# LCP 1: From Intuitive Physics to Star Trek

*I would almost contend that if something fits in with common sense it almost certainly isn't science. The reason is that the way in which the universe works is not the way in which common sense works: the two are not congruent.* (Lewis Wolpert, taken from his book *The Unnatural Nature of Science*).

**IL 1** (A review of Wolpert's book)

*Research into intuitive physics demonstrates that a large percentage of the population holds strikingly erroneous views about basic physical principles that govern the motions of objects in the world; a world in which they act and behave quite successfully. Think about the statement "heavier things fall faster". It is false, but without more thought would appear true.* (C.R. Riener)

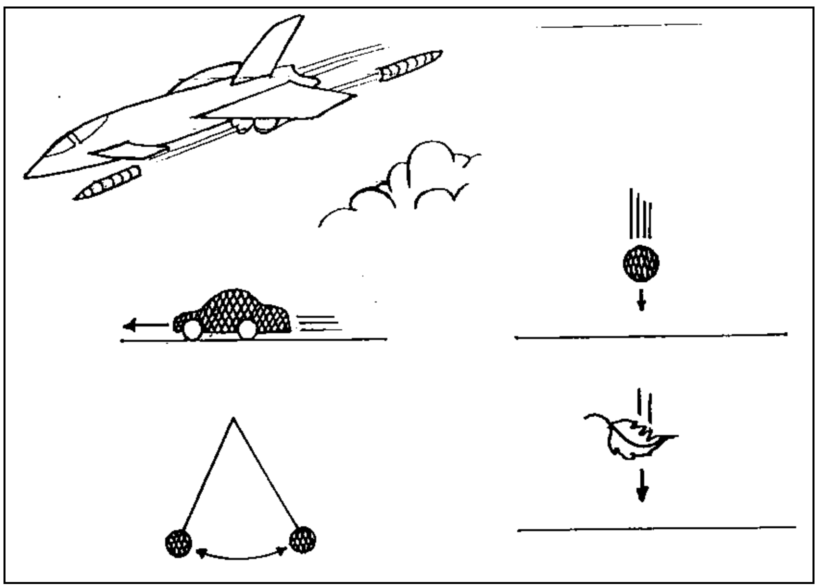


**Fig. 1: Examples of Motion I**

**IL 2** (Quotation source for Riener)

*One of the reasons that students are thought to find physics so difficult is that much of the subject is somewhat counterintuitive* (Keith Taber).
(See: The article Keith S Taber 2004 *Phys. Educ.* **39** 123-124)

**IL 3** *** Article in *Physics Education*: "**Students' conceptions of ideas in mechanics**", Roger J Osborne *et al* 1980 *Phys. Educ.* **15** 376-379. This is not a free site. Link must be copied into browser. (A technique for exploring students' views of the world)

Article in *Physics Teacher*, **"Children's Dynamics"**, v22 n8 p504-08 Nov 1984. (Discusses children's conceptions of dynamics, comparing them to those of scientists and examining how they are acquired).

Article in *Physics Education,* **Intuitive physics: but whose intuition are we talking about?** Keith S Taber 2004 *Phys. Educ.* **39** 123-124. (Very comprehensive short review of Taber's discussion of *intuitive physics*)

Note: websites in this document are evaluated according to the scheme

- **=good, **=very good, ***=excellent **** = outstanding**

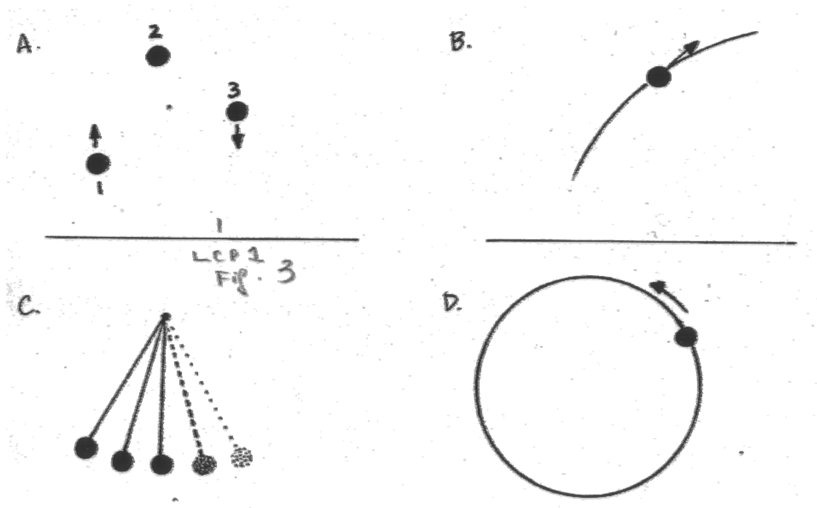



**Fig. 2: Examples of Motion II**

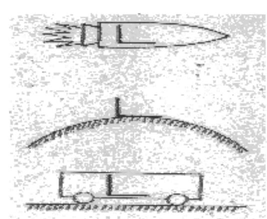


**Fig. 3: Frames of Reference**

## THE MAIN IDEA

Living in the modern world familiarizes us with motion in all its complexity. Research in science education clearly shows that all of us develop a personal set of ideas that seem to be coherent, or at least allows us to gain an informal grasp of general principles that are involved in motion. We might call this understanding "*intuitive physics*" or "common-sense physics" about motion.

Clearly, this "common-sense physics "serves to ensure survival because we can make reliable judgements and predictions about motion when we walk, play ball, ride a bicycle, drive a car, or fly in an airplane. Most of us also realize that forces and motion are somehow related. If Aristotle suddenly appeared in our world he would probably have difficulties crossing a busy city intersection.

For developing this large context problem (LCP) we will use the results of contemporary research in conceptual development and especially refer to the findings and ideas of the New Zealand physics educator Roger Osborne (See **IL 3** ). He argued that students see the world of motion by way of what he calls "clusters of mini-theories" that allows them to interact with their environment, to make a coherent sense of the world. He believed that children possess "gut dynamics", that are based on trial and error and direct experience rather than language, and are mostly unarticulated and unconscious. Examples of "gut dynamics" would include assertions such as, "heavy things fall faster", and "things must be pushed to keep them going", "if there is no air, there is no gravity", and "gravity increases with the height above the earth".

Older students possess "lay dynamics", that are based on the 'wealth of visual and verbal information received-from such sources and science fiction movies like "Star Wars" and "Star Trek" involving ideas about time, force fields, and time warps. Examples of "lay dynamics" would include "astronauts are weightless in the space shuttle", "space travel requires powerful engines at all times" and "the force field kept him out".

Finally, we have what Roger Osborne called "physicists' dynamics", that we teach to students in elementary physics classes. To most students this is seen as a strange world of frictionless slopes and pulleys, uniform gravitational fields, point masses, and massless strings of uniform tension. In other words, school physics is perceived as some fantasy world invented by such scientists as Galileo, Newton and Einstein, that is *set apart from the real world of experience.*

Osborne warns physics teachers that just because students are able to do well in the idealized world of the classroom and laboratory, they may still operate outside the classroom with their gut and lay dynamics. He says:

*…To retreat into a world of applied mathematics of recall and substitution problems involving algebraic and numerical manipulations, provides a haven for pupils, teachers, and examiners in an otherwise frightening world misunderstandings and misinterpretations.*

His ironing conclusion is that:

*Gut dynamics enables one to play ice hockey, lay dynamics enables one to talk about Star Wars, and physicists' dynamics enables one to do physics assignments. There is no problem!*

Note: These comments are all taken from his excellent article in *Physics Teacher*, "Children's Dynamics", V. 22, p504-08 Nov. 1984.

There is strong evidence for believing that science (physics) that is learned in a contextual setting that attracts the attention of the student will considerably lessen the separation between "science in the classroom" and "science in the outside world".

The "large context problem" (LCP) approach was originally developed as a response to the discovery that

> *…. learning could be well motivated by a context with one unifying central idea capable of capturing the imagination of the students.*

It is not easy, however, to move from textbook-centered teaching to teaching that is based on a contextual approach. To escape the teaching of science from a textbook-centered approach to a context-centered one is difficult. The American science /technology educator, John Souders, elaborates on this difficulty this way:

> *It takes a lot of work to move from a traditional teaching style to a contextual learning style. To move from traditional to contextual learning, teachers need new equipment, new strategies, new expectations, new skills and new roles. Teachers have to learn how to ask different questions. With contextual learning a teacher's role is to guide, discuss, create an environment, question, listen and clarify. A student's role is to explore, investigate, validate, discuss, represent and conduct. And both teachers and students have to learn together.* John Souders Jr, (1999) taken from his website:

IL 4 ***

a The booklet that accompanies the LCP describes the background theory and rationale for contextual presentation and is prepared for instructors and teachers.

This is the first of 10 large context problems that sets the stage for 10 contextual presentations (see content description on author's website). These are:

LCP 1: INTUITIVE PHYSICS AND MOTION

LCP 2: MOTION AND THE PENDULUM

LCP 3: GALILEO, NEWTON, AND ROBOTICS

LCP 4: MACROROBOTS FOR ENERGY PRODUCTION

LCP 5: THE ULTIMATE MACROROBOT: A ROTATING SPACE STATION

LCP 6: PHYSICS ON THE MOON

LCP 7: JOURNEY TO MARS: THE PHYSICS OF TRAVELLING TO THE RED PLANET

LCP 8: THE AGE OF THE EARTH AND THE SUN

LCP 9: ASTEROID/EARTH COLLISIONS

LCP 10: THE PHYSICS OF STAR TREK

LCP1 begins with the intuitive understanding of motion, then continues to discuss motion in qualitative terms first, before appealing to Galileo's kinematics and Newton's dynamics in quantitative terms. We will continue discussing these laws in LCP 2 by following the history of the concepts about forces and motion, using the pendulum as the central idea. In LCP 2 we will recapitulate (re-discover) the intuitive physics discussed in LCP 1. *However, these ideas will be* *discussed in a richer context and on a more sophisticated level*. Rich concepts, such as those found in Newton's dynamics, must be mastered and ultimately understood in a deep sense, and not just superficially memorized. If these important concepts and ideas are later presented in the same way as it was done the first time, learning becomes boring and many of the ideas and concepts will become inert. Roger Osborne believed that if concepts, such as the Newtonian idea of force, are taught too early, students will simply memorize the definition and the mathematical representation, but continue to see motion and force using their gut or lay dynamics outside the school. If, however, the concept is taught too late, he believed that students' gut and lay dynamics will have become 'ossified' to the extent that they will not be able to think about motion in terms of 'physicist dynamics'.

