FIELDS

Farewell to the Mechanical Universe

As late as 1900, physicists generally conceived of the universe in mechanical terms. Newton had revealed the solar system as a collection of material objects interacting through forces that acted at a distance. By 1900, evidence began to accumulate for the existence of atoms as real things, and not just as imaginary models of reality. In this microscopic realm, the same (successful) Newtonian picture tended to be transferred over to the microscopic world. Now the actors on the stage were atoms rather than planets, and the forces were electrical rather than gravitational, but it seemed to be a variation on the same theme. Some physicists, however, began to realize that the old mechanical picture would not quite work. At a deeper level, the operation of the universe came to be understood in terms of *fields*, the general idea being embodied fairly well in "The Force" from the Star Wars movies: "... an energy field created by all living things. It surrounds us, penetrates us, and binds the galaxy together." Substitute "massive" for "living," and you have a fairly good description of the gravitational field. Substitute "charged" instead, and it is a depiction of the electric field.

Time delays in forces exerted at a distance

What convinced physicists that they needed this new concept of a field of force? Although we have been dealing mostly with electrical forces, let's start with a magnetic example. (In fact the main reason I've delayed a detailed discussion of magnetism for so long is that mathematical calculations of magnetic effects are handled much more easily with the concept of a field of force.) First a little background leading up to our example. A bar magnet, a, has an axis about which many of the electrons' orbits are oriented. The earth itself is also a magnet, although not a bar-shaped one.

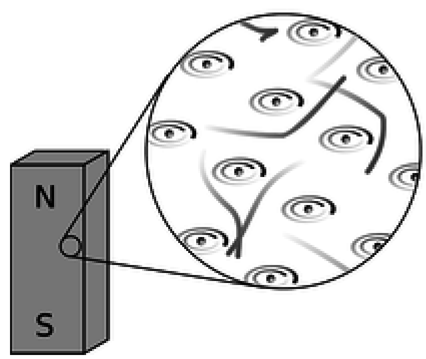


Figure a: A bar magnet's atoms are (partially) aligned.

The interaction between the earth-magnet and the bar magnet, b, makes them want to line up their axes in opposing directions (in other words such that their electrons rotate in parallel planes, but with one set rotating clockwise and the other counterclockwise as seen looking along the axes).

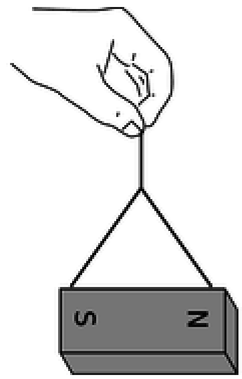


Figure b: A bar magnet interacts with our magnetic planet.

On a smaller scale, any two bar magnets placed near each other will try to align themselves head-to-tail, c.

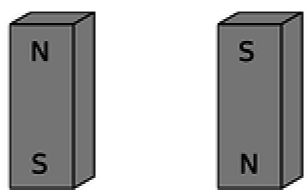


Figure c: Magnets aligned north-south.

Now we get to the relevant example. It is clear that two people separated by a paper-thin wall could use a pair of bar magnets to signal to each other. Each person would feel her own magnet trying to twist around in response to any rotation performed by the other person's magnet. The practical range of communication would be very short for this setup, but a sensitive electrical apparatus could pick up magnetic signals from much farther away. In fact, this is not so different from what a radio does: the electrons racing up and down the transmitting antenna create forces on the electrons in the distant receiving antenna. (Both magnetic and electric forces are involved in real radio signals, but we don't need to worry about that yet.)

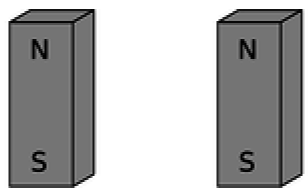
A question now naturally arises as to whether there is any time delay in this kind of communication via magnetic (and electric) forces. Newton would have thought not, since he conceived of physics in terms of instantaneous action at a distance. We now know, however, that there is such a time delay. If you make a long-distance phone call that is routed through a communications satellite, you should easily be able to detect a delay of about half a second over the signal's round trip of 50,000 miles. Modern measurements have shown that electric, magnetic, and gravitational forces all travel at the speed of light, 3×10^8 m/s.[1] (In fact, we will soon discuss how light itself is made of electricity and magnetism.)

