoms mimicking a planetary system (electrons orbiting a central nucleus as planets orbit a star) seems, intuitively, to serve well as an adequate and logical model of reality.

It is, however, abysmally simplistic and mostly wrong.



Newtonian physics implies that the universe is populated with only non-sentient objects. Scientists of Newton's era believed that there was some force separate from the forces acting on material objects—an omniscience or omnipotence—that exists as "first cause" of everything, a creator. Life, and especially humankind, was therefore not subject to the physical laws of the rest of the universe.

## Newton's Laws of Motion

Newton's Laws of Motion apply to large objects; these physical principles become insignificant for very small objects because other physical forces dominate smaller objects.

- **Newton's First Law of Motion (Inertia)**: if an object is left undisturbed, it will continue undisturbed, remaining either at rest or moving in a straight line with uniform motion.
- **Newton's Second Law of Motion**: A force applied to an object will cause a change in the momentum of the object. Momentum = mass x velocity: F = *p!* (force *F* causes momentum *p* to increase *!*).

**Newton's Second Law**

$$F = p\,!$$

- **Newton's Third Law of Motion**: To every action, there is an opposite and equal reaction. (Envision a cue stick and billiard balls in use.)
- **Newton's Law of Gravitation**: Every object in the universe exerts a gravitational force on every other object; this force depends on the masses of the objects and is the square of the distance separating them.

**Gravity Inverse Square Law**

$$F = g \times Mm/r^2$$

While Newton's Laws of Motion are still an accurate description of how large objects move in space, these laws are by no means a *complete* representation of how everything behaves in the universe. As we venture further into particle physics and cosmology, the most important concept to understand is that regardless of what we are discussing or how we describe it, we must always consider its *relationship* to all other things. Though science often employs reductionism in its pursuit of truth, the idea of *relationship* must never be forgotten or dismissed.

Relationship is at the heart of understanding energy and matter, and space and time. It is not possible to discuss energy without invoking mass (how much matter is present), or to discuss space without invoking time (as both are a measure of distance).

## Dimensions: Space and Time

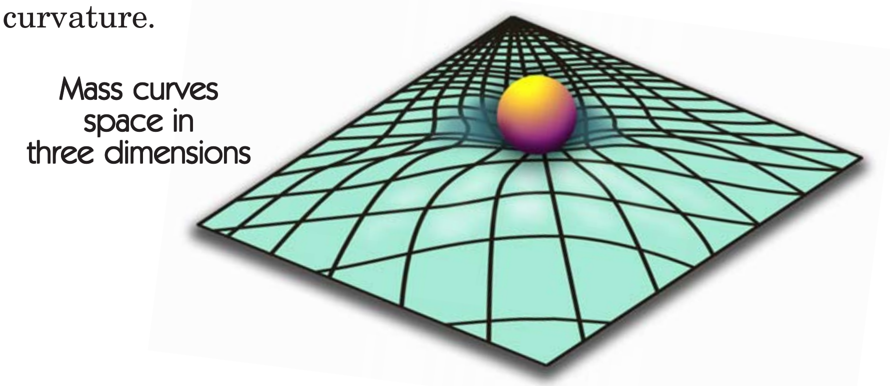
### Space

*What is space made of?* Democritus argued for "nothingness," while Aristotle rejected the notion of emptiness in favor of "something"—a background medium he called the "plenum." James Clerk Maxwell argued for the existence of the "ether." Einstein was the first to postulate that the mechanical properties of spacetime are determined by matter/energy (as matter and energy are equivocal: $E = mc^2$). Matter curves spacetime; this curvature is dependent on the distribution of matter (mass) within space.

### Gravity

Gravity is the weakest force in the universe, yet is by far the most long-reaching—it is infinite. Gravity's domain includes everything in the universe, but its effects are significant only for things larger than atoms.

Gravity is the effect of mass on the matrix of spacetime, creating curved space. Gravity describes the geometry of spacetime; the geometry of spacetime is determined by all the sources of gravity in that spacetime. Objects in space move the way they do, not because they "tug" on each other, but because mass curves space and moving objects follow the curvature.




Gravity and accelerated motion are equivalents as matter and energy are equals. Gravity and acceleration *both* curve space. The geometry of space and gravitational force are therefore equal. In the words of physicist John Wheeler: "Mass grips spacetime, telling it how to curve; spacetime grips mass, telling it how to move."

