UNIT IV: Free Particle Model
Inertia and Interactions

Instructional Goals

1. Newton's 1st law (Galileo's thought experiment)
   Develop notion that a force is required to *change velocity*, not to *produce motion*
   Constant velocity does not require an explanation.

2. Force concept
   View force as an interaction between and agent and an object
   Choose system to include objects, not agents
   Express Newton's 3rd law in terms of paired forces (agent-object notation)

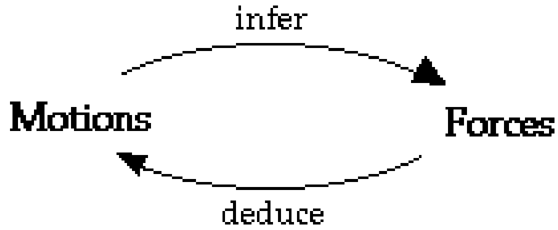
3. Force diagrams
   Correctly represent forces as vectors originating on object (point particle)
   Use the superposition principle to show that the net force is the vector sum of the forces

4. Statics
   •F = 0 produces same effect as no force acting on object
   decomposition of vectors into components

Overview

In this unit, students are introduced to the first half of Newton's Modeling Cycle:

a) from motions (read: changes in velocity) infer forces
b) from forces deduce motions



We are moving from the realm of descriptive models (kinematical laws of motion) to that of causal models: dynamics.

> "The dynamical laws connect interactions with kinematics and so determine the particle motions. The subtle, almost superfluous, role of Newton's First law should be noted. A *free particle* is, of course, defined as one on which the net force is zero. This provides a criterion distinguishing inertial systems from other reference systems, and to say that free particles have constant velocities is to say that they define a uniform time scale. The definition of this time scale is an essential prerequisite to Newton's Second Law. The First Law has been previously classified as a kinematical law, but here it is classified as a dynamical law because it is an essential prerequisite to the Second Law and it involves the concept of force."[1]

It is essential that you get students to see that the constant velocity condition does not require an explanation; that *changes* in velocity require an interaction between an agent and an object. We quantify this interaction by the concept of force. After the dry ice and normal force demos, one can use worksheet 1 as an opportunity to deploy the force concept in a qualitative way. It is important to carefully treat how to go about drawing force diagrams in which one represents the object as a point particle. Drawing the dotted lines around the object helps students distinguish between the object and the agent(s).

Now is an appropriate time to teach addition of vectors that are no longer restricted to 1-D cases. It might be useful to have the students do worksheet 1 on graph paper for them to represent the force vectors accurately.

Some students may notice the connection between the magnitudes of the acceleration of an object undergoing free fall (end unit III) and the gravitational field strength. Postpone discussion of this connection until the next unit in which we will quantify the relationship between force, mass and acceleration.

At this point, depending on your equipment, either an experiment or demonstration on statics would serve as an ideal vehicle to the study of the decomposition of vectors into components using trigonometry. This could be an appropriate time to use a spreadsheet to perform the calculations to determine the sum of the **x** and **y** components of the forces acting on the object.

Newton's Third Law

"The great majority of [university] students can state Newton's Laws when they begin the course, but careful evaluation reveals that even at the end of the course they cannot consistently apply the laws correctly. Instead the students' reasoning is still guided primarily by their intuitive

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[1] D. Hestenes, "Modeling games in the Newtonian World". *Am. J. Phys.* **60** (8), Aug 1992

misconceptions. Researchers have identified and categorized many such misconceptions, but two of them are particularly important, because they are persistent common sense alternatives to Newton's Laws. Ignoring variations and nuances, these misconceptions can be formulated as intuitive principles.

I. The Impetus Principle: Force is an inherent or acquired property of objects that make them move.

II. The Dominance Principle: In an interaction between two objects, the larger or more active object exerts the greater force."[2]

Hestenes goes on to say that the reason most attempts to eliminate misconceptions are less than successful is that they tend to deal with them piecemeal, separate from the others.