If it takes some time for forces to be transmitted through space, then apparently there is some *thing* that travels *through* space. The fact that the phenomenon travels outward at the same speed in all directions strongly evokes wave metaphors such as ripples on a pond.

More evidence that fields of force are real: they carry energy

The smoking-gun argument for this strange notion of traveling force ripples comes from the fact that they carry energy.

First suppose that the person holding the bar magnet on the right decides to reverse hers, resulting in configuration d. She had to do mechanical work to twist it, and if she releases the magnet, energy will be released as it flips back to c. She has apparently stored energy by going from c to d. So far everything is easily explained without the concept of a field of force.



d / The second magnet is reversed.

But now imagine that the two people start in position c and then simultaneously flip their magnets extremely quickly to position e, keeping them lined up with each other the whole time.

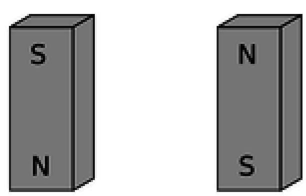


Figure e: Both magnets are reversed.

Imagine, for the sake of argument, that they can do this so quickly that each magnet is reversed while the force signal from the other is still in transit. (For a more realistic example, we'd have to have two radio antennas, not two magnets, but the magnets are easier to visualize.) During the flipping, each magnet is still feeling the forces arising from the way the other magnet *used* to be oriented. Even though the two magnets stay aligned during the flip, the time delay causes each person to feel resistance as she twists her magnet around. How can this be? Both of them are apparently doing mechanical work, so they must be storing magnetic energy somehow. But in the traditional Newtonian conception of matter interacting via instantaneous forces at a distance, interaction energy arises from the relative positions of objects that are interacting via forces. If the magnets never changed their orientations relative to each other, how can any magnetic energy have been stored?

The only possible answer is that the energy must have gone into the magnetic force ripples crisscrossing the space between the magnets. Fields of force apparently carry energy across space, which is strong evidence that they are real things.

This is perhaps not as radical an idea to us as it was to our ancestors. We are used to the idea that a radio transmitting antenna consumes a great deal of power, and somehow spews it out into the universe. A person working around such an antenna needs to be careful not to get too close to it, since all that energy can easily cook flesh (a painful phenomenon known as an “RF burn”).

The gravitational field

Given that fields of force are real, how do we define, measure, and calculate them? A fruitful metaphor will be the wind patterns experienced by a sailing ship. Wherever the ship goes, it will feel a certain amount of force from the wind, and that force will be in a certain direction. The weather is ever-changing, of course, but for now let's just imagine steady wind patterns.

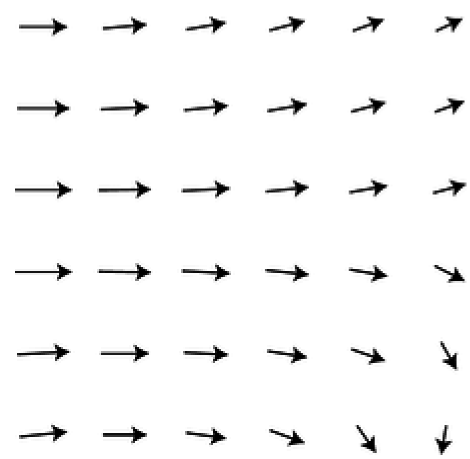


Figure f: The wind patterns in a certain area of the ocean could be charted in a “sea of arrows” representation like this. Each arrow represents both the wind's strength and its direction at a certain location.