In an effort to move toward a 'physicist understanding' of force and motion we will present major ideas and concepts by way of moving from *qualitative* to *verbal* to *quantitative* presentation. The basic ideas of kinematics (the study of motion, without considering the forces involved), and dynamics, (the study of motion and the forces involved). LCP1 ends with a brief foreshadowing of the "Physics of Star Trek", which will be topic of the LCP, the last large context problem presented.

## DESCRIPTION OF THE CONTEXT

The context for this LCP is simply the motion we observe in the world around us. This LCP can be seen as the necessary one to begin the study of motion.

One might argue that we should have a much better understanding of the nature of motion than Aristotle had, because we are involved daily with the products of modern technology. These products make us conscious of many different kinds of motion and provide us with high-acceleration and high-velocity travelling. We ride on bicycles, in cars, in elevators, trains, subways, and fly in planes. The stout-hearted among us even thrill to the motion experienced in looping-the-loop and in riding giant roller-coasters in amusement parks.

Out of this bewildering ensemble of movements physicists, beginning with Galileo, modern physicists chose to study two specific examples of controlled motion, namely the motion of a metallic sphere along an inclined plane and the oscillation of a pendulum. This idealization of the complex world of motion allowed them to escape into an ideal world in which the mathematical treatment of moving bodies was possible. Man has walked on the moon, and satellites are being placed into orbit as a matter of course. Even interplanetary flights, such as Mars landings fail to evoke awe or disbelief.

## PRESENTATION OF THE CONTEXT

This will be a first attempt to understand motion around us.

Let us try to make sense of the motion around us, using our unaided eyes and intuitive ideas only. A good way to start would be to model our first attempt toward understanding motion after Galileo, the first scientist to successfully challenge Aristotle's ideas about motion. He was the first to understand and describe motion the way physicists do today.

Galileo began his study of motion this way, as recorded in his book, *The Two Sciences*:

> *This discussion is divided into three parts: the first part deals with motion which is steady and uniform; the second treats motion as we find it accelerated in nature; the third deals with the so-called violent motions and with projectiles.*

We will, however, add another category, ignored by Galileo, and place the various "motions" around us in *four* categories:

| |
|---|
| **I: Constant speed.** |
| **II: Constantly changing speed (uniform acceleration).** |
| **III: Complex motion, mathematically describable.** |
| **IV: Complex motion, mathematically not describable.** |

First, try to find clear examples for these categories. It will soon become obvious to you that it is not easy to find examples for category I; easier, but still difficult for category II; fairly easy for III; but you should have no trouble to find examples for category IV.

Motion for category I (constant speed) and category II (constantly changing speed) were solved by Galileo. He was able to describe mathematically the motion of free fall by having a metallic sphere roll down an inclined plane and then extrapolating to free fall. He also solved the more complicated projectile motion by combining the inclined plane with the study of the trajectory of a rolling ball leaving a table. Later, Newton and others were able to describe the motion of objects belonging to category III, such as the speed of a pendulum at a given moment. We will discuss the inclined plane experiment later, as well as the motion of a projectile.

**Activity**: Choose from the following examples of motion and place them in what you think is the proper category. Give reasons for choosing a particular category.

1. The falling of a leaf.
2. The flight of a bird.
3. The running of a deer.
3. The free fall of a heavy stone.
4. The motion of an artificial earth satellite.
5. The motion of a heavy stone freely falling through water.
6. The motion of a space ship in deep space *without* thrust.
7. The motion of molecules from a bottle of perfume when it is opened.
8. The motion of a simple pendulum.
9. The motion of a point on the rim of an industrial flywheel.
10. The motion of a roller coaster.
11. The motion of the Shuttle in orbit
12. The motion of a car
13. Suggest other examples and place them in their appropriate categories

You could use the following table to sum up your answers

| **Example** | **Category of motion** | **Comments** |
|---|---|---|
| The motion of a roller coaster<br><br>**Complete this table...** | Category II and III. Constant acceleration and complex motion, mathematically describable | The motion is along a track that is either straight (inclined plane) or an arc of a circle. |

This exercise should be done in groups of three or four, without the aid of any textbook or appeal to "formulas" that you may have memorized. You are encouraged to discuss verbally, and write down your answers in complete sentences. Rely on your own everyday experiences and your personal knowledge of how things move and what it is that makes them move. We will continue our study of motion by considering first motion without forces and then continue with a study of motion with forces.

It should be clear after a little reflection that motion around us is predominantly the motion described by categories III and IV. We will now discuss motion in categories I and II . In fact, it is difficult to think of clear examples of Category I motion.

**Examples of Motion: A Qualitative Study**

The following are questions about motion that test students' conceptual understanding of motion. These situations connect to kinematics as well as dynamics, that is, to the students' concepts about motion as well as the "cause" of motion.

These examples should be demonstrated where possible, discussed in small groups and then presented to the class. Students are encouraged to describe their personal experience, use sketches, analogies, and present arguments when defending their position. Some of these questions will be repeated later when quantitative answers for them will be required,

1. A ping pong ball and a ball bearing are dropped from the same height. Which one will reach the floor first?

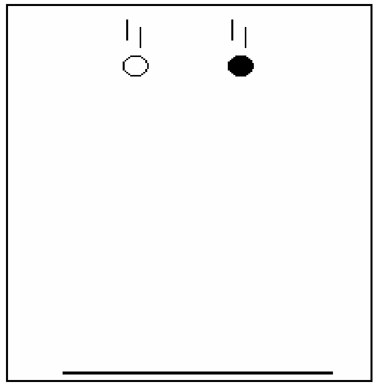


**Fig. 4: Ping Pong Ball and Ball Bearing Falling Towards the Floor. I**

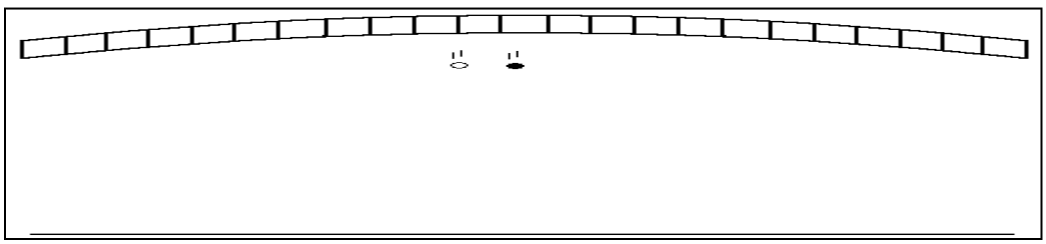


**Fig. 5: Ping Pong Ball and Ball Bearing Dropped From Bridge**

2. The same ping pong ball and ball bearing are dropped from a very high bridge. Which one will reach the water first?
3. A car is travelling on a level highway at a constant velocity. Study the figure below and decide which condition must be true. A is the "push force" provided by the engine, B the total frictional forces opposing the car's motion.

   a. A is smaller than B

   b. A is equal to B

   c. A is larger than B

   Defend your choice.

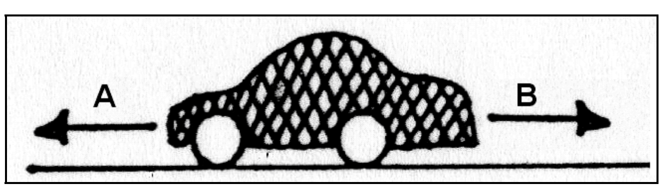



**Fig. 6: A Car Travelling On a Level Highway**

4. A ball leaves the hand of the thrower and after travelling a few meters vertically, returns to the hand of the thrower, at about the same position as before, when leaving the hand.
   a. Describe the motion of the ball, indicating how the speed changes.
   b. The ball is now thrown with twice the velocity.
      i. Compare the two heights the ball travels,
      ii. Compare the times the balls stay in the air
   c. Draw a simple diagram to show the magnitude of force and the direction of the force acting on the ball when it is
      i. just leaving your hand.
      ii is half way up,
      iii at the very top
      iv. half way down on the return trip
      v. just about to reconnect with the hand of the thrower
   d. Once the ball is released, what keeps the ball moving?

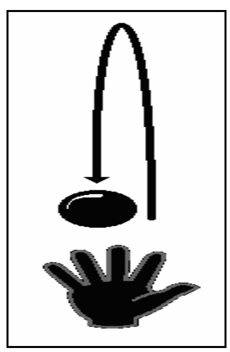


**Fig. 7: A Ball Being Thrown Vertically. I**

5. You are sitting in a car in which all windows are darkened so that you cannot see outside. Describe the motion of the car when:
   a. you feel yourself being pushed back into your seat.
   b. you feel yourself being pushed forward against your seatbelt. (Is there an unambiguous answer for a. and b.? Discuss briefly.)
   c. you are sitting freely without feeling a push or pull.
   d. you feel a force to your right, toward the door.

