

## 1.4: The Scope of Physics

Physics describes a wide range of phenomena within the physical sciences, ranging from the behaviour of microscopic particles that make up matter to the evolution of the entire Universe. We often distinguish between “classical” and “modern” physics depending on when the theories were developed, and we can further subdivide these areas of physics depending on the scale or the type of the phenomena that they describe.

The word physics comes from Ancient Greek and translates to “nature” or “knowledge of nature”. The goal of physics is to develop theories from which mathematical models can be derived to describe our observations. One of the ambitious goals of physicists is to develop a single theory that describes all of nature, instead of having multiple theories to describe different categories of phenomena. This is in stark contrast to other fields of science, as Rutherford famously quipped: “All science is either physics or stamp collecting”. That is, physicists hope that there exists one single mathematical theory (like Chloë’s theory of falling objects) that describes the entire physical world. In Biology, for example, this would not be a reasonable goal, as one needs to describe every single living being, and there is no overarching “theory of what all living things look like”. Currently, physicists have been able to narrow down the number of theories required to describe all of the physical world to only three, which is impressive (the theory of gravity, the theory of the strong nuclear force, and physicists have now further unified the weak nuclear force with electromagnetism to make the “electroweak force”).

### 1.4.1: Classical Physics

This textbook is focused on classical physics, which corresponds to the theories that were developed before 1905.

#### 1.4.1.1: Mechanics

Mechanics describes most of our everyday experiences, such as how objects move, including how planets move under the influence of gravity. Isaac Newton was the first to formally develop a theory of mechanics, using his “Three Laws” to describe the behaviour of objects in our everyday experience. His famous work published in 1687, “Philosophiae Naturalis Principia Mathematica” (“The Principia”) also included a theory of gravity that describes the motion of celestial objects.

Following the 1781 discovery of the planet Uranus by William Herschel, astronomers noticed that the orbit of the planet was not well described by Newton’s theory. This led Urbain Le Verrier (in Paris) and John Couch Adams (in Cambridge) to predict the location of a new planet that was disturbing the orbit of Uranus rather than to claim that Newton’s theory was incorrect. The planet Neptune was subsequently discovered by Le Verrier in 1846, one year after the prediction, and seen as a resounding confirmation of Newton’s theory.

In 1859, Urbain Le Verrier also noted that Mercury’s orbit around the Sun is different than that predicted by Newton’s theory. Again, a new planet was proposed, “Vulcan”, but that planet was never discovered and the deviation of Mercury’s orbit from Newton’s prediction remained unexplained until 1915, when Albert Einstein introduced a new, more complete, theory of gravity, called “General Relativity”. This is a good example of the scientific method; although the discovery of Neptune was consistent with Newton’s theory, it did not prove that the theory is correct, only that it correctly described the motion of Uranus. The discrepancy that arose when looking at Mercury ultimately showed that Newtons’ theory of gravity fails to provide a proper description of planetary orbits in the proximity of very massive objects (Mercury is the closest planet to the Sun).

#### ? Exercise 1.4.1

What did the inability to find the planet Vulcan show:

- A. It showed that Newton’s model of Mercury was correct.
- B. It showed that Newton’s theory did not correctly describe the orbits of all planets.
- C. It showed that the technology at the time was inadequate.
- D. It showed that Einstein’s theory of General Relativity was correct.

**Answer**

#### 1.4.1.2: Electromagnetism

Electromagnetism describes electric charges and magnetism. At first, it was not realized that electricity and magnetism were connected. Charles Augustin de Coulomb published in 1784 the first description of how electric charges attract and repel each

other. Magnetism was discovered in the ancient world, when people noticed that lodestone (rocks made from magnetized magnetite mineral) could attract iron tools. In 1819, Oersted discovered that moving electric charges could influence a compass needle, and several subsequent experiments were carried out to discover how magnets and moving electric charges interact.

In 1865, James Clerk Maxwell published “A Dynamical Theory of the Electromagnetic Field”, wherein he first proposed a theory that unified electricity and magnetism as two facets of the same phenomenon. One important concept from Maxwell’s theory is that light is an electromagnetic wave with a well-defined speed. This uncovered some potential issues with the theory as it required an absolute frame of reference in which to describe the propagation of light. Experiments in the late 1800s failed to detect the existence of this frame of reference.

### 1.4.2: Modern Physics

In 1905, Albert Einstein published three major papers that set the foundation for what we now call “Modern Physics”. These papers covered the following areas that were not well-described by classical physics:

- A description of Brownian motion that implied that all matter is made of atoms.
- A description of the photoelectric effect that implied that light is made of particles.
- A description of the motion of very fast objects that implied that mass is equivalent to energy, and that time and distance are relative concepts.

In order to accommodate Einstein’s descriptions, physicists had to dramatically re-formulate new theories.

#### 1.4.2.1: Quantum mechanics and particle physics

Quantum mechanics is a theory that was developed in the 1920s to incorporate Einstein’s conclusion that light is made of particles (or rather, quantized lumps of energy called quanta) and describe nature at the smallest scales. This could only be done at the expense of determinism, the idea that we can predict how particular situations evolve in time. This led to a theory that could only provide the *probabilities* that certain outcomes will be realized. Quantum mechanics was further refined during the twentieth century into Quantum Field Theory, which led to the Standard Model of particle physics that describes our current understanding of matter through the theories of the electroweak and strong forces.

#### 1.4.2.2: The Special and General Theories of Relativity

In 1905, Einstein published his “Special Theory of Relativity”, which describes how light propagates at a constant speed without the need for an absolute frame of reference, thus solving the problem introduced by Maxwell. This required physicists to consider space and time on an equal footing (“space-time”), rather than two independent aspects of the natural world, and led to a flurry of odd, but verified, experimental predictions. One such prediction is that time flows slower for objects that are moving fast, which has been experimentally verified by flying precise atomic clocks on airplanes and satellites. In 1915, Einstein further refined his theory into General Relativity, which is our best current description of gravity and includes a description of Mercury’s orbit which was not described by Newton’s theory.

#### ? Exercise 1.4.2

Special relativity can be applied to which of these science fiction plots?

- A. An eccentric duo travel back in time to alter the past.
- B. An astronaut traveling near light speed for many years comes home to find that he has aged less than his family on Earth.
- C. A superhero harnesses lightning to use as a weapon.

**Answer**

#### 1.4.2.3: Cosmology and astrophysics

Cosmology describes processes at the largest scales and is mostly based on applying General Relativity to the scale of the Universe. For example, cosmology describes how our Universe started from the Big Bang and how large scale structures, such as galaxies and clusters of galaxies, have formed and evolved into our present day Universe.



Figure 1.4.1: A galaxy in the Coma cluster of galaxies (credit: NASA).

Astrophysics is focused on describing the formation and the evolution of stars, galaxies, and other “astrophysical objects” such as neutron stars and black holes.

#### 1.4.2.4: Particle astrophysics

Particle astrophysics is a relatively new field that makes use of subatomic particles produced by astrophysical objects to learn both about the objects *and* about the particles. For example, the 2015 Nobel Prize in Physics was awarded to Art McDonald (a Canadian physicist from Queen’s University) for using neutrinos<sup>1</sup> produced by the Sun to both learn about the nature of neutrinos and about how the Sun works.

### 1.4.3: Footnotes

1. Neutrinos are the lightest subatomic particles that we know of

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