Definitions in physics are operational, i.e., they describe how to measure the thing being defined. The ship's captain can measure the wind's “field of force” by going to the location of interest and determining both the direction of the wind and the strength with which it is blowing. Charting all these measurements on a map leads to a depiction of the field of wind force like the one shown in the figure. This is known as the “sea of arrows” method of visualizing a field.

Now let's see how these concepts are applied to the fundamental force fields of the universe. We'll start with the gravitational field, which is the easiest to understand. We've already encountered the gravitational field, *g*, which we defined in terms of energy. Essentially, *g* was defined as the number that would make the equation *GE=mgh* give the right answer. However, we intuitively feel that the gravitational field has a direction associated with it: down! This can be more easily expressed via the following definition:

definition of the gravitational field

The gravitational field, *g*, at any location in space is found by placing a test mass *m* at that point. The field is then given by *g*=*F*/*m*, where *F* is the gravitational force on the test mass. With this new definition, we get units of N/kg, rather then J/kg/m. These are in fact equivalent units.

The most subtle point about all this is that the gravitational field tells us about what forces *would* be exerted on a test mass by the earth, sun, moon, and the rest of the universe, *if* we inserted a test mass at the point in question. The field still exists at all the places where we didn't measure it.

Sources and sinks

If we make a sea-of-arrows picture of the gravitational fields surrounding the earth, g, the result is evocative of water going down a drain. For this reason, anything that creates an inward-pointing field around itself is called a sink. The earth is a gravitational sink. The term “source” can refer specifically to things that make outward fields, or it can be used as a more general term for both “outies” and “innies.” However confusing the terminology, we know that gravitational fields are only attractive, so we will never find a region of space with an outward-pointing field pattern.

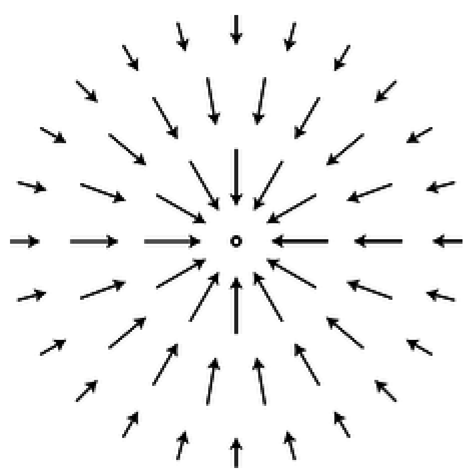


Figure g: The gravitational field surrounding a clump of mass such as the earth.

Knowledge of the field is interchangeable with knowledge of its sources (at least in the case of a static, unchanging field). If aliens saw the earth's gravitational field pattern they could immediately infer the existence of the planet, and conversely if they knew the mass of the earth they could predict its influence on the surrounding gravitational field.

The electric field

The definition of the electric field is directly analogous to, and has the same motivation as, the definition of the gravitational field:

The electric field, E, at any location in space is found by placing a test charge q at that point. The electric field vector is then given by E=F/q, where F is the electric force on the test charge.

Charges are what create electric fields. Unlike gravity, which is always attractive, electricity displays both attraction and repulsion. A positive charge is a source of electric fields, and a negative one is a sink.

Electromagnetic waves

Theorist James Clerk Maxwell was the first to work out the principle of induction (including the detailed numerical and geometric relationships, which we won't go into here). Legend has it that it was on a starry night that he first realized the most important implication of his equations: light itself is an electromagnetic wave, a ripple spreading outward from a disturbance in the electric and magnetic fields. He went for a walk with his wife, and told her she was the only other person in the world who really knew what starlight was.

Figure y: / James Clerk Maxwell (1831-1879)

The principle of induction tells us that there can be no such thing as a purely electric or purely magnetic wave. As an electric wave washes over you, you feel an electric field that changes over time. By the principle of induction, there must also be a magnetic field accompanying it. It works the other way, too. It may seem a little spooky that the electric field causes the magnetic field while the magnetic field causes the electric field, but the waves themselves don't seem to worry about it.

