CHAPTER 2

THE EVOLUTION OF THE CONCEPT OF A FIELD

(or: Reality is a Concept)

Ref: The Evolution of Physics, by A. Einstein and L. Infeld, published by Touchstone Books, Simon & Schuster, New York, N.Y.

2.1 The Rise of the Mechanical View

The investigation of nature is somewhat like a detective story: gather clues and try to devise the scheme of things from the clues.

2.1.1 The First Clue

Aristotle wrote in "Mechanics":

"The moving body comes to a standstill when the force which pushes it along can no longer so act as to push it."

This is wrong but the concept held until Galileo changed peoples' view of reality. One generation later Newton formulated the LAW OF INERTIA:

> "Every body perseveres in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed thereon."

This concept destroyed the intuitive view of Aristotle and replaced it with a new one.

But what is FORCE?

In "Principia", Newton wrote:

> "An impressed force is an action exerted upon a body, in order to change its state, either of rest, or of moving uniformly forward in a right line.
>
> This force consists in the action only; and remains no longer in the body, when the action is over. For a body maintains every new state it acquires, by its vis inertiae only. Impressed forces are of different origins; as from percussion, from pressure, from centripetal force."

Aside:

What we are doing is describing the result of a force or what a force does. But the question still remains:

What is Force?

We all have an intiuitive, mechanical view or feel of what force is, but it is merely our view of reality. It is not reality.

2.1.2 Vectors

A vector is a concept of space and direction in space. It is purely an abstraction needed to sort out forces (whatever they are).

Vectors are not needed so much to recognize the facts as they are to build on the fundamental facts.

2.1.3 The Riddle of Motion

Investigation of motion along a curved path led to phrases like "very short", "very small", etc. This was imprecise so Newton and Leibnitz founded CALCULUS. The gained precision allowed a great leap into formalization of planetary motion, gravity, etc.

2.1.4 One Clue Remains: Mass

Two types of mass were recognized: inertial mass and gravitational mass. How are they related? Experimentally they turned out to be identical, i.e.:

$$\frac{M_A \text{ inertial}}{M_B \text{ inertial}} = \frac{M_A \text{gravitational}}{M_B \text{gravitational}}$$

Galileo showed this by dropping masses from a tower and found that the mass resisting acceleration was proportional to the mass being attracted to the earth by gravity.

Classical physics said that the identity is accidental. Modern physics says that the identity is fundamental and is an essential clue. This leads to the general theory of relativity.

2.1.5 Is Heat a Substance?

It took an unbelievably long time to separate the concept of heat from the concept of temperature. Specific heats were measured and it was determined that the specific heats were not a function of the method of heating. Hence heat is not a substance (Rumford in the 1800's). It was concluded that heat is a property of ......" motion".

2.1.6 The Roller-Coaster

It was found experimentally that the sum of potential, kinetic and heat energy is a constant. Energy is like a substance: it is indestructible. For example, a roller coaster is given an initial amount of energy which is transformed back and forth between potential and kinetic energy, and is eventually dissipated as heat energy.

2.1.7 The Rate of Exchange

Joule related mechanical (Kinetic and potential) energy to heat energy and worked out the exchange rate, i.e. he related foot-pounds force to Δ°F/pound mass. Thus, physicists of the 1800's announced:

1. Matter is conserved and is invarient in the universe.
2. Energy is conserved and is invarient in the universe.

2.1.8 The Philosophical Background

The Philosophical basis of scientific inquiry was that there is a unifying theory governing nature in all its complexity. This was expressed from the time of the Greeks through to Galileo and beyond[1] to Helmholtz of the previous century. Helmholtz writes:

"Finally, therefore, we discover the problem of physical material science to be to refer natural phenomena back to unchangeable attractive and repulsive forces whose intensity depends wholly upon distance. The solubility of this problem is the condition of the complete comprehensibility of nature."
and again:

"And its vocation will be ended as soon as the reduction of natural phenomena to simple forces is complete and the proof given that this is the only reduction of which the phenomena are capable."

Force and mass were underlying concepts and are dependent on each other to exist. How could one demonstrate the existance of mass without force or force without mass? This is the mechanical view.

2.1.9 The Kinetic Theory of Matter

How is heat related to motion?

Based on experiments of Brown (of Brownian motion fame), heat is mechanical energy, a collective motion of particles. Temperature is a measure of kinetic energy.

Considerations of the concepts of pressure of gases and energy led to the conclusion that for the same volume, temperature and pressure, different gases contain the same number of molecules (Recall Avagadro's Number from Physical Chemistry).