## Time

In classical physics, time is a measurement of motion in space. Time is regarded primarily as a fourth dimension, an *effect of an expanding universe*, which is revealed as *entropy,* the tendency of a system to go from order (symmetry) to disorder (asymmetry). Entropy may also be described as an ultimate state of inert uniformity. Entropy within a closed system must increase with time. Entropy is what causes the contents of a glass to reach a uniform temperature when ice cubes melt in room-temperature water. Entropy is loss of energy—specifically, heat. Everything loses heat. Energy must be pumped back into a system to equalize this loss—this does *not* happen in a closed system. Since the universe *is* a closed system, it has been losing heat since the Big Bang. From a trillion degrees Fahrenheit, it has cooled to 2.7 degrees Kelvin in about 15 billion years. The remaining background radiation in the universe is in the microwave range.

### Temperature Table 4.c

| °F | °C | °K | Effect |
|---|---|---|---|
| 212 | 100 | 373 | water boils |
| 32 | 0 | 273 | ice melts |
| -459.8 | -273.2 | 0 | absolute zero* |
| | | | * no energy; all chemical and physical reactions cease |

Time's arrow has only one direction—*outward* from the initial singularity explosion and inflation known as the Big Bang—so humans perceive that time passes. This is the perception of a linear mind, a mind able to understand only sequential reality.

Entropy is the way we measure time "passing"…or rather, it is the way we *used* to measure it. Our concept of time has matured, as we will see later.

## *Special Theory of Relativity*

Time is relative—meaning that it is not a constant, is not the same for everyone at every place in the universe. Velocity changes the experience of time as well as that of space. *Increased velocity expands time, which contracts and condenses space; decreased velocity contracts time, which expands space.* From a spaceship, for example, the universe looks huge and infinite at low speeds. Bring that spaceship's velocity up to near-light speed and a peculiar thing happens: The faster we go, the more contracted our view of the universe becomes until all the stars seem to squeeze to a pinpoint at the center of a long black tunnel.

This is in direct conflict with popular science-fiction movie depictions of "warping" into light-speed and watching all the stars streak *outwards* from our direction of travel. It is wrong. (And so are those noisy explosions in space we have all come to expect in the movies. Sound does not travel without an atmosphere as a medium. It is air molecules colliding into each other that creates sound.) In summary:

- **Time Dilation Effect** of the **Special Theory of Relativity**: The rate of time changes for an object in motion; the faster an object moves, the more slowly time flows, and the more contracted space becomes.
- **Lorentz-Fitzgerald Contraction**: the observer's perception that an object shortens towards the direction of its motion; the faster an object moves, the more "scrunched up" it appears.

As we will discover, classical physics is woefully incomplete and inadequate in describing spacetime. Quantum physics has shed new light on spacetime, gravity, and the special theory of relativity.

## Energy and Matter

In classical physics, matter is simply whatever is *not* space. Mass is how much matter is in an object. Mass does not mean *weight*—weight changes with the gravitational field in which the matter resides; mass does not. In addition, energy and matter are interchangeable entities—they are *identical*. Remember $E = mc^2$? Einstein's famous equation literally means that energy is the same as mass multiplied by *ceritas* (the speed of light) squared. As a result, in physics the mass of a particle is measured in electron volts—an *energy* measurement. (See tables 4.d and 4.e on p. 94.)

Also according to Einstein, an accelerating object increases in mass due to the increase in *energy* from the acceleration (mass and energy being equals, as in $E = mc^2$). This increase in mass would increase its energy *requirement* to maintain momentum. (Momentum is the result of mass times velocity, in which velocity is defined as the derivative of position with respect to time.) This is why it is currently not possible to even approach the speed of light in space travel.

### Multiples of Electron Volts Table 4.d

| ABBR. | NAME | VALUE |
|---|---|---|
| eV | electron volt | 1 |
| KeV | kiloelectron volt | $10^3$ eV |
| MeV | millielectron volt | $10^6$ eV |
| GeV | gigaelectron volt | $10^9$ eV |
| TeV | teraelectron volt | $10^{12}$ eV |

### Energy/Mass Equivalents Table 4.e

| PARTICLE | MASS | EV |
|---|---|---|
| electron (e-) | 0.511 | MeV |
| muon ($\mu$) | 105.7 | MeV |
| pion ($\pi\pm$) | 139.6 | MeV |
| pion ($\pi^0$) | 135.0 | MeV |
| kaon (K) | 493.7 | MeV |
| proton (p) | 988.3 | MeV |
| neutron (n) | 939.6 | MeV |
| lambda ($\lambda^0$) | 1115.6 | MeV |
| photon ($\gamma$) | ~ 10 | eV |
| x-ray | ~ 100 | keV–10MeV |

Remarkably, matter is 90% or more empty space. If all space were eliminated from the atoms that make up a human being, the mass volume would be the size of a pinhead.

