§1. THE FOUR FORCES OF NATURE

We see the effects of force all around us. The force of gravity, the electric and magnetic forces of natural and manmade objects, and the mechanical force of machines all have well known effects. In pre–twentieth century science, natural philosophers asked many of the same questions that are asked here — why does nature behave in the way it does? Although these questions have the tone of theological or philosophical inquiries, the study of these forces and their interaction with matter is generally the domain of physics [Alio87].

The development of the concept of a force marks the boundary between science and pre–science [Jamm62], [Agas68], [Cajo29]. In early history, objects were believed to have internal powers, which could account for their movements. The motion of the planets through the night sky was associated with gods, and supernatural powers. It was realized during the time of Galileo that the function of a force was not to produce the motion, but to produce a change in the motion [Whit58], [Koyr55], [Jamm62], [Hawk87], [Roge60]. This description of force was not significantly different from the previous occult force, since the origin of the force was not known. However, these forces could be measured which allowed quantitative order to be brought to nature.

One of the most significant scientific developments in the past several centuries was the concept of a continuous field of force [d’Abro39], [Adai87], [Hess61], [Sach73]. This discovery replaced action–at–a–distance with action conveyed through a field. The application of this concept by 19th century scientists lead to a new understanding of electricity and magnetism which strongly influenced 20th century physics [Beck74]. The special theory of relativity exploited the concept of a continuous field to describe the motion of objects, including electromagnetic waves, independent of any special reference frame. The second revolution in 20th century physics was quantum theory, which describes matter at the atomic level in the form of fields. With electromagnetism's fields of force, special relativity's fields of geometry and quantum theory's fields of probability, the notion of a field is capable of describing nearly all aspects of physical processes [Sach73], [Agas68].

> *I do not know what I may appear to the world; but to myself I seem to have been only like a boy, playing on the sea–shore, and diverting myself, in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me*
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> *— Isaac Newton [Brew55]*

§1.1 THE EVERYDAY FORCE OF GRAVITY

The most familiar force in everyday life is the gravitational force, which unifies the behavior of objects on the human scale of a few centimeters to the galactic scale of $10^{25} cm$. This force holds objects to the earth, it keeps the planets in their orbits, it maintains the path of stars in the galaxy and it forms the glue the binds the galaxies together. The strength of the gravitational force is proportional to the product of an object's mass and inversely proportional to the square of the distance between the objects. Gravity is the only force that acts in the same manner between all types of matter. Neutrons, protons, electrons, and the matter they form all attract each other according to the law of gravity. Since the same law applies to all objects, gravity can be considered the result of the geometrical properties of space itself [Tayl66], [Hawk87]. Einstein formulated the general theory of relativity on this basis. Unlike Newton's inverse square law of gravity, the strength of the gravitational force in general relativity is not a simple inverse square relationship. [1] Although the force of gravity dominates the human experience, it is in fact the weakest force of nature.

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[1] The concept of the gravity in Newtonian mechanics implies that a test particle is subject to an external force — the gravitational force. This force acts in a linear fashion on the test particle as it travels through the gravitational field. In the General Theory of Relativity, the presence of the test mass influences the behavior of the gravitational force, so that the *force* felt by the test particle is non–linear. In the Newtonian view of gravity, the force field is *static* and can be represented by a scalar potential, just as the electrostatic potential can be represented by the Coulomb potential. When the electromagnetic field is not static — it is dynamic — the addition of the vector field is required to represent the complete system. These scalar and vector portions of the electromagnetic field can be represented by a 4–vector potential. The consequence of this form of representation is that electromagnetic disturbances are propagated with the speed of light. In Maxwell's representation, the potentials satisfy the wave equation, rather than the Poisson's static potential equation. In General Relativity the Poisson equation $\nabla^2 U = -4\pi\kappa\rho$ describing the static gravitational potential is replaced by $\nabla^2\sqrt{-g_{00}} = 4\pi\kappa\rho^*$, where ρ^* is the density of mass–energy, not just mass and g_{00} is the metric tensor describing the curvature of space–time. Space–time is *curved* as a result of the presence of matter [Fran79], [Misn75].

The discovery of the gravitational force was made by Sir Isaac Newton (1642–1726) while attempting to explain Johannes Kepler's (1571–1630) three laws of planetary motion [Koyr55], [Holt56], [Step94]. The history of Newton's discovery of the laws of gravity is surrounded in popular myth. The 17th century laws governing the motions of celestial objects were regarded quite differently from those governing the motions of bodies on earth. The study of the motion of a heavenly body, particularly the planets and the sun, was the primary subject taught in the university in the mid 1600's. Students of *natural philosophy* at Cambridge in 1664 discussed these motions in detail. In 1665, the plague broke out in England and classes at Cambridge were suspended [Manu68], [Chri97], [Shre70]. The 23 year old Isaac Newton student was sent home in June to Woolsthrope of that year and did not return until March of 1666 [Manu68]. While pursuing his B. A. Degree in the Lent Term of 1665, Newton remained home to think about the question of planetary motion [Sedg39]. He was apparently inspired as he saw an apple fall to earth in an orchard. [2] It occurred to

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[2] Newton's contribution to the science of physics is well documented. His formulation of mechanics and his ideas of absolute space and time were not seriously challenged until Albert Einstein developed the theory of special relativity nearly 250 years after Newton, in 1905. Newton also invented the fluxional calculus, conceived the idea of universal gravitation, discovered its law, and discovered the composition of white light [Resn60].

In a biography written by Newton's friend Dr. William Stukeley in 1752, *Memoirs of Sir Isaac Newton*, Stukeley states that he was having tea with Newton in a garden under some apple trees, when Newton said that the setting was the same as when he got the idea of gravitation, earlier as he noticed an apple *drawn to earth* in his mother's Woolsthrope garden [Asim82], [West80], [Fren88], [Stuk36], [Manu68], [Chan95].

> It was occasioned by the fall of an apple, as he sat in a contemplative mood. Why should that apple always descend perpendicularly to the ground, thought he to himself? Why should it not go sideways or upwards, but constantly to the earths centre? Accordingly, the reason is that the earth draws it.

Another account of this incident is given by Newton himself through the words of his associate John Conduitt:

> Whilst he was musing in a garden came into his thought that the power of gravity (which brought an apple from the tree to the ground) was not limited to a certain distance from the earth but that this power must extend much further then was usually thought. Why not as high as the moon said he to himself and if so that must influence her motion and perhaps retain her in her orbit, where upon he fell to calculating that would be the effect of that supposition. [West80]

The particular tree under which Newton was to have been siting has been identified as a yellow–green cooking apple in the front garden of Newton's home in Woolsthrope. When the tree collapsed in the 18th century, a cutting was grafted to another tree in the botanical garden of Kew outside London.