The overall consistency adds credibility to the mechanical view and helps to fulfil the general philosophical program: to reduce the explanation of all phenomena to the interaction between particles of matter.

2.2 THE DECLINE OF THE MECHANICAL VIEW

2.2.1 The Two Electric Fields

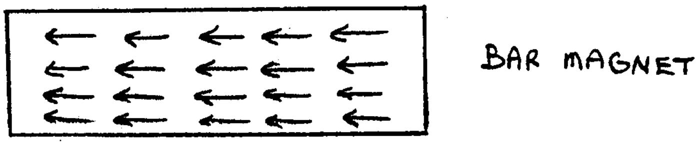
We can perform experiments with rubber rods and cat fur to show the existence of positive and negative substances. Like substances repel , dislike attract.

Now, every theory has its development, triumph and ultimately, its decline. Nearly every great advance in science arises from a crises in the old theory. We must examine old ideas to understand the importance of the new ones and to extend their validity.

Can the mechanical view explain the electrical phenomena? Coulomb measured force as a function of distance and formulated the $\frac{1}{r^2}$ relation like gravity. The electrical potential is like temperature and the charge is like heat. But how do charges equalize? By flow? But what flows? Does the +ve charge flow or does the -ve charge flow? We know of no experiment to denote the + or - sign so we simply adopt a convention and call a positive a positive and say that charge flows from + to -. This is pure convention and is arbitrary.

2.2.2 The Magnetic Fluids

Experiments were performed with bar magnets and it was found that there were attractions and repulsions just like the electrical case. But it was found that you cannot isolate a magnetic pole, whereas you can isolate a charge. An electric dipole behaves like a bar magnet except, again, you cannot isolate the magnetic poles. This led to the concept of many elementary magnetic dipoles.



The force of a magnet also drops off as $\frac{1}{r^2}$.

Once again we see the application of a general point of view: the tendency to describe all phenomena by means of attractive and repulsive forces depending only on distances and acting between unchangable particles. But physicists had to invent new weightless substances unrelated to the fundamental substances: Mass. This is all rather artificial.

2.2.3 The First Serious Difficulty

Towards the end of the 1700's Galvani experimented with frog's legs and Volta built a battery. In the early 1800's Oersted related magnetism and electric current by a simple experiment of a compass needle in a loop of wire connected to a battery. A force on the needle was created perpendicular to the current direction and perpendicular to the magnetic force direction. Compare this to Newton's and Coulomb's work where forces acted along the line of attracting or repelling bodies.

Around 1880, Rowland rotated a charge and got the same effect. He found that the velocity of the charge was important in determining the size of the force. This shakes the mechanical view since this new force does not depend only on distance. The old force did not depend on velocity.

2.2.4 The Velocity of Light

This was determined experimentally to be 300,000 km/s.

2.2.5 Light as Substance

We all know the following: we do not need air to transmit light; propagation is rectilinear (travels in a straight line); light refracts.

The mechanical approach penetrated optics. Lighted bodies emit particles (corpuscles): a new substance. This works well in covering off rectilinear motion, refraction, reflection, etc.

2.2.6 The Riddle of Colour

With the aid of a prism, Newton explained the rainbow and prism effect by introducing a separate corpuscle for each colour. He assumed that all corpuscles have the same velocity in vacuum. The theory works well but we have many new substances.

2.2.7 What is a Wave?

A new idea is introduced: We consider the motion of energy propagated thru matter as opposed to the motion of matter itself. The wave has two characterisitics:

(1) Velocity
(2) Wave Length

This is still a mechanical concept. We can have longitudinal (sound) and transverse (water) waves. Plane waves can be considered as segments of spherical waves as long as r is large.

2.2.8 The Wave Theory of Light

Huygenes, a contemporary of Newton, suggested that light travelled in waves. But all waves (up to now) need a medium to travel in. Enter a new substance: ETHER. Now we can replace all those corpuscles with just one new substance. If the wave length is small you get rectilinear motion and distinct shadows. Refraction is explained by different speeds in different media. Different wave lengths give different colours.

For ∿ 100 years after Newton, most physicists favoured corpuscular theory. But in mid 1800's the verdict came out in favor of wave theory due to experiments on interference patterns (Young and Fresnal). In modern physics, a choice still exists but in a more profound and intricate form.

2.2.9 Longitudinal or Transverse Light Waves?

What are the properties of ether? Polarization experiments show that a light wave is transverse. This makes mechanical explanations difficult.

2.2.10 Ether and the Mechanical View.

Since planets travel through space without resistance and since ether is everywhere, then ether does not interact with particles of matter. But ether does interact optically since the velocity of light changes in different matter). This leaves a paradox.

