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Excerpt
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Part I
Introduction

1
Matter and Light

1.1 Introduction

The physical world we see around us has two main components, matter and light, and it is the modern explanation of these things which is the purpose of this book. During the course of the story, these concerns will be restated in terms of material particles and the forces which act between them, and we will most assuredly encounter new and exotic forms of both particles and forces. But in case we become distracted and confused by the elaborate and almost wholly alien contents of the microworld, let us remember that the origin of the story, and the motivation for all that follows, is the explanation of everyday matter and visible light.

Beginning as it does, with a laudable sense of history, at the turn of the last century, we have only to appreciate the level of understanding of matter and light around 1900, and some of the problems in this understanding, to prepare ourselves for the story of progress which follows.

1.2 The Nature of Matter

By 1900 most scientists were convinced that all matter is made up of a number of different sorts of atoms, as had been conjectured by the ancient Greeks millennia before and as had been indicated by chemistry experiments over the preceding two centuries. In the atomic picture, the different types of substance can be seen as arising from different arrangements of the atoms. In solids, the atoms are relatively immobile and in the case of crystals are arranged in set patterns of impressive precision. In liquids they roll loosely over one another and in gases they are widely separated and fly about at a velocity depending on the temperature of the gas; see Figure 1.1. The application of heat to a substance can cause phase transitions in which the atoms change their mode of behaviour as the heat energy is transferred into the kinetic energy of the atoms' motions.

Many familiar substances consist not of single atoms, but of definite combinations of certain atoms called molecules. In such cases it is these molecules which behave in the manner appropriate to the type of substance concerned. For instance, water consists of molecules, each made up of two hydrogen atoms and one oxygen atom. It is the molecules which are subject to a specific static arrangement in solid ice, the molecules which roll over each other in water and the molecules which fly about in steam.

The laws of chemistry, most of which were discovered empirically between 1700 and 1900, contain many deductions concerning the behaviour of atoms and molecules. At the risk of brutal over-simplification the most important of these can be summarised as follows:

(1) Atoms can combine to form molecules, as indicated by chemical elements combining only in certain proportions (Richter and Dalton).

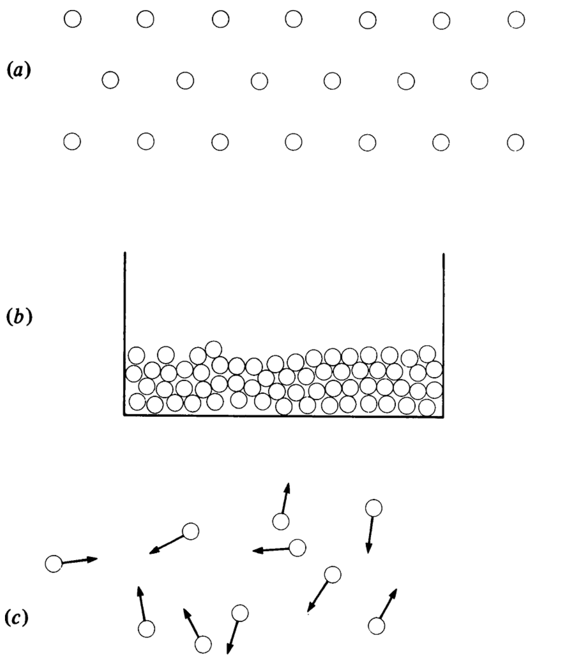


Figure 1.1. (*a*) Static atoms arranged in a crystal. (*b*) Atoms rolling around in a liquid. (*c*) Atoms flying about in a gas.

(2) At a given temperature and pressure, equal volumes of gas contain equal numbers of molecules (Avogadro).
(3) The relative weights of the atoms are approximately multiples of the weight of the hydrogen atom (Prout).
(4) The mass of each atom is associated with a specific quantity of electrical charge (Faraday and Webber).
(5) The elements can be arranged in families having common chemical properties but different atomic weights (Mendeleeff's periodic table).
(6) An atom is approximately 10^{-10} m across, as implied by the internal friction of a gas (Loschmidt).