Newton that the same force that attracts the apple to the earth could also attract the moon to the earth. Newton postulated that the centripetal acceleration of the moon in its orbit and the downward acceleration of a body on the earth might have the same origin. The idea that celestial motions and terrestrial motions followed similar laws was a major break in the tradition of 17th century science [d'Arbo27], [d'Arbo39]

Newton postulated that a universal attractive force between two bodies could explain the motions of the moon around the earth as well as the motions of the planets [3]. Before the time of Galileo, most natural philosophers thought that some external influence or force was needed to keep a body moving. They thought that a body was in its natural state when it was at rest. In order for a body to move in a straight line at constant speed, they believed that some external agent had to continually propel it along — otherwise the body in motion would naturally stop [Resn60].

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[3] Newton wrote down his *laws of motion* in *Philosophiae Naturalius Principia Mathematica*, between 1684 and 1687. In this text, Newton collected his previous incomplete studies in mechanics and mathematics. The writing of *Principia* arose from a discussion at the Royal Society in 1684 between astronomer Edmond Halley (1656–1742) the architect Sir Christopher Wren (1632–1723) and Newton's archival Robert Hooke (1635–1703) [Manu68], [Rona69], [Chri97], [Hall32]. The discussion revolved around the conjecture by Wren that the inverse square law implies that elliptical orbits of the planets must be produced. Hooke claimed that he had a proof of this theory, but could not actually produce the mathematics. Halley went to ask Newton the same question. Newton claimed he could prove this conjecture, but he also did not have the mathematics to back up his claim. Using Kepler's observations, Newton produced, in April of 1685, a nine page paper (in Latin) *De Motu Corporum* (*On the motion of bodies in Orbit*), which described the elliptical paths of the planets in terms of the Laws of Gravitation and the Laws of Motion [Manu68]. This paper laid the foundation for the mathematical description of the laws of classical mechanics described in *Principia*, first published in 1687.

Newton reasoned that the forces between bodies must be the consequences of a force between particles, which make up the bodies. 22 years after the Lent Term, Newton consolidated his ideas in *Principia*. Newton wrote the *Principia* in three parts, using the methods of Euclidean geometry to derive his results. The first part describes the motion of a body from the forces acting on it. The second part describes the forces encountered in nature and the third examines the solar system and the motion of planets under the force of gravity. All of these subjects are developed through axioms, lemmas and theorems in the same manner as a Greek mathematical exposition. The result is a text that is very difficult to read, even by today's standards, because of the geometric language. The differential and integral calculus that was invented for describing motion was not included in *Principia*.

§1.2 EARLY ASTRONOMY — THE HISTORY OF THEORY

Early astronomy provides a clear example of the growth and use of theory in the development of a deeper understanding of nature. Astronomy is almost as old as mankind. When early civilization ventured outside their known world, trade routes were formed. These routes required navigation aides in order to be reliably traveled. The compass, clock and calendar became essential components of modern civilizations. Astronomy provided all three.

> *The relative individualism of the history of science as opposed to general history, is also due to the fact that if it is not altogether easy to analyze and to estimate a man's contributions in the field of science, at least it is a good deal easier than is any other field, except art.*
>
> *— George Sarton [Sart31]*

The earliest attempts to describe the solar system were made by the Greeks in the 4th century BC. Aristarchus of Samos (310–230 B.C.) proposed a heliocentric system [Heat13], [Clag55], [Cole60], [Neug52]. Archimedes (287–212 B.C.) assumed the earth moved in an orbit whose radius, when compared to the fixed stars, was the same ratio of the center of the earth to its surface. A detailed description of the conclusions of the Greek astronomers was published in the 2nd century by (Claudius Ptolemaeus) Ptolemy [4] and described a geocentric system in which the earth is stationary at the center of the universe. The sun, planets and all stars revolve around the earth in complex orbits. This theory had great influence on the philosophy and literature for fifteen centuries. Since the theory was computationally complex, it could not be used to quantitatively

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[4] The Egyptian astronomer Ptolemy (90–168 AD) recorded his astronomical observations in *The Almagest* (Arabic for *The Greatest*). The exact birth, death and publication dates of Ptolemy are not reliably known. He lived during the reigns of emperors Trajan, Hadrian, Antonious Pius and Marcus Aurelius from around 100 AD to 178 AD. He worked in or near Alexandria Egypt. Ptolemy drew on the works of Hipparchus of Nicaea (180–125 BC) [Sart31], [Clag55], [Farr49], [Ging93], who was a well-respected Greek astronomer. Hipparchus' observations led to the development of trigonometry using theorems of similar triangles. From these theorems, the concepts of sine, cosine and tangent were defined.

Ptolemy also wrote *Geography*, which summarizes all Greek knowledge on the subject of maps, including various methods of projecting the surface of the earth onto flat maps. Ptolemy's book was lost during the Dark Ages and cartography became a lost science. Ptolemy remained one of the greatest astronomers until Copernicus, Tycho and Brahe [Farr49], [Whit58], [Adle60].

account for the increasing number of accurate observations of the motions of the stars and planets. In 1514 Nicolus Copernicus (1473–1543) suggested that a simpler description of the motions of the planets could be developed, by placing the sun at the center of the universe, with the earth, planets orbiting this center [Rose71], [Kuhn56], [Kuhn57], [Ging93], [Armi57], [Banv76].

Copernicus agreed that for certain phenomena, which were used to justify the evidence for the stationary theory of the earth, this evidence would not be altered if the earth moved and the sun was stationary.

> The centre of the earth is not the centre of the universe. We revolve around the sun like any other planet. The earth's unmobility (is) due to an appearance [Rose59].

The controversy over the heliocentric theory prompted astronomers to gather more accurate data about the motions of celestial objects. The observations made by Tycho Brahe (1546–1601), [5] recorded in *Astronomiae Instauratae Mechanica*, were analyzed and interpreted by Kepler, who had been Brahe's assistant [Holt56], [Banv81].