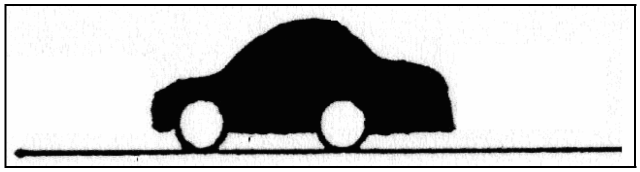


**Fig. 8: A Car with Darkened Windows**

6. You are standing in a subway that is travelling on a straight, level track with constant speed.
   a. You drop a ball. What do you observe?
   b. The train suddenly decelerates. What happens to your body?
   c. What would happen to the ball if it were dropped just at the moment the train started to decelerate, accelerate?
   d. As in case c above, if you jumped up, where would you land, relative to your original position?

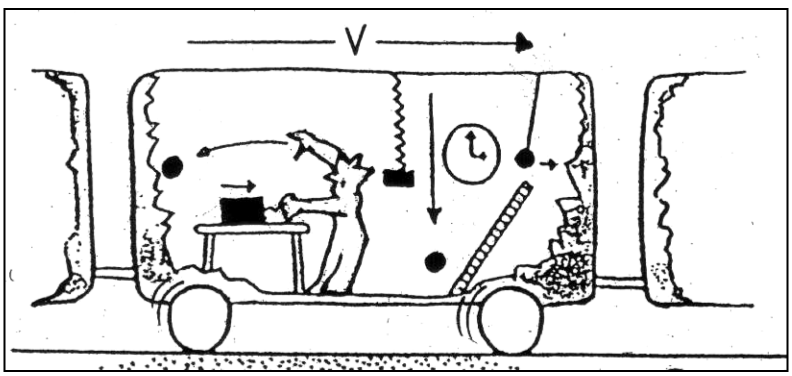



**Fig. 9: A Man Standing In a Subway Car**

7. You are walking at constant speed in a straight line (constant velocity) with a ball in your hand. There is a target (a small circle) on the floor that you want to hit with the ball. When should you release the ball?

8. Study the sketch below (Fig. 8), then draw and describe the motion of the ball when it leaves the cylinder.

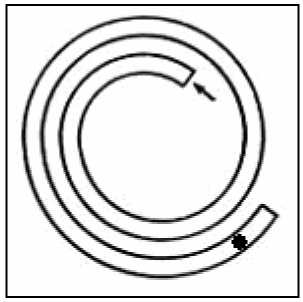


**Fig. 10: A Ball Rolling In a Curved Cylinder**

9. When you are driving in a curve, you feel a force, and when you try to keep a mass attached to a string moving in a circle you also feel a force. What is puzzling is that even when the rotational speed of the mass is constant there is a force. Discuss your pears and your instructor.

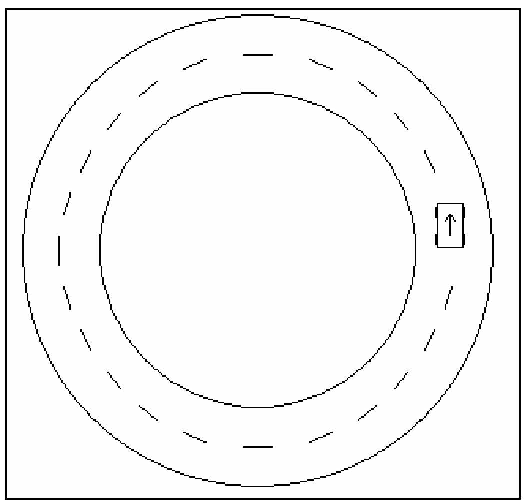


**Fig. 11: Driving In a Circle**

**IL 5** *** Intuition and how it applies to circular motion

10. Take two identical balls (tennis balls are fine) and drop one from a table. Observe the motion. Now take the other and take the other ball and give it a push along the table, so that it falls at least about two meters from the table.
    a. After several tries decide how the times of descent of the two balls compare.
    b. Now try to project the balls so that they leave the table top at the same time.
    c. What is your conclusion about the time of travel of the two balls?

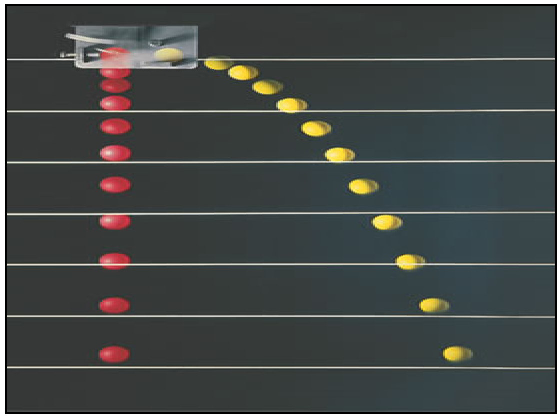


**Fig. 12: Ball Dropped and Rolled Off a Table Simultaneously**

IL 6 *** The physics of projectile motion. Fig. 1-11 from here.

11. A car is travelling on a curve on a wide highway. The driver suddenly encounters an ice section of the road where the friction is effectively zero. Study the sketch below and decide which way the car will move.

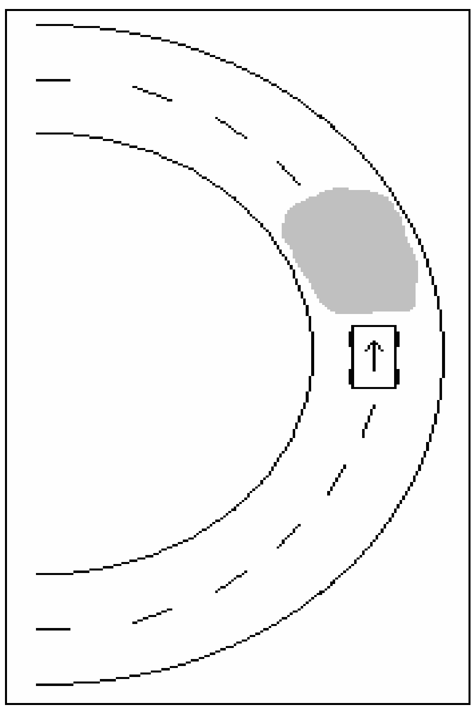


**Fig. 13: A Car Travelling On a Curved Highway Encounters an Icy Patch**

12. An earth satellite is moving at a constant speed in a circular orbit.
    a. Compare the gravity "out there" with the gravity on earth.
    b. Imagine that suddenly the earth's gravitational force is removed. Describe the motion of the satellite now.

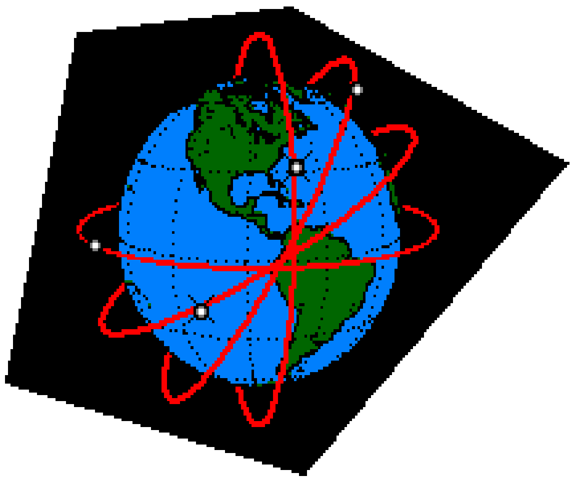


**Fig: 14: A Satellite Orbiting the Earth**

13. Two blocks, one twice the mass of the other, and made of identical material are pushed with the same initial velocity along a smooth wooden floor (See Fig. 1–13). Compare the distances they slide.

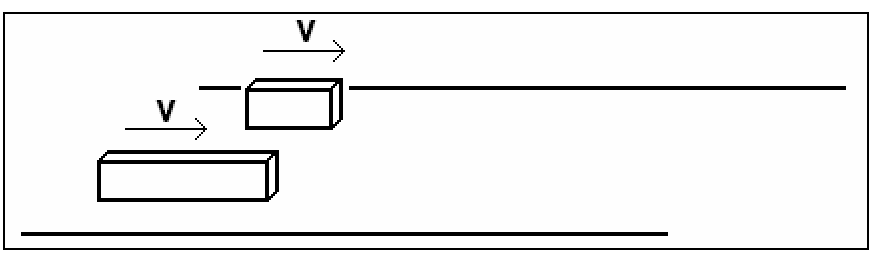



**Fig. 15: Two Blocks Moving On the Floor**

14. One of the blocks in problem 13 is released with twice the velocity. How far will it slide, in comparison to the original distance?

**Related links**

**IL 7** *** A very comprehensive definition of inertia

**IL 8** *** A very comprehensive description of the history of understanding of inertia and motion

**IL 9** ** Early development of Galileo's ideas about motion

**IL 10** ** A brief history of Galileo's ideas about free fall

### A Quantitative Description of Straight Line Motion: Kinematics I

The following are "idealized" motion examples that belong to Category I and Category II motion. Many of these are clearly textbook examples that students are asked to solve in their introductory physics courses. What differentiates these examples from those one finds in most textbooks is that here we will go beyond the application of formulas and algorithms to a qualitative to quantitative discussion that tests the conceptual understanding of the student.

In this section we will extend our discussion of motion and try to graphically and mathematically describe examples of simple motion of category one and category two, that is, constant speed and constant acceleration. We will not discuss here "the cause" of motion, or the forces that are involved. That comes later. The main concepts for this section are: distance and displacement, speed and velocity, average speed and average velocity, and acceleration. Before reading on, try to define these verbally, and then mathematically.

When studying motion, we should remember that physicists have chosen as the basic units for expressing motion in kinematics and dynamics as distance, time and mass.

What is surprising is that

a. for all problems in kinematics we only need distance and time as our basic units, and

b. for all problems in dynamics we only need distance, time and mass.

Remember, the basic units "stand by themselves", that is, they are supposed to be "intuitively" understood. They cannot be defined in terms of anything more basic. In this section we will discuss only kinematics (motion without considering forces).