One of the philosophical motivations behind the atomic theory (a motivation we shall see repeated later) was the desire to explain the diversity of matter by assuming the existence of just a few fundamental and indivisible atoms. But by 1900 over 90 varieties of atoms were known, an uncomfortably large number for a supposedly fundamental entity. Also, there was evidence for the disintegration (divisibility) of atoms. At this breakdown of the 'ancient' atomic theory, modern physics begins.

1.3 Atomic Radiations

1.3.1 *Electrons*

In the late 1890s, J. J. Thomson of the Cavendish Laboratory at Cambridge was conducting experiments to examine the behaviour of gas in a glass tube when an electric field was applied across it. He came to the conclusion that the tube contained a cloud of minute particles with negative electrical charge – the electrons. As the tube had been filled only with ordinary gas atoms, Thomson was forced to conclude that the electrons had originated within the supposedly indivisible atoms. As the atom as a whole is electrically neutral, on the release of a negatively charged electron the remaining part, the ion, must carry the equal and opposite positive charge. This was entirely in accord with the long-known results of Faraday's electrolysis experiments, which required a specific electrical charge to be associated with the atomic mass.

By 1897, Thomson had measured the ratio of the charge to the mass of the electron (denoted e/m) by observing its behaviour in magnetic fields. By comparing this number with that of the ion, he was able to conclude that the electron is thousands of times less massive than the atom (and some 1837 times lighter than the lightest atom, hydrogen). This led Thomson to propose his 'plum-pudding' picture of the atom, in which the small negatively charged electrons were thought to be dotted in the massive, positively charged body of the atom (see Figure 1.2).

1.3.2 *X-rays*

Two years earlier in 1895, the German Wilhelm Röntgen had discovered a new form of penetrating radiation, which he called X-rays. This radiation was emitted when a stream of fast electrons (which had not yet been identified as such) struck solid matter and were thus rapidly decelerated. This was achieved by boiling the electrons out of a metallic electrode in a vacuum tube and accelerating them into another electrode by applying an electric field across the two, as in Figure 1.3. Very soon the X-rays were identified as another form of electromagnetic radiation, i.e. radiation that is basically the same as visible light, but with a much higher frequency and shorter wavelength. An impressive demonstration of the wave nature of X-rays

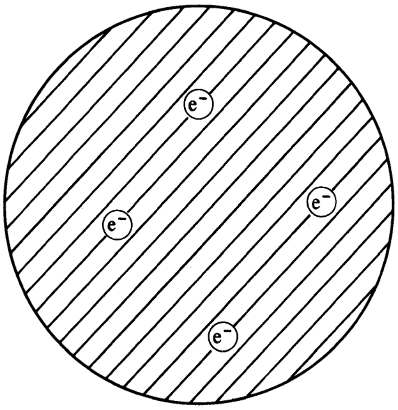


Figure 1.2. Thomson's 'plum-pudding' picture of the atom.

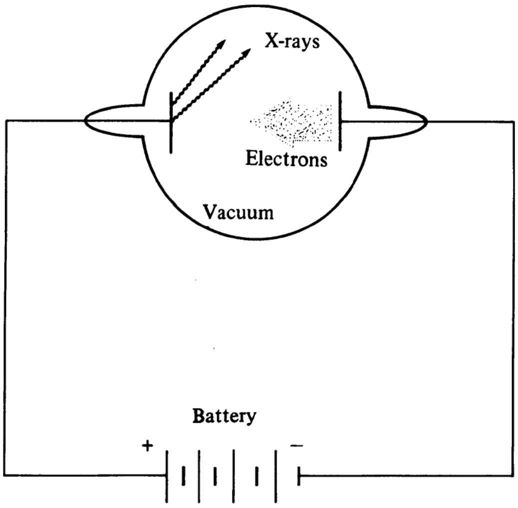


Figure 1.3. The production of X-rays by colliding fast electrons with matter.

was provided in 1912 when the German physicist Max von Laue shone them through a crystal structure. In doing so, he noticed the regular geometrical patterns characteristic of the diffraction which occurs when a wave passes through a regular structure whose characteristic size is comparable to the wavelength of the wave. In this case, the regular spacing of atoms within the crystal is about the same as the wavelength of the X-rays. Although these X-rays do not originate from within the structure of matter, we shall see next how they are the close relatives of radiations which do.