> "That approach ignores one of the most fundamental characteristics of the force concept, the *coherence* of Newtonian theory. the significance of Newton's Third law cannot be understood apart from its relation to the other laws."[3]

Because we are waiting until Unit V to treat Newton's Second Law, arguments for this law should depend on evidence students can observe in the lab.

Instructional notes

Demo - Inertia

Apparatus

block of dry ice (1-2 lbs) with flat, smooth surface
long table or clean tile floor
gloves

Pre-demo discussion

The naive belief that forces are properties of objects and that forces are carried along with objects, perhaps wearing out over time or distance, is a persistent belief reminiscent of the pre-Newtonian teachings about impetus. The presence of impetus assures an on-going motion; its disappearance will result in an object coming to rest. It is an indirect goal of this activity to provide students an opportunity for arguing that a free particle, i.e. one subject to zero net force, will have a constant velocity. Also, students should conclude that any apparent change in velocity of an object indicates that a non-zero net force is acting upon it, provided that the observer is in an inertial frame of reference.

Performance notes

- You can purchase dry ice at many local supermarkets. Two-three pounds will last through the day if kept in a cooler. Get pieces that have a smooth surface and are at least 2" thick.
- With a cordless drill you can firmly attach a drywall screw into the block. Make the bottom surface as smooth as possible by rubbing it with fine sandpaper.
- If the table is level, the block should remain motionless, floating on a layer of sublimed CO_2. Given an impulse, the block will undergo uniform translational motion until someone catches it before it falls off the table. You and student helpers can play catch with the sliding block.

[2,3] D. Hestenes, "Modeling games in the Newtonian World", *Am J. Phys*, **60** (8) Aug 1992

- Make the point that when no force acts on the block in the horizontal direction, the block maintains constant velocity.
- Point out that an impulse applied perpendicular to the original trajectory does not result in the block making a right angle turn.
- Be sure to ask why they think the block continues to move once it leaves the hand. Some are likely to answer " due to the force of the hand."
- Attach a rubber band to the screw in the to of the block. Apply a constant force by keeping the rubber band stretched a constant amount. The block clearly accelerates.

The conclusions should be clear: in order to change the velocity (speed or direction), a force must be applied; in all of these cases, the force is a contact one. If one applies a steady force to the block, then the change in velocity (acceleration) is steady.

Worksheet 1

Lab - Gravitational force law

Apparatus

Spring scale or force sensor and interface (Lab-Pro, ULI, Data Studio)
mass hanger and lab masses sufficient to allow 6 data pairs within range of scale (probe).

Pre-lab discussion

The purpose of this experiment is to create a force law to describe the effect of gravitation on matter.

- Hold an abject above the table and let it go. Ask students what force(s) act on the object. Most, no doubt, will answer, "Gravity." It's worthwhile to spend some time defining gravity as a long range force exerted by one body (in this case, the Earth) on another. Ask students to identify the characteristics of some object that affect the force of gravity on it.
- While the mass of the object is the only significant characteristic, many others will be mentioned. Among other nominations may be air pressure, the height of an object above the floor, the object s weight, etc.
- Ask what variables might be measured. Foster a consensus that the force of gravity and the mass are the significant variables and that they may be measured. Don't rush through this, however, as there's evidence that many students have a poorly formed concept of gravity. (See *Heavy Boots*)
- This is the first encounter with measuring forces. We simply grant that spring scales or force probes measure what we mean by force and that the unit we use for measurement is the newton (N).

Performance notes

- Students will measure the force of gravity on various objects using spring scales. The masses of the objects can be measured by balances. It may be interesting to have a mislabeled mass, i.e. one that has a real mass different from the value stamped onto it.
- An alternative is to suspend a cup from the spring scale and to fill the cup with varying amounts of sand, determining its mass using a balance and the force of gravity using the spring scale.
- Groups will generate graphs of $\mathbf{F_g}$ vs $\mathbf{m}$.