Mass is partially an effect of atomic movement. The more confined in space a particle is, the faster it moves. Things are perceived as solid when electrons spin at least 600 miles per second. Consequently, there is no such thing as a solid in the subatomic realm; solidity is significant only on scales above the molecular realm.

## The Four Laws of Thermodynamics

Thermodynamics is the study of the interrelation between heat, work, and the internal potential energy (mass) of a system.

- **Zeroth Law (Law of Equivalence):** Two systems in thermal equilibrium with a third are in thermal equilibrium with each other.
- **First Law of Thermodynamics (Law of Conservation):** Einstein's famous equation, $E = mc^2$, describes the relationship between energy and matter, demonstrating that energy and matter are interchangeable. Energy can be changed from one form to another, but it cannot be created or destroyed. The total amount of energy/matter in the universe remains constant, merely changing from one form to another. Energy is always conserved. Everything in nature seeks a condition in which the energy required to maintain it is minimal. *Translation: You can't win (you cannot get something for nothing, because matter and energy are conserved).*
- **The Second Law of Thermodynamics (Law of Entropy):** in all energy exchanges, if no energy enters or leaves the system, the *potential* energy of the state will always be less than that of the initial state. In the process of energy transfer, some energy will dissipate as heat. *Entropy* is the measure of the disorder or randomness of energy/matter in a system.

  The flow of energy maintains order and life. (Living cells are *not* disordered and so have low entropy. Entropy wins when organisms cease to take in energy and die.) For example, once the potential energy locked in food is converted into kinetic energy (energy in use or motion), the organism will get no more useable energy until potential energy is input again.

  Entropy also governs the "arrow of time": Heat can never pass spontaneously from a colder to a hotter body. As a result of this fact, natural processes that involve energy transfer must have one direction, and all natural processes are irreversible. This law also predicts that the entropy of an isolated system always increases with time. The only time the universe knew perfect order (symmetry) was the instant after the Big Bang, when energy and matter and all of the forces of the universe were unified. Because of the second law of thermodynamics, both energy and matter in the universe are becoming more disordered as time goes on. *Translation: You can't break even (you cannot return to the same energy state, because there is always an increase in disorder; entropy always increases).*

- **Third Law of Thermodynamics (Absolute Zero is Unattainable):** if all the thermal motion of molecules (kinetic energy) could be removed, a state called *absolute zero* would occur. Absolute zero results in a temperature of 0° Kelvin, or -273.15° Celsius. The universe will attain absolute zero when all energy and matter is randomly distributed across space. The current temperature of empty space in the universe is about 2.7° Kelvin. *Translation: You can't get out of the game (because absolute zero is unattainable).*

## Atomic Particles

In classical physics, atoms contain many subatomic particles with specific properties. Some particles are stable and some are not. Stable particles include protons, neutrons, electrons, photons, and neutrinos. They're around all the time and generally don't change into other particles unless exposed to unusual extremes. Stable particles are sometimes called *hadrons*—which include the sub-classes *baryons* and *mesons*; and *leptons*—which include electrons and neutrinos. More on this strange zoo in the "Quantum Physics" section.