1.3.3 *Radioactivity*

At about the same time as the work taking place on electrons and X-rays, the French physicist Becquerel was conducting experiments on the heavy elements. During his study of uranium salts in 1896, Becquerel noticed the emission of radiation rather like that which Röntgen had discovered. But Becquerel was doing nothing to his uranium: the radiation was emerging spontaneously. Inspired by this discovery, Pierre and Marie Curie began investigating the new radiation. By 1898, the Curies had discovered that the element radium also emits copious amounts of radiation.

These early experimenters first discovered the radiation through its darkening effect on photographic plates. However, other methods for detecting radiation were soon developed, including scintillation techniques, electroscopes and a primitive version of the Geiger counter. Then a great breakthrough came in 1912 when C. T. R. Wilson of the Cavendish Laboratory invented the cloud chamber. This device encourages easily visible water droplets to form around the atoms, which have been ionised (i.e. have had an electron removed) by the passage of the radiation through air. This provides a plan view of the path of the radiation and so gives us a clear picture of what is happening.

If a radioactive source such as radium is brought close to the cloud chamber, the emitted radiation will trace paths in the chamber. When a magnetic field is placed across the chamber, then the radiation paths will separate into three components which are characteristic of the type of radiation (see Figure 1.4). The first component of radiation (denoted α) is bent slightly by the magnetic field, which indicates that the radiation carries electric charge. Measuring the radius of curvature of the path in a given magnetic field can tell us that it is made up of massive particles with two positive electric charges. These particles can be identified as the nuclei of helium atoms, often referred to as α particles. Furthermore, these α particles always seem to travel a fixed distance before being stopped by collisions with the air molecules. This suggests that they are liberated from the source with a constant amount of energy and that the same internal reactions within the source atoms are responsible for all α particles.

The second component of the radiation (denoted γ) is not at all affected by the magnetic field,

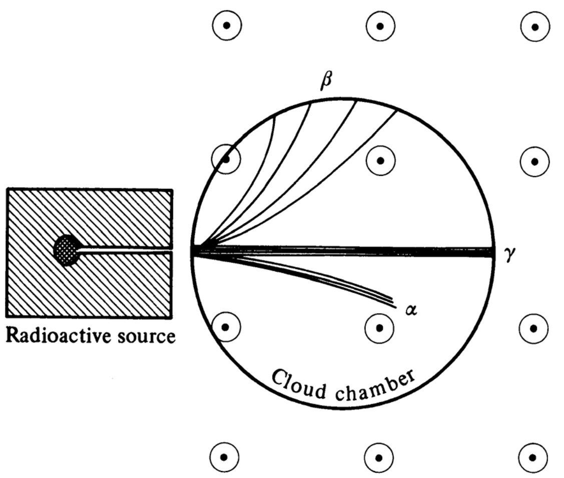


Figure 1.4. Three components of radioactivity displayed in a cloud chamber. ⊙ signifies that the direction of the applied magnetic field is perpendicular to, and out of the plane of, the paper.

showing that it carries no electric charge, and it is not stopped by collisions with the air molecules. These γ-rays were soon identified as the close relatives of Röntgen's X-rays but with even higher frequencies and even shorter wavelengths. The γ-rays can penetrate many centimetres of lead before being absorbed. They are the products of reactions occurring spontaneously within the source atoms, which liberate large amounts of electromagnetic energy but no material particles, indicating a different sort of reaction to that responsible for α-rays.