The examples of motion that follow the discussion of the concepts of motion are typical ones one finds in textbooks, but we will try to relate most of them to everyday experiences of motion around you.

It is assumed that you are already familiar with these concepts from your studies and the textbook you are using. However, here is a quick review of these basic concepts of motion with suggestions of good Internet links.

The descriptions are presented progressively according to the follow scheme:

1. **A verbal definition,**
2. **A graphical representation,**
3. **A symbolic or/and mathematical representation,**
4. **A simple example to illustrate the concept, and finally**
5. **One or more selected Internet connections are given.**

For each of these concepts, one or more appropriate Internet links are suggested for you to access. These are important supplementary connections because they reinforce, and involve you in using interactive applets (IA).

**Distance**

1. Verbal statement: The numerical description of how far apart things lie.
2. Graphical representation: Distance from Rome to Trento. See Fig. 16.
3. Symbolic/mathematical representation: **d.** The SI unit of distance is the meter, **m.**
4. Town A is 85km west of town C. Town B is 70km west f town C. How far apart are towns A and B? (Answer: 15km)
5. The following are good websites:

IL 11 *** A very detailed definition of distance.

IL 12 *** A brief description of the history of the meter as the unit of distance measurement.


**Fig. 16: Distance from Rome to Trento**

**Speed**

1. Verbal statement: "The time rate of change of distance", or "distance traveled divided by the time of travel".
2. Graphical representation: Driving speed. See Fig 17.
3. Symbolic or mathematical representation: speed = distance travelled / elapsed time, or $v = d / t$ . Note, v stands for velocity but can also stand for speed. The units are km/h or m/s.
4. A car travels a distance of 1 km at a constant speed on a level highway for 2 minutes. What is the speed of the car? (Answer: 0.5km/min = 30km/hr).
5. The following are good websites:

IL 13 *** A very detailed definition of speed

IL 14 *** A very detailed definition of speed

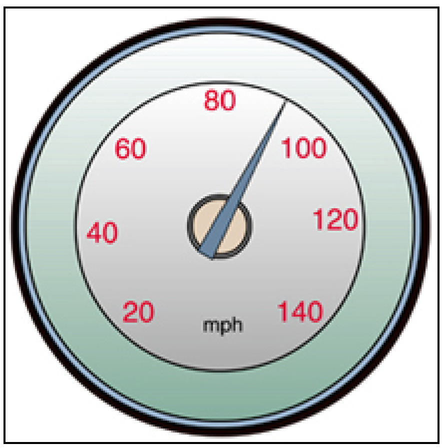



**Fig. 17: A Car's Speedometer**

**Velocity**

When studying motion we have to realize that when an object is moving the object has both a magnitude and a direction. When we are interested in the direction, the motion is thought of as a vector. So that when I throw an object into the air and want to find its range I must specify its magnitude and direction. For example: "The object left my hand with a speed of 10 m/s, in the direction of 30 degrees from the horizontal". Now I say that the velocity of the object at the moment it left my hand was 30 m/s, moving at an angle of 30 degrees to the horizontal. Velocity is a vector and speed is a scalar (not a vector). Below are good tutorials about vectors and scalars.

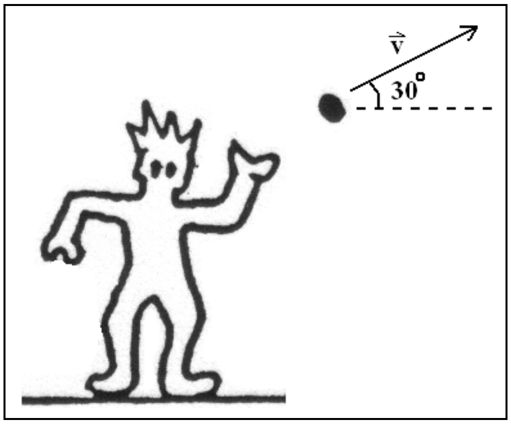



**Fig. 18: Velocity of a Ball**

IL 15 ** Vectors and scalars defines and compared

IL 16 ** Vectors and scalars defined

IL 17 *** Mathematical treatment of vectors

IL 18 ** Vectors in curved motion

**Average speed**

1. Verbal statement: "The total distance travelled over the total elapsed time". Or simply, as before, "distance travelled divided by time".
2. Graphical representation: Average speed. See Fig 19.
3. As before we write $v_{average}$ = distance travelled / elapsed time, or $v = d / t$.
4. A car travels a distance of 1 km in 2 minutes. What is the average speed of the car? (Answer: 0.5km/min = 30km/hr).
5. Websites:

IL 19 ** Definition of average speed. Compare to the concept of *instantaneous speed.*

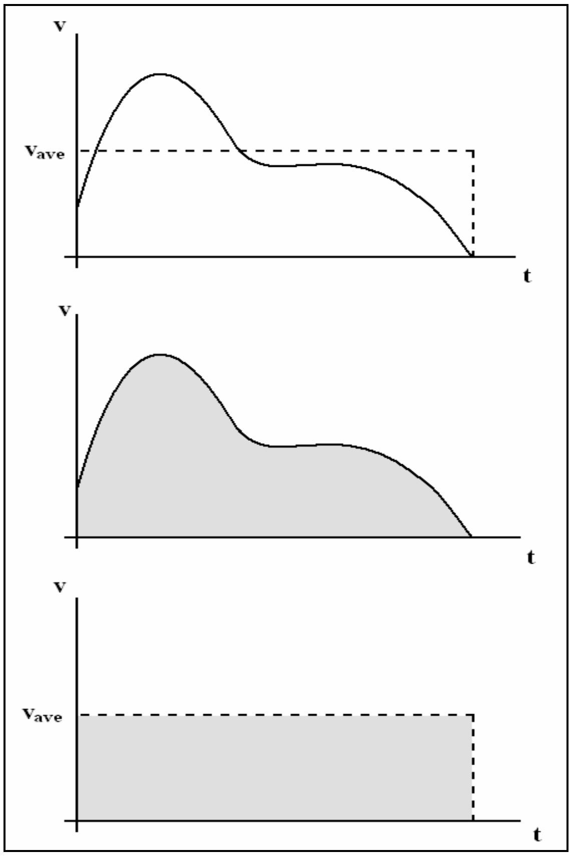



**Fig. 19: Average Speed – Shaded Regions Have Equal Area**

**Acceleration**

1. Verbal statement: "The rate of change of speed". Note uniformly accelerated motion is typified by the motion of free fall, neglecting air friction. For example, in free fall a heavy object falls with an acceleration of about 9.80 m / s each second, or 9.8 m/s$^2$.
2. Graphical representation: Acceleration. See Fig 20.
3. Symbolic / mathematical statement: $a = v/t$ . The units for acceleration are meters/second/second, or m / s$^2$.
4. A car accelerates uniformly from rest to 10 m/s in 3.0 seconds. What is the acceleration of the car? (Answer. $a = v/t = 10 / 3.0 = 3.3$ m / s$^2$)
5. Websites:

IL 20 *** Very detailed definition of acceleration

IL 21 *** Complete description of acceleration. Animation included

IL 22 *** A good site for all the terms discussed above

IL 23 *** Several IAs for motion study including acceleration

**IL 24** *** IA for studying motion on distance vs time graph

**IL 25** *** IA for projectile motion in 2D

**IL 26** ** Several kinematic IA and other IAs

**IL 27** *** Numerous kinematics applets and other applets

**IL 28** *** An excellent source of physics IA including accelerated motion

**IL 29** *** Accelerated motion IA with at, vt and dt graph descriptions

**IL 30** *** Kinematics tutorials

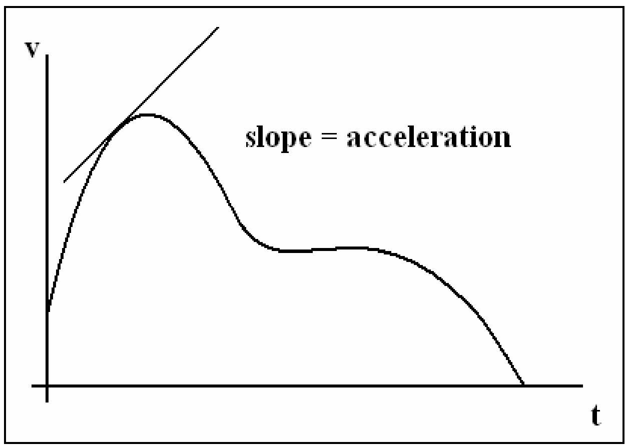



**Fig. 20: Acceleration – Slope of Velocity vs. Time Graph**

Formulas and Graphical Representation for Kinematics You Need

The formulas you need for solving problems involving constant speed and uniformly accelerated motion in kinematics are:

1. $\mathbf{d = v_{average} \cdot time}$
2. $\mathbf{v_{average} = d / t}$
3. $\mathbf{a = v / t}$
4. $\mathbf{d = \frac{1}{2} a t^2}$
5. $\mathbf{v^2 = 2a\, d}$

Where **d** is in meters**, t** in seconds, **v** in m/s, a in $m/s^2$.

Note: Formulas 4 and 5 apply only to uniformly accelerated motion that starts from rest.

**Derivation for the Formulas Above**

The following are derivations for these elementary formulas for uniformly accelerated motion from rest. For more detail, you should visit the suggested ILs below.

Study the graph below. The graph shows the motion of an object accelerating uniformly from rest (free-fall). For each problem in elementary kinematics you should sketch the motion investigated.