## Electromagnetic Spectrum Table 4.f

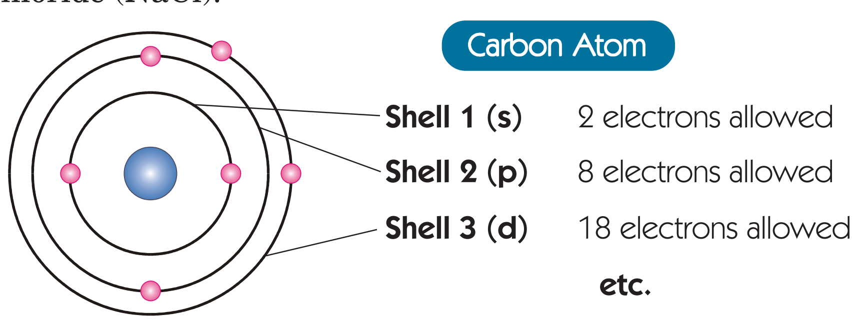
| Frequency (Hz) | Radiation | Wavelength (cm) | |
|---|---|---|---|
| $10^{23}$ | | | |
| | Cosmic Rays<br>nuclear particles | $10^{-12}$ | |
| $10^{22}$ | | | |
| | | $10^{-11}$ | |
| $10^{21}$ | | | |
| | Gamma Rays<br>(photon emission in decay) | $10^{-10}$ | |
| $10^{20}$ | | | |
| | | $10^{-9}$ | |
| $10^{19}$ | | | |
| | X-Rays<br>(bombardment from accelerated photons) | $10^{-8}$ | |
| $10^{18}$ | | | |
| | | $10^{-7}$ | |
| $10^{17}$ | | | |
| | | $10^{-6}$ | |
| $10^{16}$ | Ultraviolet | | |
| | | $10^{-5}$ | |
| $10^{15}$ | Visible Light | | |
| | | $10^{-4}$ | |
| $10^{14}$ | | | |
| | Infrared | $10^{-3}$ | |
| $10^{13}$ | | | |
| | | $10^{-2}$ | |
| $10^{12}$ | Submillimeter Waves | | |
| | | $10^{-1}$ | |
| $10^{11}$ | | | |
| | | 1 | |
| $10^{10}$ | Microwaves | | |
| | | 10 | |
| $10^{9}$ | | | |
| | TV and FM Radio | $10^{2}$ | UHF |
| $10^{8}$ | | | |
| | | $10^{3}$ | VHF<br>HF |
| $10^{7}$ | Shortwave | | |
| | | $10^{4}$ | MF |
| $10^{6}$ | AM Radio | | |
| | | $10^{5}$ | LF |
| $10^{5}$ | | | |
| | Maritime Communications | $10^{6}$ | |
| $10^{4}$ | | | VLF |

Electrons rule the atom: It is the exchange and sharing of electrons that governs how atoms bond together to form molecules, and eventually, complex material systems.

Electrons obey strict rules of behavior in some instances, and in other instances seem to behave arbitrarily, tunneling through domains and barriers like crazed escape artists (this property of electrons is discussed more in-depth in the "Quantum Bizarro" section). Inside the atom, electrons maintain their own territorial energy levels (or states) called *shells* and can't collapse into each other. This is called the *Pauli Exclusion Principle* and cannot be violated. The number of electrons in the outermost shell determines atomic stability. In general, the innermost shell (shell 1 or the "s" shell) of an atom contains two electrons (except in hydrogen). Subsequent shells contain a number of electrons dictated by the formula $2n^2$ (n = the shell number).

Atoms also obey the *Octet Rule,* meaning that if the outermost shell of an atom contains eight electrons it is fairly stable. Atoms will combine readily with other elements that have a "complimetary" number of electrons in their outer shells. This is determined by *valence,* the number of electrons atoms will "share" with other elements to complete the octet. Valence is equal to the number of outer electrons if four or less; otherwise, valence is equal to 8 minus the number of outer electrons.

For example, sodium ($Na^+$) contains one electron in its outer shell (valence +1); chlorine ($Cl^-$) contains seven (valence -1). These two elements readily combine to make up sodium chloride (NaCl).



## Forces

There are four forces in the universe: electromagnetic, strong nuclear, and weak nuclear, and gravity—which may not be a force at all according to Einstein's original thesis. (More on gravity's paradox later in the "Quantum Physics" section.)

Before the Big Bang (when the universe was "born"), all forces were unified into one. Scientists are putting it all on the line to accelerate particles at high enough energies to reunify the forces into one. This pursuit is the "Holy Grail" of particle physics, and will result in a Grand Unified Theory (GUT).

To date, two of the forces have been unified: The electromagnetic and weak forces are known collectively as the electro-weak force. Physicists are trying to collide particles in synchrotrons and cyclotrons (particle accelerators or colliders) at high enough speeds to unite the strong and electro-weak forces. Such a breakthrough would bring us closer to an understanding of how the universe formed.

### Forces Table 4.g

| Force | Range | Strength |
|---|---|---|
| Gravity | infinite | $10^{-38}$ |
| Electromagnetic | infinite | $10^{-2}$ |
| Weak Nuclear | $10^{-15}$ mm | $10^{-13}$ |
| Strong Nuclear | $10^{-12}$ mm | 1 |