The third component (denoted β radiation) is bent significantly in the magnetic field in the opposite direction to the α-rays. This is interpreted as single, negative electrical charges with much lesser mass than the α-rays. They were soon identified as the same electrons as those discovered by J. J. Thomson, being emitted from the source atoms with a range of different energies. The reactions responsible form a third class distinct from the origins of α- or γ-rays.

The three varieties of radioactivity have a double importance in our story. Firstly, they result from the three main fundamental forces of nature effective within atoms. Thus the phenomenon of radioactivity may be seen as the cradle for all of what follows. Secondly, and more practically, it was the products of radioactivity which first allowed physicists to explore the interior of atoms and which later indicated

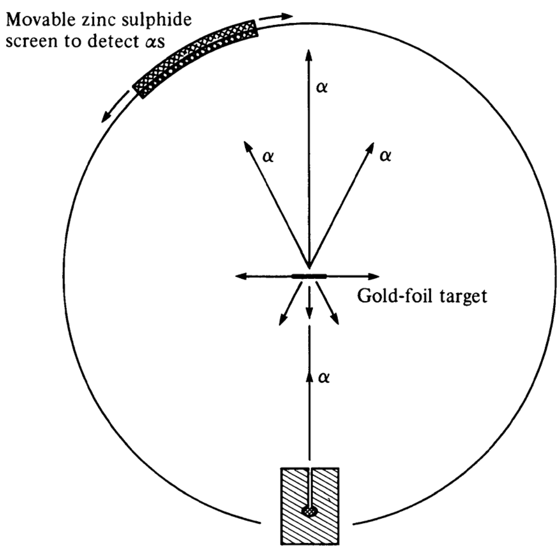


Figure 1.5. The Geiger and Marsden experiment. According to Rutherford's scattering formula, the number of α particles scattered through a given angle decreases as the angle increases away from the forward direction.

totally novel forms of matter, as we shall see in due course.

1.4 Rutherford's Atom

In the first decade of the twentieth century, Rutherford had pioneered the use of naturally occurring atomic radiations as probes of the internal structure of atoms. In 1909, at Manchester University, he suggested to his colleagues, Geiger and Marsden, that they allow the α particles emitted from a radioactive element to pass through a thin gold foil and observe the deflection of the outgoing α particles from their original paths (see Figure 1.5). On the basis of Thomson's 'plum-pudding' model of the atom, they should experience only slight deflections, as nowhere in the uniformly occupied body of the atom would the electric field be enormously high. But the experimenters were surprised to find that the heavy α particles were sometimes drastically deflected, occasionally bouncing right back towards the source. In a dramatic analogy attributed (somewhat dubiously) to Rutherford: 'It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you!'

The implication of this observation is that a very strong repulsive force must be at work within the atom. This force cannot be due to the electrons as they are over 7000 times lighter than the α particles and so can exert only minute effects on the α-particle trajectories. The only satisfactory explanation of the experiment is that all the positive electric charge in the atom is concentrated in a small nucleus at the middle, with the electrons orbiting the nucleus at some distance. By assuming that the entire positive charge of the atom is concentrated with the atomic mass in a small central nucleus, Rutherford was able to derive his famous scattering formula which describes the relative numbers of α particles scattered through given angles on colliding with an atom (see Figure 1.5).

Rutherford's picture of the orbital atom is in contrast with our perception of apparently 'solid' matter. From the experiments he was able to deduce that the atomic nucleus, which contains 99.9% of the mass of the atom, has a diameter of about 10^{-15} m compared to an atomic diameter of about 10^{-10} m. For illustration, if we took a cricket ball to act as the nucleus, the atomic electrons would be 5 km distant! Such an analogy brings home forcibly just how sparse apparently solid matter is and just how dense is the nucleus itself. But despite this clear picture of the atom, indicated from the experiment, explaining how it works is fraught with difficulties, as we shall see in Chapter 3.

