Up until now, we have only been learning how to DESCRIBE motion. The study of the description of motion is called KINEMATICS. Now we begin to examine the CAUSES of motion. The study of the relationship between motion and the causes of motion is called DYNAMICS.

The basic idea in dynamics is that an object's acceleration is caused by a non-zero total FORCE acting on that object. But what do we mean by the word "force"? Here is the definition that we will use.

DEF FORCES are interactions between objects. The typical symbol for force is $\mathbf{F}$. Force is a vector quantity, having both magnitude and direction. The unit of force is the Newton (N). 1 N = 1 kg·m/s^2.

This definition agrees well with the most modern scientific ideas about forces. Our book defines a force as a push or a pull, not a bad definition, and a definition that is more closely related to the ideas about forces that students usually have when they begin to study physics. But I have found that using this "push-or-pull" definition is a real cause of student confusion. I strongly suggest that you temporarily put aside your current ideas about forces until we have finished studying Chapters 4 and 5; at that point, sit down and reflect on how your old ideas about forces agree or disagree with our more scientific definition.

So, forces are interactions between objects. In what ways can two objects interact? For 111, there are only two ways (in 112, you will learn that there are at least two additional ways). First, they can interact by touching, i.e. by being IN CONTACT.

CONTACT FORCES

Any two objects which are in contact exert forces on each other. We will give special names to some contact forces (for example, normal force, tension force, spring force, friction, etc.), but all of them occur only as a result of contact. For right now, to indicate the force on object 1 due to its contact with object 2 we will use the following notation:

$$\mathbf{F}_{12} \equiv \text{the force ON object 1 BY object 2}$$

In this case, the order of the subscripts matters; $\mathbf{F}_{12}$ always means ON 1 BY 2.

There is only one way in which two objects can interact without touching, the FORCE of GRAVITY. If you drop an apple, the force of gravity pulls it toward the ground without any contact between the ground and the apple. Similarly, the force of gravity holds the Moon in orbit around the Earth, but there is no contact between the the two.

GRAVITATIONAL FORCES

Every two particles in the Universe interact via the attractive gravitational force. Isaac Newton was the first human being to understand this, and in 1687 he gave us

NEWTON'S UNIVERSAL LAW OF GRAVITATION

Given any two point masses m_1 and m_2, separated by a distance r, the magnitude of the force of gravity between m_1 and m_2 is

$$F_G = G\frac{m_1 m_2}{r^2}$$

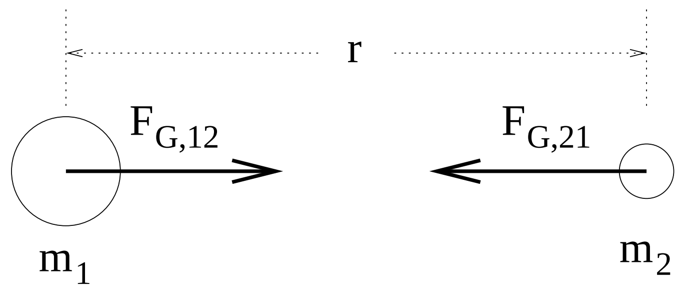
This is the magnitude of the gravitational force on m_1 by m_2. Also, it is the magnitude of the gravitational force on m_2 by m_1. In symbols,

$$F_G = |\mathbf{F}_{G,12}| \quad \text{and also} \quad F_G = |\mathbf{F}_{G,21}|$$

where $\mathbf{F}_{G,12}$ is the gravitational force ON 1 BY 2, and $\mathbf{F}_{G,21}$ is the gravitational force ON 2 BY 1. Since m_1 attracts m_2, and m_2 attracts m_1,

$$\mathbf{F}_{G,12} = -\mathbf{F}_{G,21},$$

i.e. the two vectors point in opposite directions, as shown here:



The picture also illustrates another important point. The UNIVERSAL LAW is for POINT masses, but it is exact for spherical objects if r is the distance from center to center. (By the way, some people like to use d for the distance from center-to-center; that is OK, but r is traditional.) For non-spherical objects, calculus is required to get the exact result; so, for the purpose of using the UNIVERSAL LAW, we will just assume that all objects are spherical. The symbol G in the UNIVERSAL LAW is just a constant, with dimensions; it was measured 110 years after Newton wrote down the Law. The measured value is

$$G = 6.67 \times 10^{-11} \ \ \frac{\mathrm{N} \cdot \mathrm{m}^2}{\mathrm{kg}^2}$$

The units for G just make the units for F_G come out to N, as they must.