The distance from one ripple to the next is called the wavelength of the light. Light with a certain wavelength (about quarter a millionth of a meter) is at the violet end of the rainbow spectrum, while light with a somewhat longer wavelength (about twice as long) is red. Figure z/1 shows the complete spectrum of light waves.

Maxwell's equations predict that all light waves have the same structure, regardless of wavelength and frequency, so even though radio and x-rays, for example, hadn't been discovered, Maxwell predicted that such waves would have to exist. Maxwell's 1865 prediction passed an important test in 1888, when Heinrich Hertz published the results of experiments in which he showed that radio waves could be manipulated in the same ways as visible light waves. Hertz showed, for example, that radio waves could be reflected from a flat surface, and that the directions of the reflected and incoming waves were related in the same way as with light waves, forming equal angles with the normal. Likewise, light waves can be focused with a curved, dish-shaped mirror, and Hertz demonstrated the same thing with a dish-shaped radio antenna.

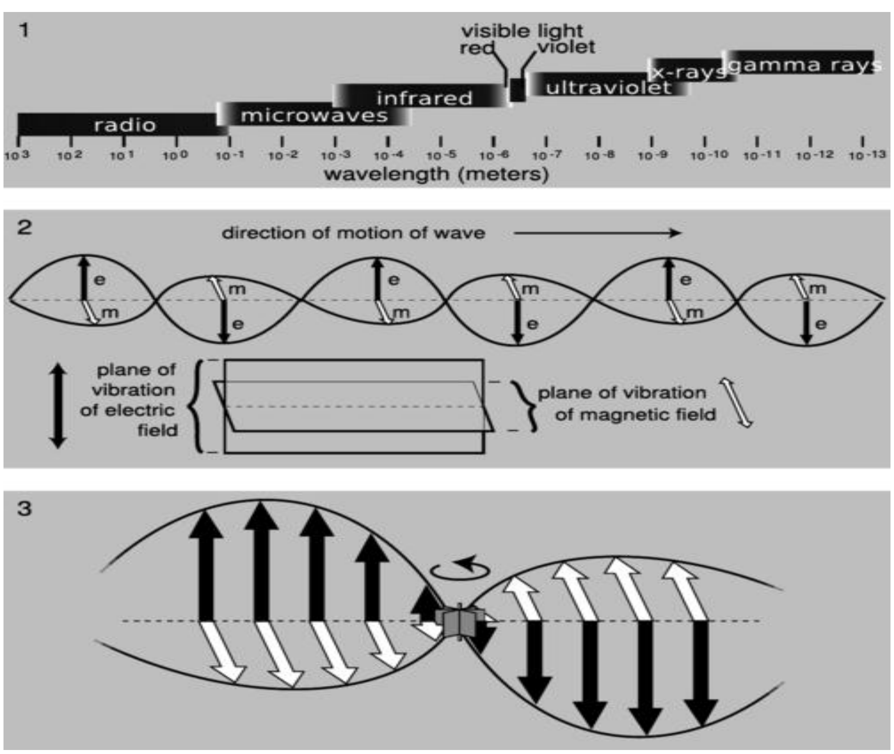


Figure z: Panel **1** shows the electromagnetic spectrum. Panel **2** shows how an electromagnetic wave is put together. Imagine that this is a radio wave, with a wavelength of a few meters. If you were standing inside the wave as it passed through you, you could theoretically hold a compass in your hand, and it would wiggle back and forth as the magnetic field pattern (white arrows) washed over you. (The vibration would actually be much to rapid to detect this way.) Similarly, you'd experience an electric field alternating between up and down. Panel **3** shows how this relates to the principle of induction. The changing electric field (black arrows) should create a curly magnetic field (white). Is it really curly? Yes, because if we inserted a paddlewheel that responded to electric fields, the field would make the paddlewheel spin counterclockwise as seen from above. Similarly, the changing magnetic field (white) makes an electric field (black) that curls in the clockwise direction as seen from the front.

Source: http://physwiki.ucdavis.edu/Electricity_and_Magnetism/Fields