Using the precise observations of Tycho Brahe, including error measurements, Kepler found regularities in the motion of the planets and formulated his three laws of planetary motion. [6] Kepler's laws reinforced

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[5] Tycho Brahe observed a supernova in 1572, which bears his name. Tycho's visual observations were made with great care and were sufficiently accurate to deduce the rate of decrease of the brightest supernova of the time. He was able to make these accurate and systematic measurements with the help of instruments constructed with funds provided by King Frederick II of Denmark. He made several advances in measuring celestial objects. He derived methods for measuring the *flex* in the instruments. He corrected for the effects of refraction when stars were observed at different elevations above the horizon. He included the error values for his observations. These techniques are recorded in *Epistolarum Astronomicarum*. This information was vital for the proper interpretation of Brahe's observation by Kepler 20 years later.

[6] Kepler assumed circular orbits, but the closest he could come to describing the plant's motion had an error of 6–8 arc minutes. This error was outside the error band of Tycho Brahe's observations. The 6–8 arc minutes is equivalent to the width of a wooden pencil when viewed from a distance of ten feet.

> From these eight minutes, we will construct a new theory that will explain the motions of the planets – Kepler.

Kepler's next attempt used *ovoid* orbits and an inverse square law of the force driving the planet's motion. Kepler attempted to use this law to describe the velocity of the planets in their orbits. After some difficulty, he *intuitively* adopted the idea of equal areas swept out in equal time – the aeral law.

the Copernican theory and showed the simplicity with which planetary motions could be described when the sun was placed at the center of the orbital system. These laws described the motions of the planets using empirical data, without any theoretical interpretation. However, Kepler had no concept of the force that caused the planets to move with regularity. It was Newton's great triumph that the laws of motion, using gravity as the force, could be derived from Kepler's laws of planetary motion. Newton could account for the motion of the planets in the solar system and for the motion of the bodies falling near the earth with the same concept. He unified, in one theory, the theory of terrestrial mechanics and celestial mechanics. [7]

Kepler's first two laws were published in *Astronomia Nova* (*The New Astronomy: Based on Causes or Celestial Physics*) (1609) [Kepl09] and the third in *Harmonice Mundi* (*Harmony of the World*) (1619) [Kepl16]. Kepler's three laws are: (i) each planet moves in an elliptical orbit, with the Sun at one focus of the ellipse; (ii) the focal radius from the Sun to a planet sweeps equal areas of space in equal intervals of time; (iii) the square of the sidereal periods of the planets are proportional to the cube of their mean distance to the Sun. This third *law* can be stated as $A^3 = kT^2$ where T is the period of the planet and A is the semimajor axis of its elliptical orbit and k can be given in terms of Newton's gravitational constant [Emch84].

Kepler's first law expresses the constancy of the observed orbits and the total angular momentum of the plant–sun system. This observation which was seen as...

> ... a marvelous manifestation of the harmony of Nature. [Banv81]

This observation revels itself today as a consequence of the laws of dynamics. In fact, Kepler's Law is incorrect because it is not the angular momentum of the plant–sun system that remains constant, but the angular momentum of the entire solar system. The angular momentum vector for the entire system is perpendicular to the *invariable plane of Laplace*. Fortunately for Newton, Kepler's error has negligible impact because of the weak interaction between the plants compared to the interaction between the Sun and the planets [Doug90].

[7] Newton was the first to state that his work was the culmination of the work of others. In a letter to Robert Hooke...

> If I have seen further (than you) it is by standing upon the shoulders of Giants.

Although the quote of Newton has been popularized into a comment regarding the substantial works of previous scientist, it is more complex. The reference to *the shoulders of giants* is taken from John of Salisbury's *The Metalogicon* [Spey94], [Thor90]...

> Bernard of Chatres used to compare us to (puny) dwarfs perched on the shoulders of giants. He pointed out that we see more and further than our predecessors, not because we have keener vision or greater height, but because we are lifted up and borne aloft on their gigantic stature [Sals55].

The quote can actually be taken as backhanded *slap* at Robert Hooke (1635–1703), who Newton carried on a life time rivalry. Newton used this quote in a letter responding to Hooke's claim that Newton stole the hypothesis on light from Hooke's *Micrographia*

The force Newton postulated would be proportional to the product of the masses of the two bodies and inversely proportional to their separation. Newton then developed the laws of motion that govern the path taken by a body in the presence of this gravitational force [Cajo62], [Fren88], [West80]. [8]

The most well known of these laws is Newton's second law of motion, $\mathbf{F} = ma$,[9] which states that a force **F** produces an acceleration on a body proportional to the mass of body — given the same force, light bodies are accelerated faster than heavy bodies. [10] This law describes the acceleration, force and mass properties of material bodies [Wein61].

[Hook61]. Newton was familiar with *Micrographia* and claimed that Hooke took much of that work from Descartes who — claimed Newton — took his work from Marcantonio de Dominis and Ariotto [Hall62], [Manu68], [Koyr65].

[8] There is evidence in Newton's student notebooks that he had learned of Kepler's first and third laws from, *Astronomia Carolina* written in 1661 by Street [Robi90].

[9] Unlike computer languages, which we are familiar with, mathematical notation is *read* left to right. As the above sentence *says*, a force produces an acceleration on a mass. In Einstein's General Theory of Relativity, accelerations produce force, so that Newton's Second Law has reciprocity. In general though equations do not exhibit such behaviors. Although the point seems trivial, the mathematics of physics, unlike the mathematics of computing (some would argue this), is a *language* in which physical phenomenon are described in a self contained manner. The language of mathematics is capable of describing the behaviors of nature that can be visualized — in addition, mathematics is capable of describing unobservable behaviors as well. It is possible to invent a mathematical model for a process of nature that has no equivalent *visualization*. There are several models of nature that can not be visualized.

The behavior of objects whose size is small compared to molecules can be described by quantum mechanics. The laws of physics at the quantum level may have no equivalent visualization in the classical world [Polk85]. The situation of increasing abstraction was *predicated* by Joseph Lamor...

> There has been of late a growing trend of opinion, promoted in part by general philosophical views in the direction that the theoretical constructions of physical science are largely factitious, that instead of presenting a valid image of the relation of things on which further progress can be based, they are still little better than a mirage [Lam05].

[10] Newton's three laws of motion are formally given in *Philosophiae Naturalis Principia Mathematica* (*Mathematical Principals of Natural Philosophy*) [Cajo62], [Andr56], [Asim82], [Motz89], [Cohe78], [Heri65] as:

> Lex I (in editions of 1687 and 1713) – Corpus omne perseverare in statu suo movendi uniformiter in directum, nisi quatenus illud a viribus impressis cogitur statum suum mutare.
>
> Lex I (in edition of 1726) – Corpus omne perseverare in statu suo

§1.3 THE FOUR FORCES OF NATURE

Although it is the electromagnetic force that is of interest here, three other forces exist in nature, the gravitational force, the nuclear or strong force and the weak force. These four forces are the source of all the variety in the universe [Neem86]. Without them attraction and repulsion of physical bodies would not be possible and interaction between matter would not take place. Bodies would simply pass through each other with no effect.