This amazing rule holds for any two objects in the Universe. Consider a 50 kg student and a 60 kg student sitting 2.0 m apart. The magnitude of the gravitational attraction between them is

$$F_G = \left(6.67 \times 10^{-11} \ \ \frac{\mathrm{N} \cdot \mathrm{m}^2}{\mathrm{kg}^2}\right) \left(\frac{(50 \ \mathrm{kg}) \cdot (60 \ \mathrm{kg})}{(2 \ \mathrm{m})^2}\right) = 5.00 \times 10^{-8} \ \mathrm{N}$$

On the other hand, what is the magnitude of the gravitational attraction between the 50 kg student and the Earth? The Earth has a mass of 5.98×10^{24} kg and a radius of roughly 6.38×10^{6} m. The student is sitting on the surface of the Earth, so the distance between the center of the Earth and the center of the student is, for all practical purposes, just the radius of the Earth. So, for the Earth and the 50 kg student,

$$F_G = \left(6.67 \times 10^{-11} \ \ \frac{\mathrm{N} \cdot \mathrm{m}^2}{\mathrm{kg}^2}\right) \left(\frac{(50 \ \mathrm{kg}) \cdot (5.98 \times 10^{24} \ \mathrm{kg})}{(6.38 \times 10^6 \ \mathrm{m})^2}\right) = 490 \ \mathrm{N}$$

We see that the force of attraction between the two students is miniscule compared to the force of attraction between the Earth and either of the two students. For this reason, for any object near the surface of the Earth, we will ignore all gravitational forces except the gravitational attraction of the Earth. The force of gravity on an object is also called the WEIGHT of the object.

DEF The WEIGHT ($\mathbf{W}$ or $\mathbf{F}_G$) of an object is the force of gravity on that object. Weight, being a force, is a vector quantity. Near the surface of the Earth, the direction of weight is always DOWN, i.e. towards the center of the Earth. The units of weight are N.

This is another case (like the case of speed and velocity) in which words that are interchangeable in everyday usage are not interchangeable in scientific usage. Weights are commonly given in kg. In science, that is not acceptable. MASS in in kg. WEIGHT is a force, and is always in N. However, you need to be aware that the word "weight" can also be used acceptably to refer to the magnitude of the force of gravity on an object. You should always be able to tell by the context in which the word is used whether weight refers to the force of gravity or the magnitude of that force. For example, if I say, "My weight is 690 N", I am refering to the magnitude of the force of gravity.

So, the first thing that we have learned about forces is that there are only two kinds, CONTACT FORCES and GRAVITY. The next thing we need to learn about forces was also given to us by Isaac Newton in 1687 and is called

NEWTON'S THIRD LAW

If two objects interact, the force exerted on object 1 by object 2 is equal in magnitude but opposite in direction to the force exerted on object 2 by object 1. In symbols,

$$\mathbf{F}_{12} = -\mathbf{F}_{21}$$

I have written the law for contact forces. We already knew that it was true for gravitational forces, i.e. $\mathbf{F}_{G,12} = -\mathbf{F}_{G,21}$. The THIRD LAW is true for all forces. It makes sense because two objects are required to have an interaction. There are then two objects but only one interaction, so the forces on either object must have only one common magnitude.

The THIRD LAW is short but very powerful. It first reminds us:

(0) All forces occur between objects.

And the THIRD LAW tells us four new things:

(1) ALL forces occurs in pairs, which we will call THIRD-LAW PAIRS.

(2) The two forces in a Third-Law pair point in opposite directions.

(3) The two forces in a Third-Law pair have equal magnitudes.