1.5 Two Problems

Just as these early atomic experiments revealed an unexpected richness in the structure of matter, so too, theoretical problems forced upon physicists more-sophisticated descriptions of the natural world. The theories of special relativity and quantum mechanics arose as physicists realised that the classical physics of mechanics, thermodynamics and electromagnetism were inadequate to account for apparent mysteries in the behaviour of matter and light. Historically, the mysteries were contained in two problems, both under active investigation at the turn of the century.

1.5.1 *The Constancy of the Speed of Light*

Despite many attempts to detect an effect, no variation was discovered in the speed of light. Light emerging from a torch at rest seems to travel forward at the same speed as light from a torch travelling at arbitrarily high speeds. This is very different from the way we perceive the behaviour of velocities in the everyday world. But, of course, we humans never perceive the velocity of light, it is just too fast! This unexpected behaviour is not contrary to common experience, it is beyond it! Explanation for the behaviour forms the starting point for the theory of special relativity, which is the necessary description of anything moving very fast (i.e. nearly all elementary particles); see Chapter 2.

1.5.2 *The Interaction of Light with Matter*

All light, for instance sunlight, is a form of heat and so the description of the emission and absorption of radiation by matter was approached as a thermodynamical problem. In 1900 the German physicist Max Planck concluded that the classical thermodynamical theory was inadequate to describe the process correctly. The classical theory seemed to imply that if light of any one colour (any one wavelength) could be emitted from matter in a continuous range of energy down to zero, then the total amount of energy radiated by the matter would be infinite. Much against his inclination, Planck was forced to conclude that light of any given colour cannot be emitted in a continuous band of energy down to zero, but only in multiples of a fundamental quantum of energy, representing the minimum negotiable bundle of energy at any particular wavelength. This is the starting point of quantum mechanics, which is the necessary description of anything very small (i.e. all atoms and elementary particles); see Chapter 3.

As the elementary particles are both fast moving and small, it follows that their description must incorporate the rules of both special relativity and quantum mechanics. The synthesis of the two is known as relativistic quantum theory and this is described briefly in Chapter 4.

2
Special Relativity

2.1 Introduction

A principle of relativity is simply a statement reconciling the points of view of observers who may be in different physical situations. Classical physics relies on the Galilean principle of relativity, which is perfectly adequate to reconcile the points of view of human observers in everyday situations. But modern physics requires the adoption of Einstein's special theory of relativity, as it is this theory which is known to account for the behaviour of physical laws when very high velocities are involved (typically those at or near the speed of light, denoted by c).

It is an astonishing tribute to Einstein's genius that he was able to infer the special theory of relativity in the almost total absence of the experimental evidence which is now commonplace. He was able to construct the theory from the most tenuous scraps of evidence.

To us lesser mortals, it is challenge enough to force ourselves to think in terms of special relativity when envisaging the behaviour of the elementary particles, especially as all our direct experience is of 'normal' Galilean relativity. What follows is of course only a thumbnail sketch of relativity. Many excellent accounts have been written on the subject, not least of which is that written by Einstein himself.

2.2 Galilean Relativity

Any theory of 'relativity' is about the relationships between different sets of coordinates against which physical events can be measured. Coordinates are numbers which specify the position of a point in space (and in time). However, for these numbers to have any meaning, we must also specify the particular coordinate system (or frame of reference) they refer to. For example, we might choose the origin of our coordinates to be the Royal Greenwich Observatory, and choose to specify coordinates in terms of the distance east of the observatory, the distance north and the height. Hence, the choice of a coordinate system involves specifying (1) an origin from which to measure coordinates (e.g. the observatory), and (2) three independent directions (e.g. east, north and up). So, relative to any chosen coordinate system, the position of a point in space is specified in terms of three independent coordinates, which we may write as (x, y, z). These three coordinates can be denoted collectively as a vector, $\mathbf{x} = (x, y, z)$. A further coordinate, t, is required to specify time.