Gravity or the gravitational force was first identified by Isaac Newton in the 1680's. Although the gravitational force acts on all matter, its strength is the weakest of the four forces. As humans, we are conscious of

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> quiescendi vel movendi uniformiter in directum, nisi quantenus illud a viribus impressis cogitur statum suum mutare. (Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.)

A Body at rest remains at rest and a body in a state of uniform linear motion continues its uniform motion in a straight line unless acted on by an unbalanced force. This law is often called the law of inertia. This means that the state of motion in a straight line remains at rest of continues its uniform motion unless acted on by an unbalanced force. The presence of the unbalanced force is indicated by changes in the state of motion of a body.

> Lex II – Mutationem motis proportionalem esse vi motrici impressae, et fieri secundum lineam qua vis illa imprimitur. (The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed).

An unbalanced force, F, applied to a body gives it an acceleration, a, in the direction of the force such that the magnitude of the force divided by the magnitude of the acceleration is a constant, m, independent of the applied force. This constant, m, is identified with the inertial mass of the body. The inertial mass is a derived rather than basic quantity. Newton's equations of motion establish a procedure for measuring this mass. This is done by applying a known force to a body and measuring its acceleration. The result of this measure is the mass of the body. There is an additional interpretation of the second law of motion. If a body is observed to be accelerating than a force must be acting on it, but if no force is known to be physically applied to the body, Newton concluded that this force must act–at–a–distance.

> Lex III – Actioni contrariam semper et aequalem esse reactionem: sive corporum duorum actiones is se mutuo semper esse aequales et in partes contrarias dirigi. (To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.)

If a body exerts a force of any kind on another body, the latter exerts an exactly equal and opposite force on the former. This law introduces a symmetry that does not appear in the first two laws. It states that forces appear in equal and opposite pairs.

the force of gravity only because of the immense mass of the earth and celestial objects.

The weak and strong forces are not detectable at human scales, not because of their relative strength but because of their short range. The weak force has a range of $10^{-17} m$ to $10^{-18} m$. At distances small compared to the range of these forces, both the strong and the weak force obey the inverse square law the same as the gravitational and electromagnetic forces [Hugh91]. Although unfelt by humans, the weak force plays a critical role in the generation of energy in the sun and the building of heavy elements through nuclear synthesis [Kane93]. The weak force is also responsible for the instability of neutrons. Although neutrons are stable within the nucleus of an atom, under the influence of the weak force a neutron placed in isolation will split into a proton, an electron and an antielectron neutrino within fifteen minutes. [11] This instability is called Beta Decay.

In 1958 Robert E. Marshak (1916–1992) and E. C. G. Sudarshan (1931 –) observed that the weak force appeared to involve an action between two currents similar to the attraction or repulsion between two current carrying wires [Neem86], [Mars92]. In the 1960's and 1970's a theory emerged which unified the weak force with the electromagnetic force — the electroweak force [Rent90], [Mars92].

The strong force which acts between protons and neutrons (nucleons) is effective only when the nucleons are within $10^{-15} m$ of each other. The strong force is responsible for the interactions between nucleons, nucleons and mesons and a number of other particles. The nucleus contains both protons and neutrons and the electrostatic repulsive force of protons must be overcome by an attractive force in order to maintain the stability of the nucleus. Since the 1930's, some form of nuclear force has been postulated. In modern particle physics, it is believed the quarks are the particles that undergo strong nuclear interactions and are described by the theory of Quantum Chromodynamics (QCD).

A century after the discovery of the gravitational force, Charles A. Coulomb (1736–1806) measured the electrostatic force acting between two

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[11] One of the first experimental confirmations of the neutron's instability was performed by Enrico Fermi (1901–1954). Using the *atomic pile* at the University of Chicago, Fermi placed an evacuated spherical container inside the reactor. After some time some of the fission neutrons while passing through the container would decay into a proton an electron and an antielectron neutrino. The electron and the proton would become trapped in the container and be combine to form hydrogen gas. The rate at which the gas formed could be used to estimate the neutron's mean half–life of approximately 14 minutes [Gamo65].

charged bodies. Like Newton's inverse square law for gravity, the electromagnetic force obeys an inverse square law — Coulomb's Law. Instead of being proportional to the masses of the bodies, the electric force is proportional to the product of the bodies’ electric charge. Since electric charges can be positive as well as negative, the electric force can attract as well as repel bodies.

In the late 19th century, the effects of magnetism were carefully measured and it was determined that magnetism was a force created by the current produced by the motion of electrically charged objects. The electromagnetic force was first thought to be two unrelated forces, electricity and magnetism. Experiments showed that they were connected and are a single force.

Although the electrostatic force acts only between charged bodies, the electromagnetic force can effect uncharged bodies as well. The neutral charged neutron has a non–zero magnetic moment and is influenced by magnetic fields. The photon, which has no charge or magnetic moment, is effected by the electromagnetic force during its absorption and remission by atoms.

§1.4 THE PARTICLE ZOO

The study of the universe can be described as the search for the basic constitutes of matter, the forces that effect this matter and the calculation of the motions of this matter given these forces [Kane92]. Starting with the Greeks and Chinese, there have been theories that describe the behavior of matter. The Greeks thought all matter was made up of four elements — air, fire, water and earth. This atomistic theory originated with the Greek philosopher Leucippus, the probable founder of the School of Abdera in Thrace, 5th century B.C. [12] This school of thought claims that both empty space and the matter composed of atoms that filled the space are real. The changing world was described in terms of the isolation of groups of atoms, which was in direct conflict with the views put forth by the teachings of the Eleatic School of Parmenides of Elea (515–450 B.C.), which stated that everything that had existed had always done so and could never change.

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[12] Little is known of the life of Leucippus. He was probably a contemporary of Empedocles (490–435 B. C.) and Anaxagoras (499–428 B. C.) [Gres64] and possibly a pupil of Zeno of Elea (~462 B.C.). Leucippus assumed the existence of empty space as well as matter and held that all things are composed of *atoms*. Space is infinite in extent and atoms are infinite in number and are indivisible. The atoms are always engaged in activity and the worlds produced by them have various shapes and weights [Sedg39].