Post-lab discussion

- The equation of the regression line should be $\mathbf{F_g} = (9.8\ \text{N/kg})\ \mathbf{m}$
- Students can interpret the slope of the $\mathbf{F_g}$ vs $\mathbf{m}$ graph. We will call the slope $\mathbf{g}$, the gravitational field strength. Students will doubtless see a connection between the acceleration of an object in free fall

and **g**, but until the 2nd law is developed, it is better to stick with gravitational field strength, with units of N/kg, than to call it the acceleration due to gravity, with units of m/s^2. Here we introduce the field concept that underlies electrical and magnetic fields, too. At this point, one should introduce "weight" as the common name for the force of gravity.

Reading - Force diagrams

Demo - Normal force

Apparatus

standard lab mass (500 - 1000 g)
compressible spring (alt: spring scale)
foam pad
thin wooden slats and two bricks or blocks
laser
mirror or device for amplifying minute variations

Pre-demo discussion

This bridging demonstration helps students to recognize that the agent in an interaction can be inanimate. Their naive conception is that a mass resting on a table doesn't fall to the floor simply because "the table gets in the way."[1]

Place a book or some other object on a table or desk. Ask students why it is at rest. Represent the book as a particle on the board and ask students to draw the forces acting on the book. Ask them to compare the magnitudes of the forces that they draw. Some will respond that the air holds the book down in addition to gravity. Others will assert that the table exerts a force, too.

Performance notes

Start by holding the object motionless in your hand. Since its velocity is constant (zero), there must be some force to oppose the long-range force of gravity. Students easily recognize that you are the agent.

- Place the object on the compressible spring. Once it reaches an equilibrium position, students will state that the spring is providing the upward force that cancels the force of gravity. One could also hang the object from a spring scale.
- Place the object on the foam pad; it should sink somewhat. Students readily agree that the pad exerts an upward force on the block.
- Place the thin slats across the bricks or blocks. When you set the block on the middle of the slats, they bend somewhat. In each of the three cases, students are prepared to accept that the inanimate object exerts an upward force because the supporting object is deformed.
- If you have access to a section of bedsprings, compare the atoms in the surface of the table to the network of interconnected springs. PASCO now sells a atomic model of matter kit in which you can connect little balls with springs to form a network solid.
- Assert that when you press on a table, it presses back because it, like the other objects, also experiences a deformation. Students are not likely to accept this claim. The problem is that the amount of deformation is so small, that the unaided eye is not able to perceive it. A device to amplify the deformation is needed.

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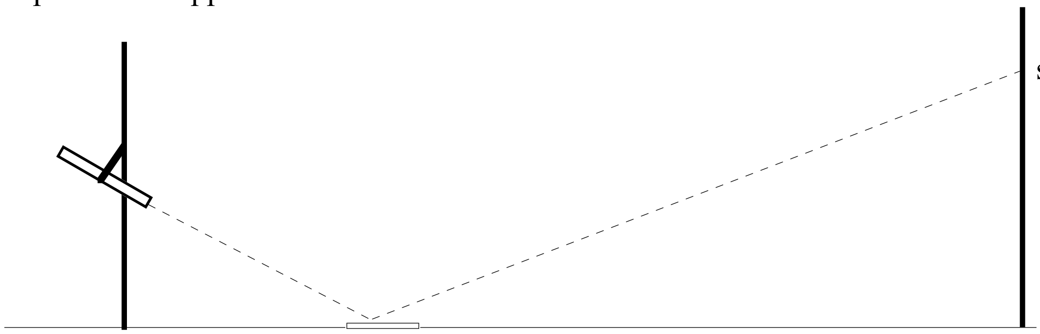
[1] A thorough discussion can be found in Camp and Clement's book Preconceptions in Mechanics, Kendall-Hunt Publishing, 1994.