All this points to a fault in the fundamental assumption: the mechanical point of view.

Science did not succeed in carrying out the mechanical program convincingly. The problems so far:

1. Unnoticed clue of equality of gravitational and inertial mass.
2. Artificial character of the electric and magnetic fluids.

3. Unsolved interaction between electric current and magnetic needle (lines of force $\perp$, not in-line).
4. Ether.

Modern physics has attacked all these problems and solved them but it has created new and deeper problems. Knowledge is now wider and more profound, but so are our difficulties.

2.3 FIELD, RELATIVITY

2.3.1 The Field as Representation

From 1850 to 1900, a new philosophical view, different from the mechanical view, emerged. The work of Faraday, Maxwell and Hertz led to the development of modern physics.

A logical development took place based on the graphical form of the lines of force. The lines showed direction and intensity ($\frac{1}{r^2}$ behaviour). The concept required no matter since the lines were a property of space. The field indicates only how a test body would behave in that field. Time does not enter into the picture.

Construction of a graphical field shows that the fields for a bar magnet and a solenoid are identical. This was the first fruit of the field representation.

The field representation indicates that the source of the field is not important but that the field is. This was confirmed experimentally.

Electrostatic, magnetostatic and gravitational fields are all of different character. They do not interact. Revisiting Rowland and Oersted's experiments from the point of view of fields, the change in electric field leads to a magnetic field.

2.3.2 The Two Pillars of The Field Theory

1. Change in magnetic field produces a change in the electric field. Faraday induced currents in this manner.
2. Changes in an electric field produces a change in the magnetic field (Rowland and Oersted).

The field is a storage of energy since the sudden loss of a field gives an energy discharge. Thus a field is associated with the conservation of energy.

The attribution of energy to the field is one step further in the development in which the field concept was used more and more, while the concept of substances, so essential to the mechanical view, was more and more suppressed.

2.3.3 The Reality of The Field

Quantitative, mathematical descriptions of the field laws are summed up in Maxwell's equations. The formulation of these laws was the most important event in physics since Newton's time. Maxwell's equations are laws representing the structure of the field.

These laws describe a connection between changes in magnetic and electric fields at an arbitrary point in space and at an arbitrary instant in time. Further, we don't need a wire to produce current to give a field. An electromagnetic field is, in Maxwell's theory, something real. But it does not require matter as in the mechanical laws.

But there are similarities in the two views. As per mechanics, if we know the position, mass and velocity of a particle and the forces on it, we can predict the future path of the particle. In Maxwell's theory, if we know the field at one instant only, we can deduce how the whole field will change. in time and space. The differences are that in Maxwell's theory, there are no material actors and his theory refers to local events, not as per Newton's gravitational theory, although Maxwell's equations can be integrated up to the global picture. Maxwell's equations have shown new and unexpected conclusions which are testable. The equations give electromagnetic waves if electric charges oscillate. This leads to the radiation of energy as transverse waves. The original experiments now have a deeper meaning. The result that electromagnetic waves spread in free space with the velocity of light is one of the greatest achievements in the history of science.

All this from the results expressed in field language It was around 1880 that Hertz proved the existance of the electromagnetic wave and got its velocity.

2.3.4 Field and Ether

The fact that an electromagnetic wave moves at the speed of light suggests a close relationship between optical and electromagnetic phenomena. The only difference is the wave length: long for electromagnetics, short for light.

The idea of a field started out only as a convenient construct but it soon overshadowed the use of "substance". A new reality was created for which there was no place in the mechanical description. The electromagnetic field is for the modern physicist as real as the chair on which he sits.

This does not invalidate the old results and physical theories. It just gives a different perspective.

Field theory started out as a means to help ether theory but this did not happen. Field theory took off on its own. Our only way out seems to be to take for granted the fact that space has the physical property of transmitting electromagnetic waves and not to bother too much about the meaning of this statement.

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This concludes my attempt at warping your sense of reality and generally making your life uncomfortable by casting serious doubt on the very things you probably believe most.

We now proceed to wander through electricity and magnetism as seen from the point of view of field theory. From the following detailed,and mostly mathematical treatment,a practical knowledge (and wisdom) about things electric and magnetic can be gained. At times, the relation and relevance to mechanical engineering may seem dubious at best but the payoff comes in gaining a broader view of things, of perhaps seeing applications to mechanical engineering such as manufacturing techniques, in appreciating how mechanical aspects of products like cars should evolve given the switch to electronics in cars, in appreciating the problems of electrical engineers whom you will be teamed up with at some stage in your life, etc.,etc., etc.