The Chinese on the other hand thought there were five elements rather than four — metal, wood, water, fire and earth and named five planets accordingly.

Along with Newton's work in celestial mechanics, he laid the groundwork for particle physics. Newton's reasoning is considered traditional and theologically based in the times.

> All these Things being considered, it seems probable to me that God in the beginning formed Matter in solid, massy, hard, impenetrable, moveable Particles, of such Sizes and Figures, and with other Properties, and in such Proportion to Space, as most conduced to the End for which He formed them; and that these primitive Particles being Solids are incomparably harder than any porous Bodies compounded of them; even so very hard, as never to wear or break in Pieces; no ordinary Power being able to divide what God himself made in the first Creation ... And therefore that Nature may be lasting, the Changes of corporeal Things are to be placed only in the various Separations and new Associations and Motions of these permanent Particles. [Cohe52]

With the beginning of chemistry in the early 17th century, John Dalton (1776–1844) proposed there was an elementary component within each element, which itself was unalterable, called an atom. [13] In the middle of the 19th century, Dmitry Ivanovich Mendeleyev (1834–1907) discovered that the chemical elements could be classified into a table that had a periodic structure.

In 1897 the electron was discovered by Joseph John (J. J.) Thompson (1856–1940) [Thom99] followed by the discovery of the nucleus of the atom by Ernest Rutherford (1871–1937) in 1911 [Ruth11]. These discoveries resulted in a model of the atom based on the planetary like motion of electrons orbiting the nucleus. The nucleus of an element can have the same numbers of electrons but have a different mass and still have identical chemical properties. These elements are called isotopes. The study of chemical isotopes suggested that it is the number electrons in the element that is responsible for its chemical properties. With the discovery of the neutron by Sir James Chadwick (1891–1974) in 1932, the behavior of

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[13] In the *Principia*, page 6, Newton laid the foundation of the atomic theory ...

> Because the hardness of the whole arises from the hardness of the parts, we ... justly infer the hardness of the individual particles not only from the bodies we fell but of all others.

isotopes was explained [Chad32]. Since the electrically neutral neutron resides in the nucleus it has no effect on the chemistry of the element, but changes its atomic weight. With the additional discovery of the proton, the description of the nucleons making up the nucleus of the atom was complete. Isotopes are now understood to be elements with different numbers of neutrons, but the same numbers of proton and electrons.

With the detection of cosmic rays in the 1930's, other particles were discovered to exist. Using accelerators, still other constituents of matter were produced through the collisions between particles. The existence of these particles lead to the discovery of the nuclear force and the classification of particles that are subject to the nuclear force — hadrons. Protons and neutrons are hadrons that are held together in the nucleus of the atom by the nuclear force. Electrons are not hadrons since they are held in the atom by the electromagnetic force. By 1939 the fundamental constituents of matter were composed of the proton (p), the neutron (n), the electron (e) and the neutrino (ν), plus their anti–particles [Mars93]. After World War II, the number of particles exploded. Using accelerators hundreds of particles were created adding to the complexity of the underlying structure of nature.

This situation can be simplified if there is some order given to the vast zoo of particles. The first approach is to classify a particle by how it behaves in the presence of an identical particle. This can be done by describing the statistics of its interaction between large numbers of identical particles. Two types of particles exist using this description — *fermions* and *bosons*. If a number of identical fermions are placed in a confined area, they will statistically tend to avoid each other. If a number of identical bosons are placed in a confined area together, they will statistically tend to stay together [Kim91].

A second method of classifying particles is by describing their interaction with the forces of nature. By sorting through the remnants of the particle collisions, it was discovered that there are two nuclear forces at work, the weak nuclear force and the strong nuclear force. Particles subject to the weak nuclear force and the electromagnetic force are a class of fermions called leptons. These leptons are — the electron (e), muon (μ), tau (τ) and the neutrino (ν). The particles that are subject to the strong nuclear force remained hadrons. The hadrons can be further classified into mesons and baryons. [Clos87], [Clos86], [Dodd84], [Frau74], [Schw92].

As early as 1964, Murray Gell–Mann (1929–) and George Zweig (1937–) independently produced a theory that would explain the growing complexity of the hadrons and their interaction. Their original theory described a universe made up of three types of elementary particles: (i) quarks, which come in two flavors, up and down, (ii) the electron and (iii) electron neutrino. In this theory, forces including gravity are carried by other particles — gauge bosons [Bloo82].

In 1970, there was no theory capable of describing the strong force. A nuclear force had been postulated in the 1930's since the nucleus contains several protons that must be held together while the electrical force attempts to pull them part. It is the quarks that participate in the strong force [Ishi82], [Clos79]. Quarks carry color charge and combine to make color neutral hadrons just as electrically charged electrons combine with charged nuclei to form electrically neutral atoms [Chew64].

The material of the universe can be described as being made up of leptons and quarks, which are held together by the force carrying bosons. The force carriers are the photon for the electromagnetic force, gluons for the strong force and the W^{+}, W^{-} and Z^{0} for the weak force [Garv93].

The theory of quarks and their interaction with each other and other matter is called Quantum Chromodynamics (QCD). The simplifying theory of quarks quickly became complex as more behaviors of hadron interaction were discovered at higher collision energies.

The original up and down quarks were joined by four other quarks named charm, strange, top, and bottom [Namb76]. These six quarks and their related leptons can be classified into three generations. The first generation makes up the matter we see in everyday life. The constituents of the second and third generation are unstable at normal energies and are only produced in accelerators — or during the formation of the universe.

The six quarks can be arranged into three groups or doublets $\left[\begin{array}{c|c|c} u & c & t \\ \hline d & s & b \end{array}\right]$. The top rows of quarks have charge $2/3$ and the bottom row have charge $-1/3$. The six leptons can also be arranged in three doublets $\left[\begin{array}{c|c|c} \nu_e & \nu_\mu & \nu_\tau \\ \hline e & \mu & \tau \end{array}\right]$ where e is an electron, μ is a muon, τ is a tau all of which have charge –1, while each particles' neutrino has no charge [Namb76], [Neem86], [Okun85]. [14]

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[14] Neutrinos are massless (or nearly massless) particles with no charge. The neutrino was *invented* by Wolfgang Pauli (1900–1958) in 1930 to account for the missing energy created during Beta decay [Rein79]. Beta decay was discovered in 1896 when it was observed that certain atoms decay into other atoms [Frit83]. Early theories of Beta decay predicted

that the neutron in the nucleus of an atom would be changed into a proton and a free electron [Lipk62]. It was also predicted that the products of the decay would conserve charge, energy and momentum with a fixed value. In an experiment performed in 1927 it was found that the free electron produced by the Beta decay had a *continuous* spectrum of energy values, contrary to the theory [Sutt92], [Brow78].