Set up the laser apparatus.



You can demonstrate the deformation by pushing on the table; the spot of light on the wall will move up or down as you vary the amount of force you apply to the table.

An even more sensitive apparatus can be built as follows:
Use a Radio Shack Audio Amplifier-Speaker, Cat No. 277-1008C or similar, a miniature phone jack, and a silicon solar cell. You can construct a solar cell holder by bending a piece of aluminum in the center to a sharper than right angle (between 80 and 85ß), then drill and tap about 3/4 inch from on end, a hole for a 1/4-20 screw. Turn the screw through the hole a few times with the head on the inside of the L. Attach the miniature phone jack to the solar cell. Place the solar cell against the undrilled surface of the aluminum and put a microscope slide over it. Wrap the whole thing with rubber bands. Plug the jack into the Audio Amplifier-Speaker.

Operation: Place a laser on one desk and the other components on another. Aim the laser at the solar cell and adjust the solar cell holder to reflect the beam back into the laser cavity. The unique sound will be quite apparent when the alignment is correct. When you touch either desk lightly, the modulation of the sound indicates the motion.

Worksheet 2

Worksheet 3

Quiz 1

Activity - Newton's 3rd Law

Apparatus

Low-tech	**high-tech**
spring scales (newtons)	pair of force sensors
platform or bathroom scales	Lab interface (Lab-Pro, ULI, Science Workshop)

Performance notes

The purpose of this activity is to develop a force law for two objects interacting with each other.

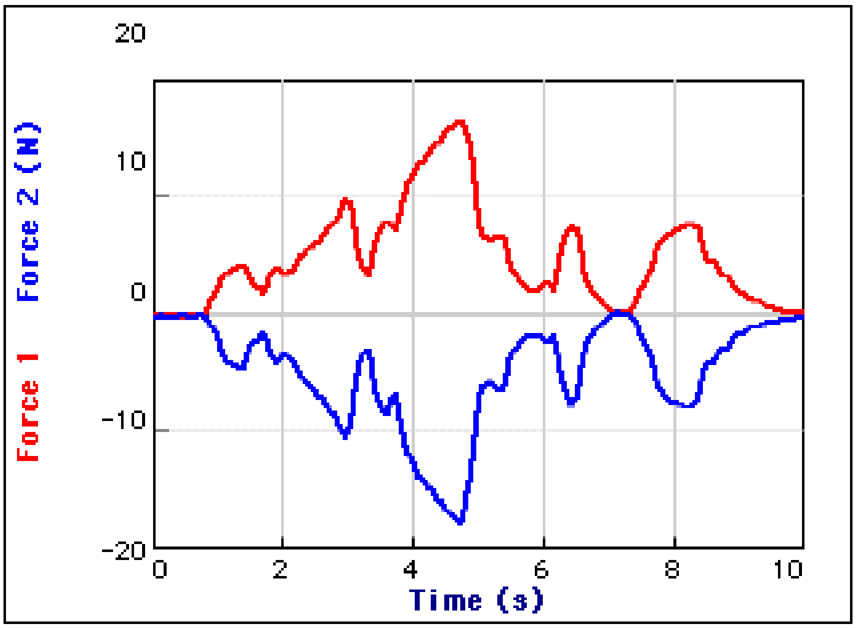
¥ Student groups should be supplied with two Newton scales and some string as well as two platform scales which can be pushed against one another.

¥ Instruct students to hook their scales together. Have both students pull on their scales and record the force on each scale.

¥ Next, have one student pull, while the other holds firm. Then they should reverse the roles, each time comparing the force that one person exerts to the force that the second person exerts.

¥ Next, have a pair of students hold bathroom scales against one another. They should compare the scale readings when both push, then when first one, then the other pushes.

If the force sensors are available, you can show that, regardless of which person pulls, the forces measured by the probes are equal and opposite.



Worksheet 4

Test