Galileo's simple example is still one of the clearest descriptions of what relativity is all about. If a man drops a stone from the mast of a ship, he will see it fall in a straight line and hit the deck below, having experienced a constant acceleration due to the force of gravity. Another man standing on the shore and watching the ship sail past will see the stone trace out a parabolic path, because, at the moment of release, it is already moving with the horizontal velocity of the ship. Both the sailor and the shoreman can write down their views of the stone's motion using

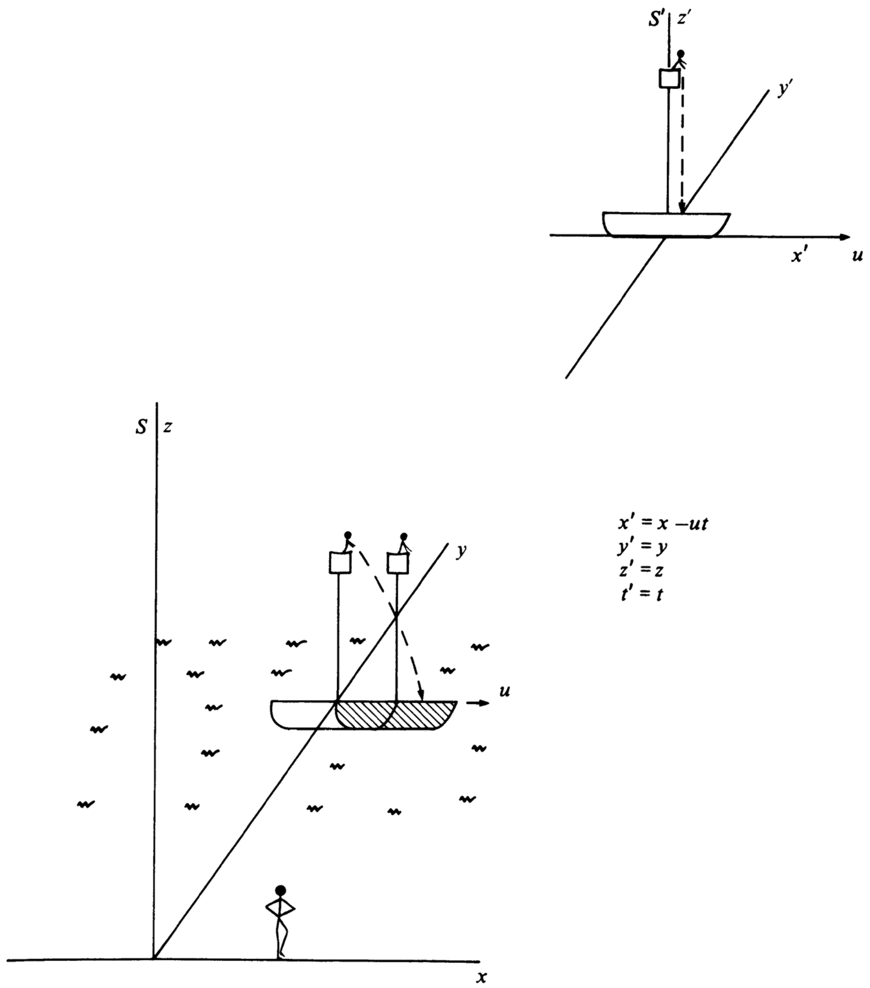


Figure 2.1. The transformations of Galilean relativity.

the mathematical equations for a straight line and a parabola respectively. As both sets of equations are describing the same event (the same force acting on the same stone), they are related by transformations between the two observers. These transformations relate the measurements of position ($\mathbf{x}'$), time (t'), and velocity ($\mathbf{v}'$) in the sailor's coordinate system S', with the corresponding measurements ($\mathbf{x}, t, \mathbf{v}$) made by the shoreman in his coordinate system S. This situation, assuming that the ship is sailing along the x-axis with velocity u, is shown in Figure 2.1.