Pauli's new particle was needed to carry off the momentum and energy, preserving the conservation laws that were violated by the earlier *naive* models [Sutt92]. This particle was named the neutrino after Enrico Fermi developed the theory of Beta decay and was quoted as saying...

> It is a little neutron, it is a neutrino [Rein79].

Pauli's original particle was named the neutron since today's chargeless particle called the *neutron* had yet to be discovered. Pauli's neutron name was not *copyrighted* since it only appeared in private correspondence and never in print. In 1932 James Chadwick (1891–1974) presented evidence of a neutral charge particle with nearly the same mass as the proton he called the neutron. When Enrico Fermi (1901–1954) reported Chadwick's discovery, a member of the audience asked if Chadwick's neutron was the same as Pauli's neutron, Fermi answered...

> No, the neutrons of Chadwick are large and heavy, Pauli's neutrons are small and light, they have to be called Neutrinos [Gamo65], [Ferm54], [Segr70].

The neutrino has an extremely low interaction rate with other forms of matter. In a cubic centimeter of water there are approximately 7×10^{22} free protons available in the nuclei of hydrogen. The protons in the nuclei of oxygen are *bound* and unavailable for any interaction. A neutrino passing through this cubic centimeter of water has one chance in 10^{44} of being *captured* by any one of the 10^{22} protons. The result is one chance in 10^{22} of *any* proton capturing the neutrino — very low odds. Converting this probability to a human scale it would require $10^{22}cm^3$ of water to capture a single neutrino. This *length* is 1000 light years or 63,000 times the distance between the sun and the earth [Sutt92].

Free neutrinos were first observed in 1956 by Fred Reines (1918 –) and Cylde L. Cowan (1919 –) using a liquid scintillator placed in a neutrino beam generated by a nuclear reactor [Cowa56], [Rein56], [Rein5]. Their first proposal was to place the scintillator 40 *m* from ground zero during the test of the first atomic bomb. After 100 days of operation over a period of a year, on June 14th, 1956 Reines and Cowan captured the *poltergeist* particle [Rein79], [Rein79a], [Rein94], [Krop94].

This discussion of neutrinos may seem far removed from the goal of the book, but it does have several connections. The speculation of the existence of the neutrino by Pauli and its subsequent theoretical prediction by Fermi lead to the theory of Beta decay. Fermi's theory was built on a quantum field theory in which particles need not preexist but can be *created* from a vacuum [Bern89]. No theorist was saying the neutrinos preexist inside the nucleus and are ejected during Beta decay. They are rather created during the Beta decay process, then ejected [Brow78]. The concept of the *creation* and subsequent *annihilation* of particles will be used later in the quantum field description of the electromagnetic field.

The second connection is between quantum field theory and observational astronomy. On the night of February 23, 1987 a star named Sanduleak (SK) –69° 202, cataloged by Nicholas Sanduleak in 1969, located in the region of the Tarantula Nebula, on the edge of the Large Magellanic Cloud became the first supernova to occur in our own galaxy in four

Why matter is composed of leptons and quarks and why these leptons and quarks should be arranged in families with specific masses is not known. The search for the answer to this question is the quest of the current generation of physicist [Wein93], [Lede93]. Using the quark model, material objects can be built from these particles. Protons, neutrons, pions, etc. are built from quarks. Since these hadrons are constructed from quarks, they are not considered elementary [Robe79]. [15]

§1.5 FUNDAMENTAL FORCES IN QUANTUM CHROMODYNAMICS

In Quantum Chromodynamics, the quarks that compose hadrons are bound together by gluons. The residual force of the gluon, when seen outside a hadron becomes the nuclear force that binds hadrons into stable nuclei. The electrically stable nuclei and the only electrically stable lepton — the electron — are bound into atoms by the electromagnetic force. The residual electromagnetic force outside the atom binds atoms into molecules. Since these molecules form the basis of life, the study of particle physics can be considered of primary interest to mankind [Geor81], [Wein93], [Lede93], [Geog80], [Frit83], [Barr91].

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centuries. Other than the observation of this very rare event SK 69° 202, a.k.a. SN 1987A was important for what was not seen by the astronomers. A burst of approximately 1×10^{58} neutrinos, lasting nearly 6 seconds were emitted from SN 1987A. Nearly 30 million billion of the neutrinos then passed through a detector located 2000 feet deep in a salt mine in Painesville, Ohio. Out of these particles 30×10^{15} neutrinos, 8 interactions occurred. Nearly three hours later the visible photons from SN 1987A arrived at the telescopes in the Southern Hemisphere. The energy necessary to produce 1×10^{58} neutrinos is approximately 3×10^{58} ergs/sec or 1×10^{20} times the total energy production of the sun.

[15] Neutrons are composed of 2 down–quarks and an up–quark whose charges are summed produced a neutral particle $(-1/3)(-1/3)(2/3)=(0/0)=0$ while a proton is composed of two up–quarks and one down–quark whose charge is $(2/3)(2/3)(-1/3)=1$. Other hadrons are composed of three different quarks and are called baryons, while other hadrons are composed of a quark and an anti–quark and are called mesons.

There is symmetry between quarks and leptons in that leptons have integral units of charge while the electrical units of quarks are multiples of 1/3. This factor of 3 is actually accompanied and *compensated* by another factor 3; each quark comes in three invented labels called *color*, which is simply a quantum number for the behavior of quarks, not an actual color as we know green or red.

All of these behaviors are described through a theory based on group symmetries called SU(3) or the *Eightfold Way* [Gell64], [Dodd84], [Clos83]. In this theory the nucleons belong to a multiplet of eight and the pions and kaons, which are mesons with quark contents $\bar{s}u, \bar{s}d, \bar{u}s, \bar{d}s$, belong to a separate multiplet which also has a multiplicity of eight.

In addition to quarks and bosons there is one more particle needed to complete the theory in a consistent manner — the Higgs Boson (Peter Ware Higgs (1929–)) [Velt86]. The theory of the electroweak interaction and the large masses of the W^+, W^- and Z^0 particles requires one electrically neutral Higgs Boson [Clin82], [Clin74]. The field produced by the Higgs Boson is a background field pervading all space, ever present, even in the vacuum state [Guid91]. The presence of this field produces an energy density in the vacuum which would curve space–time through the gravitational interaction. At this time, there is no experimental evidence for the Higgs Boson, but the search continues [Roln94].