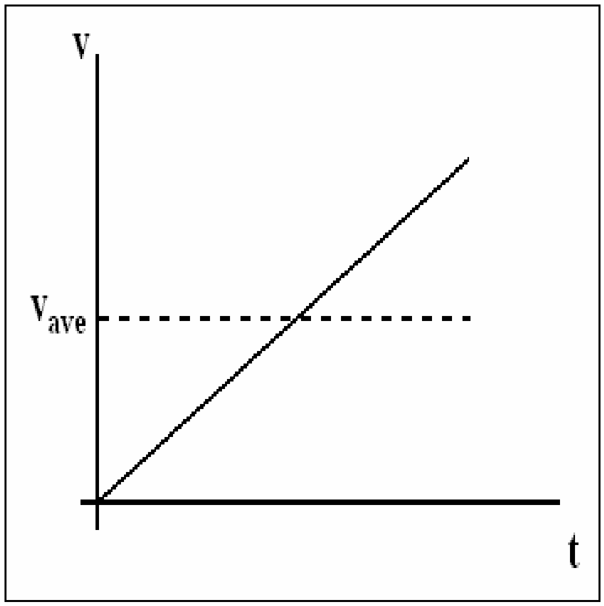



**Fig. 21: Average Velocity for Uniform Acceleration**

The average velocity of the motion of a free falling heavy from rest is simply **d/t .** That is so, because the area under the horizontal line depicting average velocity is the same as the area under the actual v-t graph.

We can generalize from this to any complex motion, including motion of categories III and IV. See Fig. 16. Therefore, it is true generally that the area (under the graph) divided by the total time is equal to the area under the horizontal line depicting the average velocity. It also follows that distance is always equal to the average velocity multiplied by the total time. Show that the area for this graph is $\frac{1}{2}\,a\,t^2$ . Therefore the $d = \frac{1}{2}\,a\,t^2$ .

The following are excellent tutorials for learning the kinematics of uniformly accelerated motion, using formulas and graphical representation:

**IL 31** *** Highly recommended discussion of simple motion

**IL 32** *** An excellent IA to show the relationship between the three graphs, d-t, v-t, and a-t

**IL 33** *** Distance vs time applets (visuals and graphs) for different accelerations

**IL 34** *** Graphical and algebraic treatment of the 5 basic kinematic equations

The following are websites for testing your understanding of kinematics:

**IL 35** *** Kinematic questions and answers

**IL 36** *** Kinematics questions and answers

**IL 37** *** 50 questions on kinematics

Problems for the Student

The following are problems that are based on our discussion.

1. A car is travelling from city A to city B, a distance of 150 km in 1 hour and 30 minutes.
   a. What was the average velocity?
   b. Now imagine that you are given the actual v-t graph of the car, shown in Fig. 19. How would you determine the average velocity? Discuss.

2. Show that:
   a. the slope of a point on the d-t graph is the velocity of the object at that moment (this is often referred to as "instantaneous velocity").
   b. the slope of a point on the v-t graph is the acceleration.

3. Show that:
   a. the area under the a-t graph is the velocity and the area under the v-t graph the distance travelled.

4. Test your understanding of the graphical approach in solving the following problem: The graph below shows the motion of a car between two stop sign, recorded on a v-t graph. Using the graphical approach described above, sketch the
   a. d –t graph
   b. the a –t graph.

   Now find;

   c. the average velocity of the car.
   d. the acceleration of the car in the beginning and the deceleration at the end.

5. Using the v-t graph of a freely falling heavy object below (Fig. 22) show that the object would fall 5m the first second, 15m during the next second, 25 m the third second, etc… Galileo showed that objects fall in consecutive time intervals as 1,3,5,7,… He then argued that this sequence proved that the distance objects fall is in proportion to the square of total elapsed time. Show that that this argument is correct.

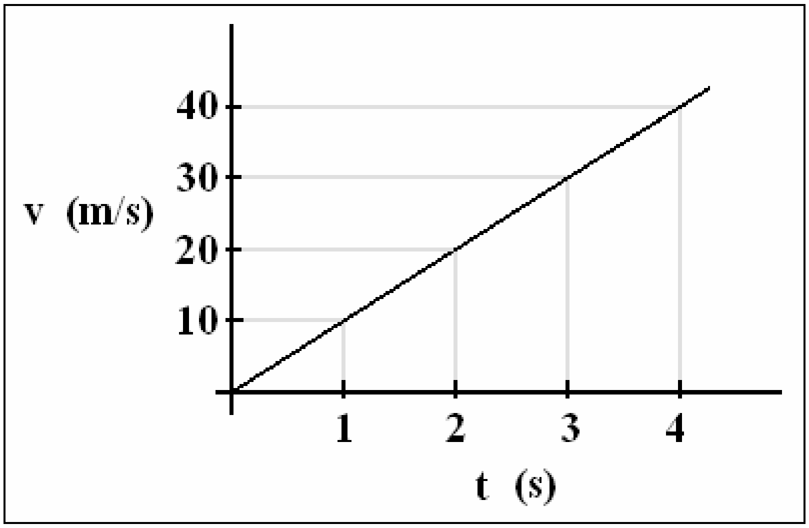



**Fig. 22: For Question 5, above (g = 10m/s$^2$ here)**

The following are typical problems of simple kinematics one would find in a textbook. The first problem is one in elementary kinematics and students use the relevant formulas the find numerical answers.

1. A ball is thrown up with an initial velocity of 20 m/s. Assuming the acceleration of gravity is 10 m/s$^2$, determine:
   a. when the ball reaches its maximum height
   b. the maximum height reached by the ball
   c. the time when the ball returns to the level of your hand.

We will now go further in testing the student's conceptual understanding and extend the problem to problems 2 and 3.

2. In the problem you have just solved numerically above:
   a. indicate in a diagram the velocity of the ball while it is rising, while at the top, and while it is falling.
   b. indicate on a diagram the acceleration of the ball while it is rising, while at the top and while it is falling
   c. Guess the force acting in each case (This is looking ahead to dynamics)

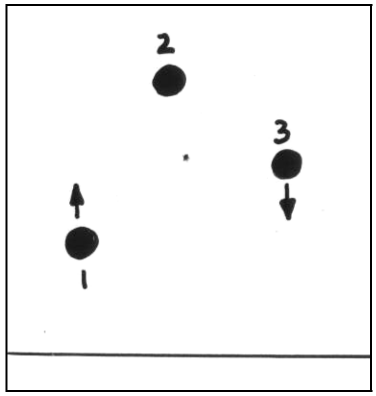



**Fig. 23: A Ball Thrown Vertically At Three Positions II**

3. In the problem above you have just solved numerically (again, looking ahead to dynamics)
   a. what keeps the ball moving?
   b. What is the force on the ball:
      i. when the ball is rising?
      ii. at the moment it reaches the top?
      iii. when it is falling back?

IL 38 *** An excellent IA for above problem

IL 39 *** IA for projectile motion in 2D

IL 40 *** A good IA on measuring free fall on Mars

IL 41 *** An excellent source of many IAs for kinematics, dynamics and more

IL 42 *** An excellent source of many IAs for kinematics and dynamics

IL 43 *** An advanced presentation of motion. Links to all physics topics

IL 44 * Advanced: Pictures of university elementary physics apparatus

IL 45 ** Advanced: A very comprehensive computer model to show the physics of free fall in vacuum as well as in a resisting medium

**A Quantitative Description of Motion in the Earth's Gravity: Projectile Motion: Kinematics II.**

Galileo was the first to clearly understand projectile motion (we will discuss Galileo's approach to studying projectile motion in LCP 2). Galileo showed that when you drop a heavy object (a ball) from a table at the same time another ball is projected horizontally from the table, the balls hit the level ground at the same time. We have already looked at that motion. See Fig. 24.

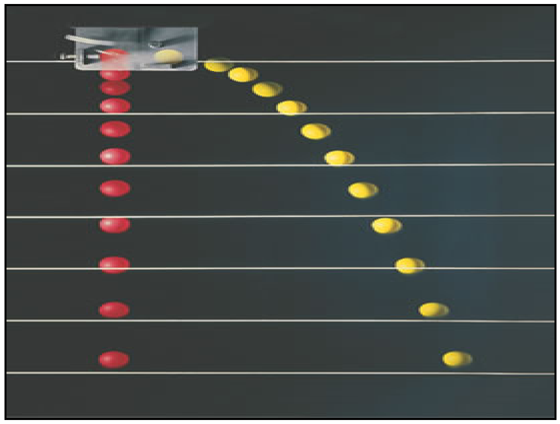


**Fig. 24: Ball Dropped and Rolled Off a Table Simultaneously I**

**IL 46** *** IA of the above motion

Use the applets below (ILs 47, 48, 49, 50, 51, and 52) to answer the following questions:

1. Study the motion of a projectile for various initial velocities and angles.
2. At what angle do you have maximum range?
3. Take an angle, say, 20 degrees and find out at what other angle you have the same range. But how do the times compare?
4. Using **IL 45**, study the motion of the projectile for angles between 0 and 90 degrees and verify the conclusions you reached when you studied the motion of the two balls above using a table.
5. In **IL 45** study the velocity vectors for various initial launching velocities and angles.

**IL 47** *** An excellent IA to study projectile motion, showing horizontal and vertical components of the velocity vector

**IL 48** *** IA for projectile motion in 2D

**IL 49** ** IA for projectile motion in 2D

**IL 50** *** IA for projectile motion in 2D

**IL 51** *** Shows how the range formula for a projectile is obtained

**IL 52** *** Shows how the range formula for a projectile is obtained

The mathematical analysis of trajectory motion is given below. You should look at the ILs above, and especially follow the arguments in IL 48 and IL 49 to ensure that you understand the argument that leads to the formulas.

Refer to Fig. 25 below.

We have seen that that a projectile in motion can be understood if we know that the vertical and the horizontal components of motion are independent of each other. That means that we can treat the horizontal and the vertical motion separately.