(4) The two forces in a Third-Law pair act on different objects.

Our book calls Third-Law pairs "action-reaction" pairs instead, but I don't like this choice because it is not always easy to figure out which force is the "action" and which is the "reaction".

Let's try a simple example in which we are asked to identify all of the forces acting on an object, and then for each of those forces, identify its Third-Law partner. Consider a block resting on the ground. We might be asked to make a list of the forces acting on the block and state the directions of those forces. Or else, we might be asked to make a FREE-BODY DIAGRAM for the block. I will do both, but first I need to define Free-Body Diagram.

DEF A FREE-BODY DIAGRAM (FBD) is a diagram containing only the object in question and showing ALL the forces acting ON that object.

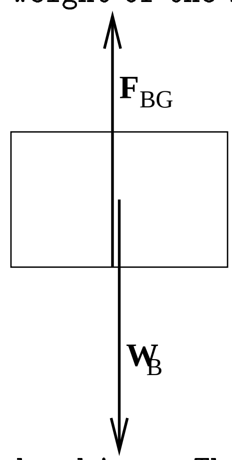
The last part of this DEF is so important that I repeat it. A Free-Body Diagram (FBD) shows ONLY the forces acting ON THE OBJECT IN QUESTION.

So, here's a drawing of the block (B) on the ground (G).

First, I will just make a list of all the forces acting on the block. The block is in contact with the ground and nothing else (we will ignore the force of air pressure until late in the semester). So there is one contact force, the force on the block by the ground, $\mathbf{F}_{BG}$. And there is the force of gravity on the block by the Earth, $\mathbf{F}_{G,BE}$, which is the same as the weight of the block, $\mathbf{W}_B$. Here then is the list, and beside it I put the FBD.

$\mathbf{F}_{\mathrm{BG}}$,the force on the block by the ground, UP

$\mathbf{W}_{\mathrm{B}}$,the weight of the block, DOWN



Many people like to make the FBD with a dot for the object. Then all of the forces start at the dot. That is a perfectly good choice; our book makes that choice. It will work fine as long as we are not considering the possibility that the object may rotate. If you choose to use my method, always draw the weight vector coming from the center of the object. The contact-force vector can be drawn either starting or ending at the point of contact.

Finally, for each of these forces, we were asked to identify the Third-Law partner. The Third-Law in symbols is $\mathbf{F}_{12} = -\mathbf{F}_{21}$, so all we ever have to do to identify a Third-Law partner is to switch the order of the symbols. For $\mathbf{F}_{BG}$, the Third-Law partner is $\mathbf{F}_{GB}$, the contact force on the ground by the block. This is a downward force acting on the ground underneath the block. For $\mathbf{W}_B$, the Third-Law partner is $\mathbf{F}_{G,EB}$, the force of gravity on the Earth by the block. This is a force acting at the center of the Earth and pointed towards the block.

A common mistake that beginning students make is to identify the two forces in the FBD as Third-Law pairs. They are not. Both of those forces act on the same object, and so cannot be Third-Law pairs. Because Third-Law pairs always act on different objects, the two partners of the pair can never appear in the same FBD.

For practice, consider a ball hanging at the end of a rope. The rope is attached to the ceiling. Make a list of all the forces acting on the ball and state their direction. Then make a FBD for the ball. Finally, identify the Third-Law partners of every force in your FBD. You will find the two lists in the ANSWERS TO EVEN-NUMBERED PROBLEMS page.

Now that we know something about forces, we are ready to study the connection between force and motion. This connection is given by Newton's First and Second Laws, and will be discussed in lecture. To understand those Laws, we need one more DEF.

DEF The NET FORCE ($\Sigma\mathbf{F}$) acting on an object is simply the vector sum of all forces acting on that object. Synonyms are the RESULTANT FORCE, the TOTAL FORCE, and the SUM OF ALL FORCES.

Please write down any questions you have about CONTACT FORCES, or the FORCE of GRAVITY, or NEWTON'S THIRD LAW. I will give you a chance to ask these questions at the beginning of lecture.