The electromagnetic and gravitational forces have long range, the weak and nuclear forces have short ranges, all four forces obey an inverse square law. Why are their ranges different? Why do all these forces obey the inverse square law? What generates these four forces? How are the forces conveyed?

Although the four forces of nature all appear to follow the inverse square law, the force binding quarks together — the chromostatic force — behaves differently. The electrostatic force described by $V(\mathbf{r}) = -e^2/4\pi\mathbf{r}$ is replaced by $V(\mathbf{r}) = \kappa\mathbf{r}$, when **r** is very large. This chromostatic force behaves Coulombic when **r** is small, but the potential increases linearly for large **r**. The result is that this force permanently confines the quarks inside their host [Adle81].

A theory of the electromagnetic force must not only explain observable effects of electromagnetic fields, but also must explain the source of the forces and the mechanism that conveys these forces. The search for the answer to these questions is similar to the mathematically undecidable question in Gödel's Theorem (Kurt Gödel (1906–1978)) [Gode62], [Hofs79], [Nage58], [Penr89b] — that in order to describe sufficiently one set of axioms, an external (super) set of axioms (theories) is needed, which in turn requires another external set of axioms. [16] Gödel summarized this

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[16] Gödel's Theorem appears as Proposition VI in his 1931 paper, "On Formally Undecidable Propositions in *Principia Mathematica* and Related Systems I". It states: "To every ω–consistent recursive class κ of *formulae* there correspond recursive *class–signs* r, such that neither $\sim$Gen r nor Neg($\sim$Gen r) belongs to $Flg(\kappa)$ (where v is a free variable of r).

In layman's terms this says: All consistent axiomatic formulations of number theory include undecidable propositions — arithmetic is not completely formalizable. Gödel observed that a statement about number theory could be about a statement of number theory (possibly even itself), if only the numbers could somehow stand for statements. Gödel's work was part of a long attempt to define what proofs are. Proofs are dilemma in the development of the understanding of nature, using the tools of mathematics as...

> The human mind is incapable of formulating (or mechanizing) all its mathematical intuitions, i.e. if it has succeeded in formulating some of them, this very fact yields new intuitive knowledge, e.g. the consistency of this formalism. This fact may be called the *incompletability* of mathematics. On the other hand, on the basis of what has been proved so far, it remains possible that there may exist (and even be empirically discoverable) a theorem–proving machine which in fact *is* equivalent to mathematical intuition, but cannot be *proved* to be so, nor even be proved to yield only *correct* theorems… [Gode51].

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demonstrations within fixed systems of propositions. Gödel was saying that the system of *Principia Mathematica* [Whit27] is incomplete — there are true statements of number theory that its methods of proof are too weak to demonstrate. (The *Principia Mathematica* is a monumental work consisting of 4 volumes that attempted to build the foundation of mathematics upon a paradox–free set of logical axioms.)

The concept that mathematics is nothing but symbols in some formal mathematical system is the definition of *formalism* in which mathematics becomes a *meaningless game*. Gödel dealt formalism a devastating blow with his theorem and restored *meaning* to the symbols. In the world of physics it is the *meaning* of the symbols that provides the means for describing nature through mathematics.

In the early 1920's the logician Alfred Tarski (1901 – 1983) took Gödel's argument further to show that logical systems are also semantically incomplete as well [Tars56]. He showed that if a mathematical system is consistent then the notion of *truth* is not definable. The result of this discovery is that logical and mathematical systems are logically incomplete in that there is no formal system in which the truth of all mathematical statements could be decided or in which all mathematical concepts could be defined [Barr92]. The totality of mathematics cannot be brought to complete order on the basis of any system of axioms. Just as Heisenberg had done for the physical sciences, Gödel ended the search for certainty in mathematics [Asim82b].

In the proof of Gödel’s theorem there are two important notions that must be dealt the simultaneously: (i) the notation that mathematics is simply the manipulation of symbols and (ii) the concept that a mathematical proof can be substituted for the concept of the truth. Together these concepts provide for the translation of a verbally stated logical paradox into an arithmetic statement. One example of such a paradox is the Liar’s Paradox: *This sentence is false*.

All of this background would be of no interest if not for the logical paradoxes that will be encounted when quantum mechanics is applied to the measurement and behavior of photons as they interact with matter [Bohm51], [Bohm62], [Stew92], [Cast96].

In the realm of classical physics, these questions are unanswerable and perhaps meaningless — the force is just there. In the quantum world however new answers may be found. [17]

§1.6 QUANTUM FIELD THEORY

In order to address the questions raised in classical physics, a new theory has been developed — Quantum Field Theory [Gros93], [Guid91], [Hari72], [Itzy80], [Kaku93], [Mand84], [Brow90], [Chai84], [Chen83], [Quig83], [Roma69], [Visc69]. When quantum mechanics and special relativity are combined, the resulting description of nature is based on the interaction of quantized fields and their associated force carrying particles — gauge bosons. Like classical field theories, quantum field theory describes a force created when one particle acts on another particle, after an appropriate delay due to the finite propagation speed of light. When quantum theory is used, the energy carriers of the force can only assume discrete values. It is these quanta of the field energy that are identified with the particles that transmit force. In quantum field theory, the interaction of elementary particles is interpreted as the exchange of force carrying particles among the material particles.

It will be shown later that these interactions obey specific symmetry rules and the force of the interaction is proportional to a charge of some kind. In such theories, the interaction of objects takes place locally in the form of the creation and annihilation of particles. Forces are transmitted by the propagation of particles known as exchange particles. These exchange particles have properties of mass, spin and charge, like the material particles. The four forces of nature differ because the exchange particles differ. In quantum field theory, the electromagnetic force is conveyed by an exchange particle — the photon.

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[17] Although it may be meaningless to ask the question *how is the force conveyed* using the vocabulary of classical mechanics, quantum mechanics produces a similar set of meaningless questions. Heisenberg's uncertainty principle restricts the description of the words *position* and *velocity* to any accuracy exceeding the uncertainty relation [Heis30]. Heisenberg cautioned that

> ... one should be particularly careful to remember that the human language permits the construction of sentences which do not involve any consequences and which therefore have no content ...

The use of the words *reality* often leads to a picture of a physical process that can neither be proved nor disproved. The description of the physical process of the electromagnetic force will become increasingly *abstract* as this book progresses. The conceptualization of modern physical theory will be the most difficult hurdle to overcome.