The horizontal motion: The horizontal component $V_x$ stays constant (why?) and can be expressed as:

$$\mathbf{V_x = V \cos \phi},\ \text{where } \phi \text{ is the angle of elevation.}$$

and the vertical component $V_y$ is given by

$$\mathbf{V = V \sin \phi.}$$

The range R of the projectile in time t is given by

$$\mathbf{R = V_x\, t = V \cos \phi\ t}$$

To find t we calculate the time the projectile reaches the highest point and multiply this by 2 (why?). Since V = at = gt, or t = $V_y$ / g. Therefore:

$$\mathbf{R = V \cos \phi \ x\ V \sin \phi \ x\ 2 / g \quad = \quad V^2 \ x\ 2 \cos \phi \ x\ \sin \phi / g}$$

Since 2 cos $\phi$ x sin $\phi$ = sin 2 $\phi$ , we finally get

$$\mathbf{R = V^2 \sin 2 \phi / g}$$

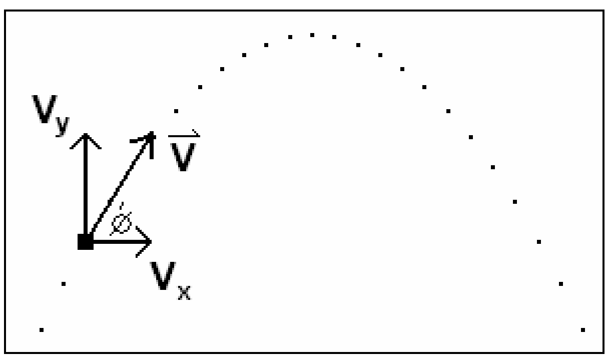



**Fig. 25: Trajectory Motion**

IL 53 ** A detailed derivation of the range formula

IL 54 ** Galileo's analysis of horizontally launched projectile motion

IL 55 *** An advanced mathematical treatment of projectile motion including graphical explanation

IL 56 ** An excellent interactive applet to study projectile motion

Questions and Problems for the Student

1. Using the formula for range, and one of the ILs, check the range for angles and velocities. Discuss with other students.
2. Show that according to the range formula:
   a. The maximum range is obtained when the angle of elevation is 45°.
   b. The range for any angle ǿ is the same as for a "complimentary angle" (90- ǿ).
   c. When ǿ = 90 degrees, the motion is equivalent to projecting the object vertically.

Student Activity: A *Discrepant Event* Involving Projectile Motion.

The following is an interesting demonstration to test your understanding of trajectory motion. Study Fig. 26 and set up a simple demonstration, using a large plastic bottle with holes punctured in it at heights as indicated.

Make sure that you look at the contact made by the water jet on horizontal surface! Predict the trajectory of the water for the three holes, assuming that the water level is kept constant. Give clear arguments for your prediction.

This is a good example of a discrepant event. An event is considered discrepant if the student finds himself/herself unable to explain the event using the concepts available to the student. The attempt to explain the phenomenon should lead to a "cognitive disequilibrium", or a feeling of intellectual discomfort.

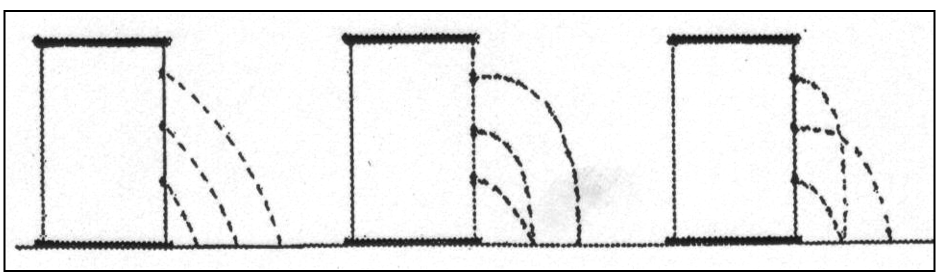


**Fig. 26: A Discrepant Event Regarding Trajectory Motion**

1. Decide which of the three predictions of the trajectories is correct. Why did you decide for the one you have chosen?
2. If the experiment were performed on the moon, where the gravity is 1/6 that on earth, would the trajectories be different? Discuss and give reasons for your answer.

A Challenging Problem

Show that trajectory motion must follow the path of a parabola. Take the simplest case; the motion of a ball rolling off a table of with a horizontal velocity of $V_x$, as shown in Fig. 24.

You can use a geometric method, based on the geometric definition of a parabola, and/or an algebraic approach based on an algebraic definition. See **IL 58** for assistance.

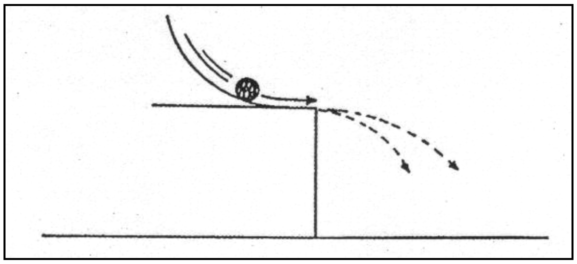


**Fig. 27: Trajectory Motion – A Parabolic Path**

**IL 57** ** * An applet of the parabolic motion of a horizontally projected object

**IL 58** *** A very comprehensive proof the parabolic motion of horizontally projected object

**IL 59** ** An advanced proof that projectile motion is parabolic

**A Quantitative Approach to Motion: Dynamics**

All students have intuitive understanding of motion and ideas or conceptions about what causes motion. For example, before studying physics, students generally believe that constant motion requires a constant force. They also generally believe the shuttle revolved around the Earth because there is no gravity "out there".

So far we have discussed motion without considering the forces involved that is the "cause" of motion. This part of physics is called *kinematics*. Galileo laid the foundation for kinematics and he often said that he will leave "the cause of motion" to others that will come after him. This part of physics is called *dynamics*. Galileo died in 1642 and Newton was born on Christmas day the same year.

See: www.Arthurstinner.com *** (Find the article in PDF: "The Story of Force, from Aristotle to Einstein" in the 'publications' section)

**IL 60** *** Test your understanding of motion and forces

**IL 61** *** The "cause" of motion: Newton's laws of motion

**IL 62** *** Many IAs to illustrate the laws of motion

**IL 63** *** An interactive lesson and a quiz, teaching the three law.

**IL 64** ** Tutorials for Newton's laws

**IL 65** *** An excellent discussion of the thee laws of motion

**IL 66** *** A clear, brief presentation of Newton's laws

## The Laws of Motion

We will see later in LCP 2 how Newton found the three laws of motion that allows us to understand what Galileo called the "cause" of motion. The laws of motion (Newton's three laws) are discussed below.

<u>Newton's Laws of Motion as Stated in the *Principia* (1687)</u>

### Newton's First Law

*Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.* (Note: The first law is often called "The Law of Inertia")

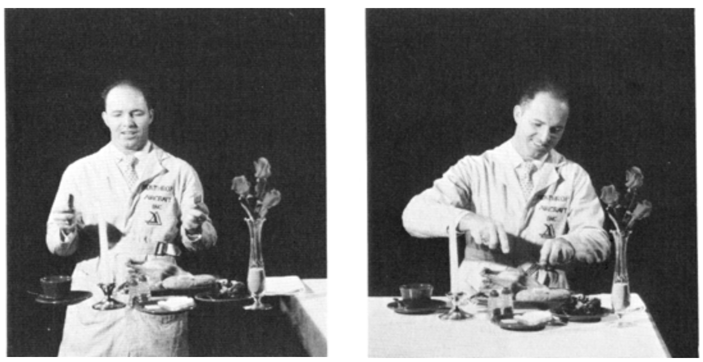


**Fig. 28: Newton's First Law**

### Newton's Second Law

*The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.*

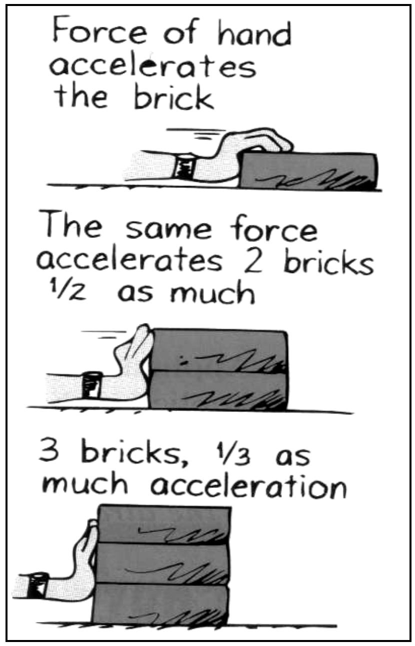



**Fig. 29: Newton's Second Law**

**Newton's Third Law**

*To every action there is always opposed an equal reaction: or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.*

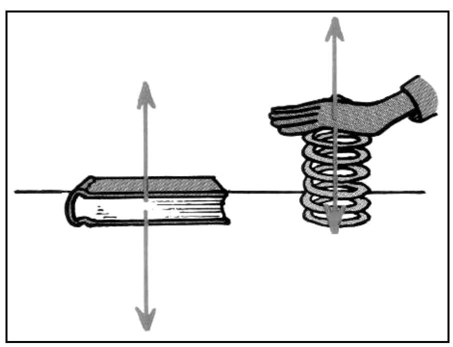


**Fig. 30: Newton's Third Law**

Here are contemporary statements taken from a textbook:

**The First law**

*An object will stay at rest or move at a constant speed in a straight line unless acted upon by an unbalanced force.*

**The Second law**

*The rate of change of the momentum of a body is directly proportional to the net force acting on it, and the direction of the change in momentum takes place in the direction of the net force.*

**The Third law**

*To every action (force applied) there is an equal but opposite reaction (equal force applied in the opposite direction).*

*Another way of stating Newton's third law, an interaction between two objects, is that, if object A exerts a force on object B, object B will exert the same magnitude force on A, but in the opposite direction.*

**Newton’s Fourth Law**

Newton’ primary objective when writing the *Principia* was to show that the elliptical motion of the planets was a result of an inverse force that was due to gravity. By using his laws of motion, the concept of centripetal force, and comparing his resultant equations with Kepler’s third law, he was able to show that:

*I deduced that the forces which keep the planets in their orbs must be reciprocally as the squares of their distances from the centers about which they revolve; and thereby compared the force requisite to keep the Moon in her orb with the force of gravity at the surface of the Earth; and found them answer pretty nearly*.