Important features of the Galilean transformations are that velocity transformations are additive and that time is invariant between the two coordinate frames. Thus if a sailor throws the stone forward at 10 m per second in a ship travelling forward at 10 m per second, the speed of the stone to a stationary observer on shore will be 20 m per second. And if the sailor on a round trip measures the voyage as one hour long, this will be the same duration as observed by the stationary shoreman.

Lest the reader be surprised by the triviality of such remarks, let him or her be warned that this is not the case in special relativity. At the high velocities, such as are common in the microworld, velocities do not simply add to give the relative velocity, and time is not an invariant quantity. But before we address these sophistications, let us see how the idea came about.

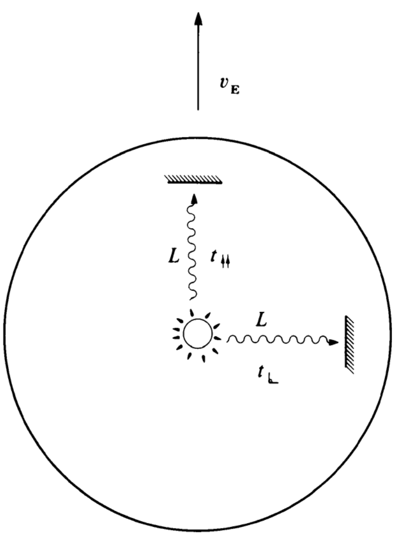
2.3 The Origins of Special Relativity

The fact that Galilean transformations allow us to relate observations made in different coordinate frames implies that any one inertial frame (a frame at rest or moving at constant velocity) is as good as another for describing the laws of physics. Nineteenth-century physicists were happy that this should apply to mechanical phenomena, but were less happy to allow the same freedom to apply to electromagnetic phenomena, and especially to the propagation of light.

The manifestation of light as a wave phenomenon (as demonstrated in the diffraction and interference experiments of optics) encouraged physicists to believe in the existence of a medium called the ether through which the waves might propagate (believing that any wave was necessarily due to the perturbation of some medium from its equilibrium state). The existence of such an ether would imply a preferred inertial frame, namely, the one at rest relative to the ether. In all other inertial frames moving with constant velocity relative to the ether, measurement and formulation of physical laws (say the force of gravitation) would mix both the effect under study and the effect of motion relative to the ether (say some sort of viscous drag). The laws of physics would appear different in different inertial frames, due to the different effects of the interaction with the ether. Only the preferred frame would reveal the true nature of the physical law.

The existence of the ether and the law of the addition of velocities suggested that it should be possible to detect some variation of the speed of light as emitted by some terrestrial source. As the Earth travels through space at 30 km per second in an approximately circular orbit, it is bound to have some relative velocity with respect to the ether. Consequently, if this relative velocity is simply added to that of the light emitted from the source (as in the Galilean transformations), then light emitted simultaneously in two perpendicular directions should be travelling at different speeds, corresponding to the two relative velocities of the light with respect to the ether (see Figure 2.2).

In one of the most famous experiments in physics, the American physicists Michelson and Morley set out in 1887 to detect this variation in the velocity of propagation of light. The anticipated variation was well within the sensitivity of their measuring apparatus, but absolutely none was found.



$$t_{\uparrow\downarrow} = \frac{2L}{c\left(1 - \frac{v_E^2}{c^2}\right)}$$

$$t_{\llcorner} = \frac{2L}{c\left(1 - \frac{v_E^2}{c^2}\right)^{1/2}}$$

Figure 2.2. Anticipated variation in the propagation of light reflected to and fro along a distance L due to the Earth's motion through space v_E.

This experiment provided clear proof that no such ether exists and that the speed of light is a constant regardless of the motion of the source.