According to the quantum theory of Maxwell's electrodynamics — quantum electrodynamics (QED) — electromagnetic forces between two charged particles are generated by the transmission of a massless gauge boson — the photon — between them. [18] This photon brings with it a command from one particle to another. The receiving particle obeys the command of the arriving gauge particle with the result interpreted as the conveyance of the force. In this theory, the photon passes a force message to the receiving particle, rather than imparting some physical force to the receiving particle. In the classical electrodynamics, during the transmission of radio waves, external energy is available to communicate commands. Such energy is not always available in the quantum world of charged particles. According to the uncertainty principle of quantum mechanics, this energy can be borrowed for a short time to enable the command to be carried by the exchange particle, thus allowing force to be conveyed while obeying the conservation of energy.

§1.7 PRELIMINARIES TO MODERN PHYSICS

Modern physics is so strongly based on quantum models of the microworld it is difficult to bridge the gap between classical electrodynamics and quantum theories of Maxwell's equations and their interaction with matter. A course of instruction at a university covers classical electromagnetic theory, developing an understanding of electrostatics, magentics and Maxwell's equations. This knowledge is then used in the formulation of electromagnetic radiation and its practical applications, usually in antenna theory, wave guides and electro–optics. In parallel, the student develops an understanding of quantum mechanics. This material describes the duality of particles and waves, which is the basis of the descriptions of atomic and subatomic phenomena. What is missing from these parallel courses of study is the description of the electromagnetic field as a Quantum Field Theory. Although the development of the quantum description of Maxwell's radiation field presented prior to proceeding with the Quantum Field descriptions of subatomic particles, the details of the

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[18] The massless nature of the photon is a consequence of the gauge (phase) symmetry of the electromagnetic field. The photon's masslessness also guarantees that the electric charge is conserved since the symmetry responsible for the masslessness is a result of the invariance of Maxwell's equations to arbitrary phase changes in the quantum fields associated with the electron and the photon. The arbitrary phase changes in the electron field can be compensated for by the redefinition of the photon field which leaves the form and structure of the equations of motion for the electromagnetic interactions unchanged [West93].

Quantum Radiation Field of Maxwell's equations is not fully developed at the undergraduate level.

There will be an attempt to bring some understanding to the phenomenon of the electromagnetic force, through the various theories beginning with Classical Electrostatics, Electrodynamics, Quantum Mechanics and concluding with Quantum Field Theory. Because of the compressed form of this book, mathematical expressions are brief and usually given in non–rigorous form and in some cases simply stated without supporting derivations. Whenever possible the derivation or expanded material is given in an endnote.

The electromagnetic force is well understood from the view of classical physics. Its characteristics include: an infinite range, allowing macroscopic phenomena to be observed and a reasonably strong force, allowing microscopic phenomena to be observed. It is the interaction of the electromagnetic force with microscopic matter that leads to the formulation of Quantum Field Theory (QFT) — the goal of this thesis.

The path taken from classical electrodynamics to quantum field theory will often take a diversion to cover background material needed to illuminate the primary subject. This approach is necessary, since the reader may require an additional understanding of the mathematical developments. [19] The unification of the concepts found in the literature and texts as well the diverse notation has been a significant effort. I apologize for any over simplifications that may have entered the text. Finally, none of the material presented here should be considered original, but is a compendium of ideas found in the literature given in the bibliography. Direct quotations have been kept to a minimum, but there is material which is best conveyed verbatim from the source. In such cases, references to the original text are given within the sentence. All other references provide the reader with a rich set of source materials to continue the search for understanding of the primary forces of nature.

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[19] Much of the difficulty in learning physics comes from understanding the background material, including the mathematical notation.

> In any branch of science the terminology becomes so cumbersome in the process of its progress that it is very difficult to put it in a simple way for a reader who encounters all these complicated notations for the first time [Gamo66], pp. 68.

A second problem is the notation used in the description of electromagnetic phenomena can be somewhat *cryptic* when compared to *ordinary* notation of calculus and differential equations. When the notation is beyond the norm, footnotes will be used to provide additional information on the subject matter.

§1.8 UNIFYING PRINCIPALS OF NATURE

One of the great achievements of 20th century physics has been the attempted unification of the four forces of nature. Although Einstein first proposed the grand unified theory, it wasn't until the 1970's that any serious progress was made. The first unification took place at the end of the 19th century, when Maxwell formulated the theory of electro–magnetism. In modern terms – Quantum Electrodynamics (QED) – all phenomena can be understood in terms of the force–carrying particles exchanged between electrically charged matter and the photon [West93].

In the last 20 years, the four forces of nature, electromagnetic, weak, strong and gravitational are being described by a small number of unifying principals [West93]. Four of these principals will be developed further in this book.

The first is the *Principal of Relativity*, which restricts the kinematic description of the motion of particles and fields, both classical and quantum. This principal states that the laws of physics are independent of spatial location and the passage of time, while being observed in a uniformly moving reference frame.

The second is the *Principal of Stationary Action* which describes the motion of both classical and quantum mechanical systems in terms of the minimization of action.

The third is the *Gauge Principal*, which describes the rules governing the interaction of fields of force with material particles. This principal is formulated as a classical description of nature, but it has inherent quantum mechanical properties. It may also be formulated as a relativity principal which allows internal and external properties of a physical system to be described independent of the observers reference frame.

The fourth principal is the *Quantum Principal*, which states that all physical systems in nature are inherently quantizable. This principal is founded on extensive experimental experience.

Using these four simple principals, it is surprising that the basic properties of various forms of matter and the interaction between matter can be described in detail. One question raised in the late 20th century is whether there is a *Theory of Everything* [Davi88], [Wein77], [Wein77], [Wein93], [Lede93]. A theory in which the forces and matter of nature are described with a very small number of principals, which would reduce the current gap between the mathematical model of the world and physical reality.

The cornerstone of all physical sciences is experiment. The understanding of the basic forces of nature is advanced through the interplay of physical experiment and theoretical ideas. The largest impediment in the formulation of the Theory of Everything is the increasing energies needed to probe deeper into nature. With this increased energy, comes increased cost. At the energy level required for complete unification of natures forces — the Planck energy $\approx 1\times10^{19}$ GeV — the direct observation of this unification may be beyond our ability to fund the experiments [Doug90].

> *I wish we could derive the rest of the phenomena of nature by the same kind of reasoning as for mechanical principals. For I am induced by many reasons to suspect that they may all depend on certain forces.*
>
> *— Preface to the 1st Edition (1686) of Newton's Principia*