2.4 The Lorentz–Fitzgerald Contraction

Around the turn of the century, many physicists were attempting to explain the null result of the Michelson and Morley experiment. The Dutch physicist Lorentz and the Irish physicist Fitzgerald realised that it could be explained by assuming that intervals of length and time, when measured in a given frame, appear contracted when compared with the same measurements taken in another frame by a factor dependent on the relative velocity between the two. Their arguments were simply that the anticipated variations in the speed of light were cancelled by compensating changes in the distance and time which the light travelled, thus giving rise to the apparent constancy observed. It is possible to calculate geometrically that an interval of length x measured in one frame is found to be x' when measured in a second frame travelling at velocity **v** relative to the first where:

$$x = \frac{x'}{\left(1 - \frac{v^2}{c^2}\right)^{1/2}}. \tag{2.1}$$

Here, c is the speed of light, which is approximately equal to 2.998×10^8 metres per second. And, similarly, the intervals of time observed in the two frames are related by:

$$t = \frac{t'}{\left(1 - \frac{v^2}{c^2}\right)^{1/2}}. \tag{2.2}$$

These empirical relationships, proposed on an ad hoc basis by Lorentz and Fitzgerald, suggest that because the 'common-sense' Galilean law of velocity addition fails at speeds at or near that of light, our common-sense perceptions of the behaviour of space and time must also fail in that regime. It was Einstein who, quite independently, raised these conclusions and relationships to the status of a theory.

2.5 The Special Theory of Relativity

The special theory of relativity is founded on Einstein's perception of two fundamental physical truths which he put forward as the basis of his theory:

(1) All inertial frames (i.e. those moving at a constant velocity relative to one another) are equivalent for the observation and formulation of physical laws.
(2) The speed of light in a vacuum is constant.

The first of these is simply the extension of the ideas of Galilean relativity to include the propagation of light, and the denial of the existence of the speculated ether. With our privileged hindsight, the amazing fact of history must be that the nineteenth-century physicist preferred to cling to the idea of relativity for mechanical phenomena while rejecting it in favour of the concept of a preferred frame (the ether) for the propagation of light. Einstein's contribution here was to extend the idea of relativity to include electromagnetic phenomena, given that all attempts to detect the ether had failed.

The second principle is the statement of the far-from-obvious physical reality that the speed of light is truly independent of the motion of the source and so is totally alien to our everyday conceptions. Einstein's achievement here was to embrace this apparently ludicrous result with no qualms. Thus the theory of relativity, which has had such a revolutionary effect on modern thought is, in fact, based on the most conservative assumptions compatible with experimental results.

Given the equivalence of all inertial frames for the formulation of physical laws and this bewildering constancy of the speed of light in all frames, it is understandable intuitively that measurements of space and time must vary between frames to maintain this absolute value for the speed of light. The relationships between measurements of space, time and velocity in different frames are related by mathematical transformations, just as were measurements in Galilean relativity, but the transformations of special relativity also contain the Lorentz–Fitzgerald contraction factors to account for the constancy of the speed of light (see Figure 2.3).

The first feature of the transformations to note is that when the relative velocity between frames is small compared with that of light (i.e. all velocities commonly experienced by humans), then $v/c \approx 0$, and the transformations reduce to the common-sense relations of Galilean relativity.

The unfamiliar effects of special relativity contained in the transformations can be illustrated by a futuristic example of Galileo's mariner: an astronaut in a starship travelling close to the speed of light c.

Because of the transformations, velocities no longer simply add. If, say, the astronaut fires photon torpedoes forward at speed $1c$ from the starship, which itself may be travelling at $0.95c$, the total velocity of the photon torpedoes as observed by a stationary planetary observer is not the sum, $1.95c$, but is still c, the constant speed of light. Also, time is dilated. So a voyage which to the stationary observer is measured as a given length of time will appear less to the kinetic astronaut.

Another intriguing feature of the transformations is that continued combinations of arbitrary velocities less than c can never be made to exceed c. Thus the transformations imply that continued attempts to add to a particle's velocity (by successive accelerations) can never break the light barrier. Indeed, the transformations themselves do not make sense for velocities greater than c, as when $v > c$ the equations become imaginary, indicating a departure from the