A typical textbook statement of this law is:

*Newton's Universal Law of Gravitation states that any two objects exert a gravitational force of attraction on each other. The direction of the force is along the line joining the objects. The magnitude of the force is proportional to the product of the gravitational masses of the objects, and inversely proportional to the square of the distance between them.*

<u>Questions for the Student</u>

a. Compare the original statements of Newton’s laws to those of a contemporary textbook. Discuss with your instructor and other students.
b. Give examples from everyday life to illustrate these laws

**Symbolic and Mathematical Representation of Newton’s Laws of Motion**

<u>The First Law of Motion</u>

If the net force (or unbalanced) force on an object of mass m is zero, then the acceleration of the object is zero. The object then is either at rest or is moving with a constant velocity in a straight line:

**If $F_{net}$ is zero then the acceleration is zero and the object continues to move in the same direction at the same speed (constant velocity).**

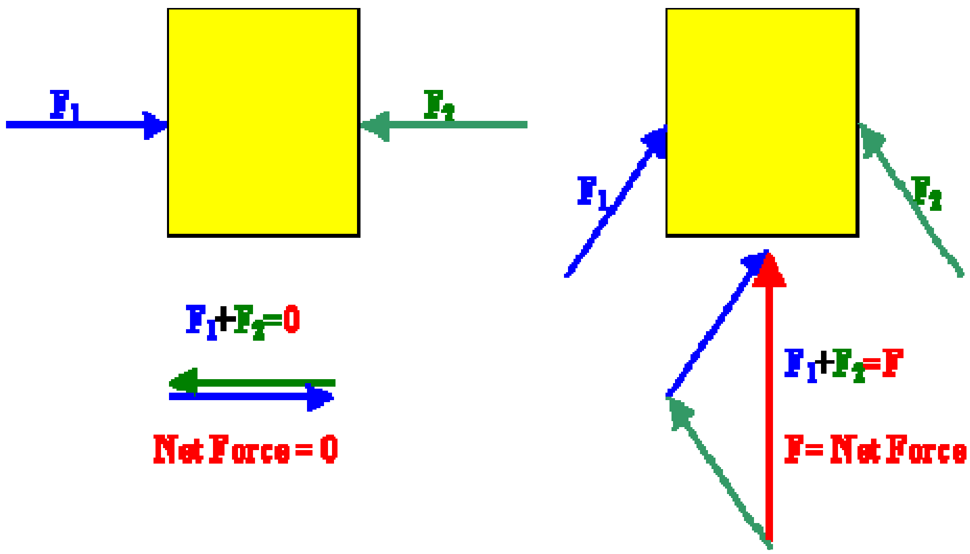



**Fig. 31: Illustrating Newton's First and Second Laws of Motion, Using Vectors**

The Second Law of Motion

**If the net force is not zero, then the object will accelerate, in the direction of the force, with an acceleration given by**

$$\mathbf{a = F_{net} / m}$$

Note that this is usually written as:

$$\mathbf{F_{net} = ma}$$

where the force is in Newtons, N. The mass in kilograms, kg, and the acceleration is given by $m / s^2$.

By definition, then, "an unbalanced force of 1 N accelerates a mass of 1 kg at 1 $m / s^2$"

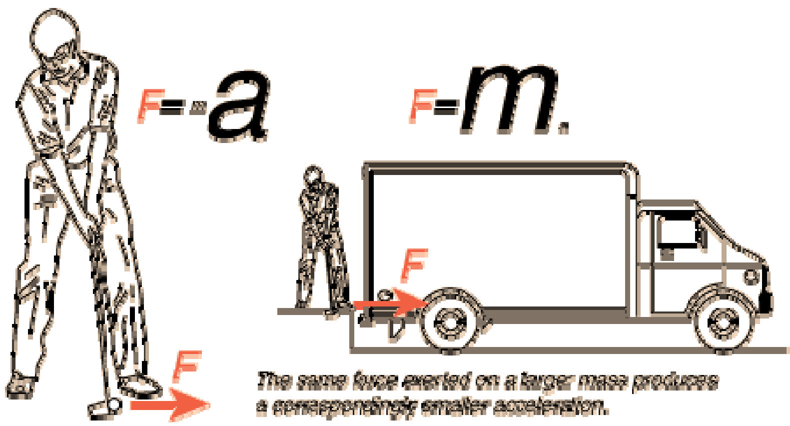



**Fig. 32: Newton's Second Law of Motion**

The Third Law of Motion

When two bodies, mass $m_1$ and mass $m_2$ interact (by contact or by other means, such as gravity, magnetic and electric fields) the force of one body on the other is equal in magnitude but opposite in direction. Mathematically,

$$\mathbf{F}_{1,2} = -\mathbf{F}_{2,1} = \mathbf{F}$$

Note: In LCP 2 we will see that the third law of motion can be expressed as "the conservation of linear momentum" when bodies interact.

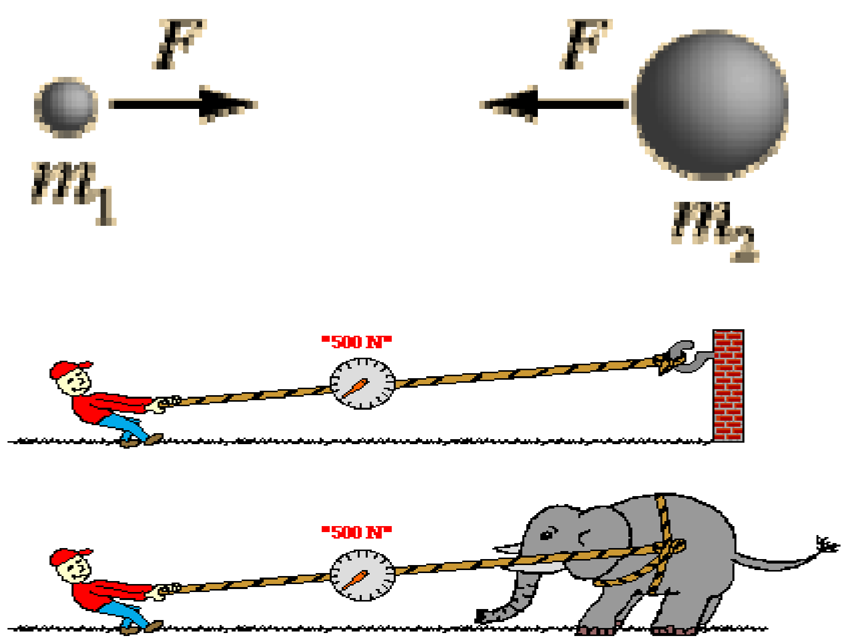



**Fig. 33: Illustrating Newton's Third Law in Three Different Ways**

The Fourth Law (Law of Gravity)

$$\mathbf{F_g \propto m_1\, m_2\, /R^2,\ \text{or}}$$

$$\mathbf{F_g = G\, m_1\, m_2\, /R^2}$$

Where G is the Universal Gravitational constant equal to 6.7 x $10^{-11}$ N $m^2$ /$kg^2$

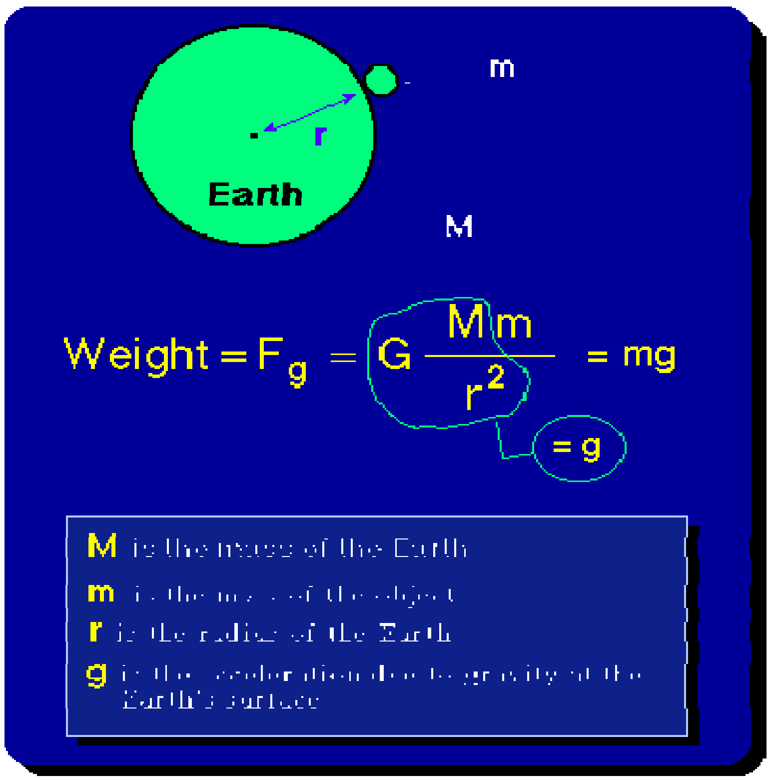



**Fig. 34: Newton's Law of Gravity**

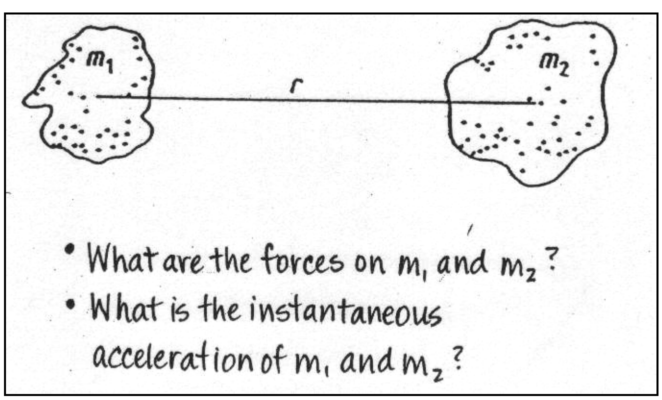



**Fig. 35: Newton's Law of Gravitation and the Third Law: Two Asteroids in Deep Space**

## Circular Motion: A Special Case

The British historian of science, John Roche, says:

*It may, indeed, seem counter-intuitive that a body moving uniformly in a circle should somehow be accelerating toward the center. Richard Westfall, pre-eminent historian of Newtonian physics, describes this insight as 'the supreme act of imagination in the construction of modern physics'.*

We will discuss the topic of centripetal force in more detail in LCP 2. For now it will be enough to say that everyone has experience that when an object is attached to a string

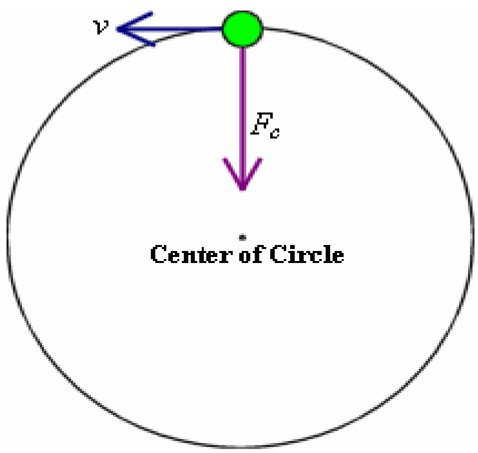



**Fig. 36: An Object Moving In A Circle with Velocity, *v***

(The object could be a mass attached to a string, or a car moving on a curve, with enough friction to keep it on the curve).

In Fig. 36 above we can imagine a car moving with a velocity v on a curve. The car is moving securely in a curve because the frictional force between the tires and the road is large enough to keep the car on the curve. Everyone has experienced this force. Which direction does this force point to? What happens if the string breaks or the car encounters a sudden icy patch?

In LCP 2 we will discuss this force in more detail. For now it is enough to say that the force depends (clearly) on the radius and the velocity of the object or the car.

Whenever an object moves in a circle with a velocity v, the force required to keep it moving in the circle of radius R is given by ;

$$\mathbf{F_c = m\,v^2 / R}$$

See **IL 69** for a derivation of this law.

Since Newton's second law is **F = ma,** we see that acceleration here can be written as $a_c = \mathbf{v^2 / R}$, **where** $a_c$ is called *centripetal* acceleration.

This is a very counter-intuitive notion. How can a constant speed produce an acceleration?

It seems that when velocity changes, that is, when speed remains constant and the direction changes, a force is necessary to maintain the speed.

So we can say that the force is necessary the keep an object moving in a circle (this force is called a *centripetal* (center-seeking) force directly proportional the square of the velocity and inversely proportional to the radius.

The following simple problem will illustrate this relationship:

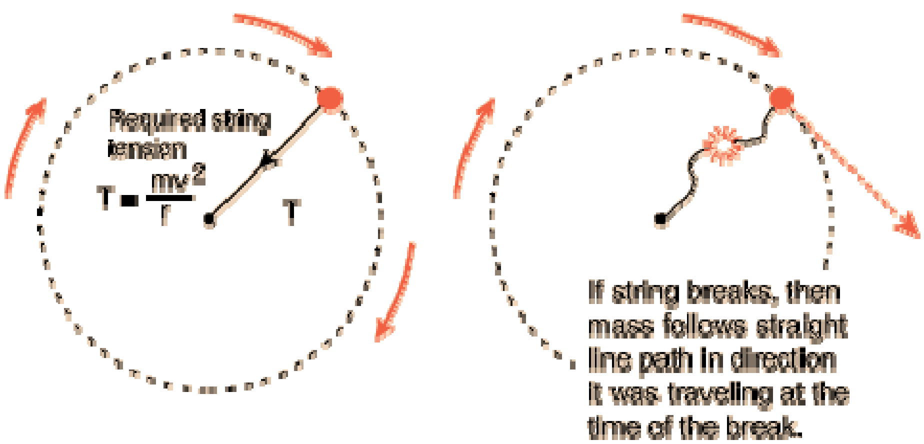



**Fig. 37: "Centripetal" and "Centrifugal" Forces in Action**

A car is moving around a curve on a highway at 100 km/h. The radius of the curve is 200m .

a. What is the centripetal acceleration of the car?

b. Calculate the force on your body in terms of your weight.

c. Which way does the force seem to act?

If you held a very heavy object (like steel ball) in your hand reaching out on the passenger side, describe the trajectory of the object, as seen by an observer standing on the ground, close to the curve.

The force that you "feel" is often called the "centrifugal" (or center-fleeing) force.

How would you explain to a friend, who has not taken physics, the difference between *centripetal* and *centrifugal* force?

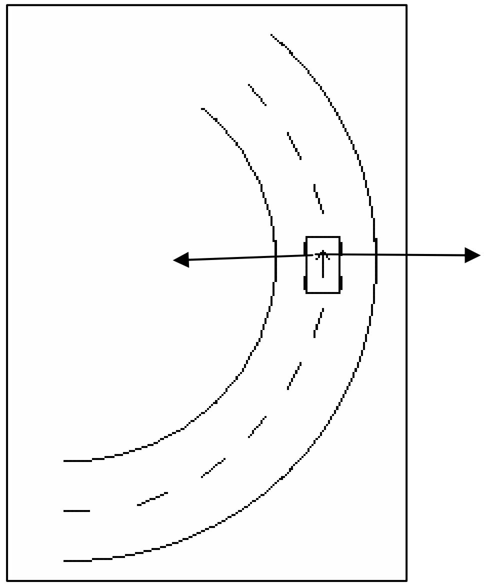


**Fig. 38: A Car Moving Around a Curve on a Highway II**

Using the ILs below, you can learn about circular motion and find out how the above formula is derived.

IL 67 **** An excellent IA to show the forces acting on a car in a curve.

IL 68 *** The forces on a car in a curve

IL 69 *** A derivation of the law of centripetal acceleration

IL 70 *** Detailed explanation of centripetal acceleration. Links to all other physics

IL 71 ** Description of centripetal and centrifugal forces and acceleration

IL 72 *** An IA showing displacement of a pendulum

IL 73 *** The loop-the–loop" problem. An advanced discussion

IL 74 *** An advanced discussion of centripetal force

IL 75 *** Newton's gravitational law in detail

**Problems Using the Laws of Motion**

We have already encountered problems 1,2 ,3 and 4. This time, however, use the laws of motion to back up your answers.

1. A car is travelling on a level highway at a constant velocity. Study Fig. and decide which condition must be true. A is the "push force" provided by the engine, B the total frictional forces opposing the car's motion, and
    a. A is smaller than B

b. A is equal to B

c. A is larger than B.

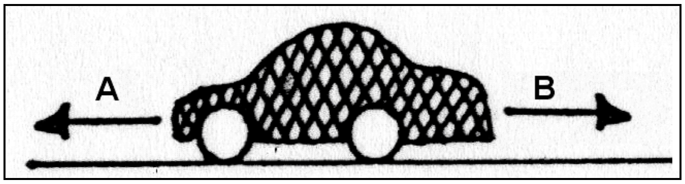



**Fig. 39: A Car Travelling On a Level Highway**

2. You are sitting in a car in which all windows are darkened so that you cannot see outside. Decide on the motion of the car when:

   a. You feel being pushed back into your seat,

   b. You feel being pushed forward against your seatbelt,

   c. You are sitting freely without feeling a push or pull.

   Is there an unambiguous answer for a. and b.? Discuss briefly.

3. Two blocks, one twice the mass of the other, and made of identical material are pushed with the same initial velocity along a smooth wooden floor. Compare the distances they slide. The mass of block 1 is 1 kg and that of the other block 2 kg.

4. The initial velocity is 1 m. The blocks in problem 3 are released with twice the velocity. How far will they slide, in comparison to the original distance?

5. A car is travelling at 20 m/s in a curve on a highway that has a radius of 100m.

   a. What keeps the car in circular motion?

   b. What force would a passenger in the car feel?

   c. What would happen if the car suddenly encountered a section of highway that has ice on it? Which direction would the car move on the ice?

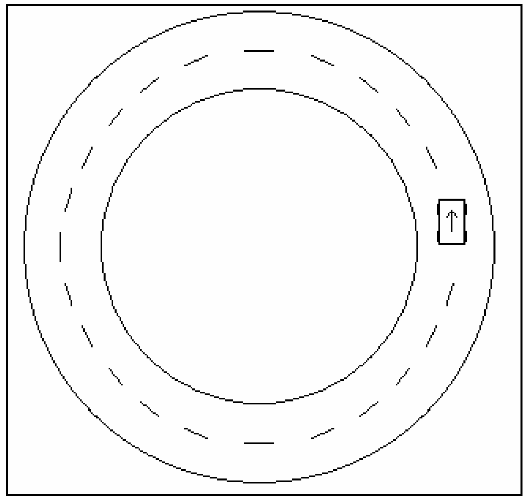


**Fig. 40: A Car Moving On a Curve III**

6. A student is twirling a ball on a string of about 1.5 m length, above her head, as shown in Fig. 41. You observe the motion from about 3-4 m away.
   a. Describe the force or forces from your point of view.
   b. Ask your student who is twirling the ball to describe the force
   c. Or forces from her point of view.
   d. If the string suddenly broke, which direction would the ball move, just after the breakage occurs?
   e. Decide in which case we can refer to the force as “centripetal” and which “centrifugal”.

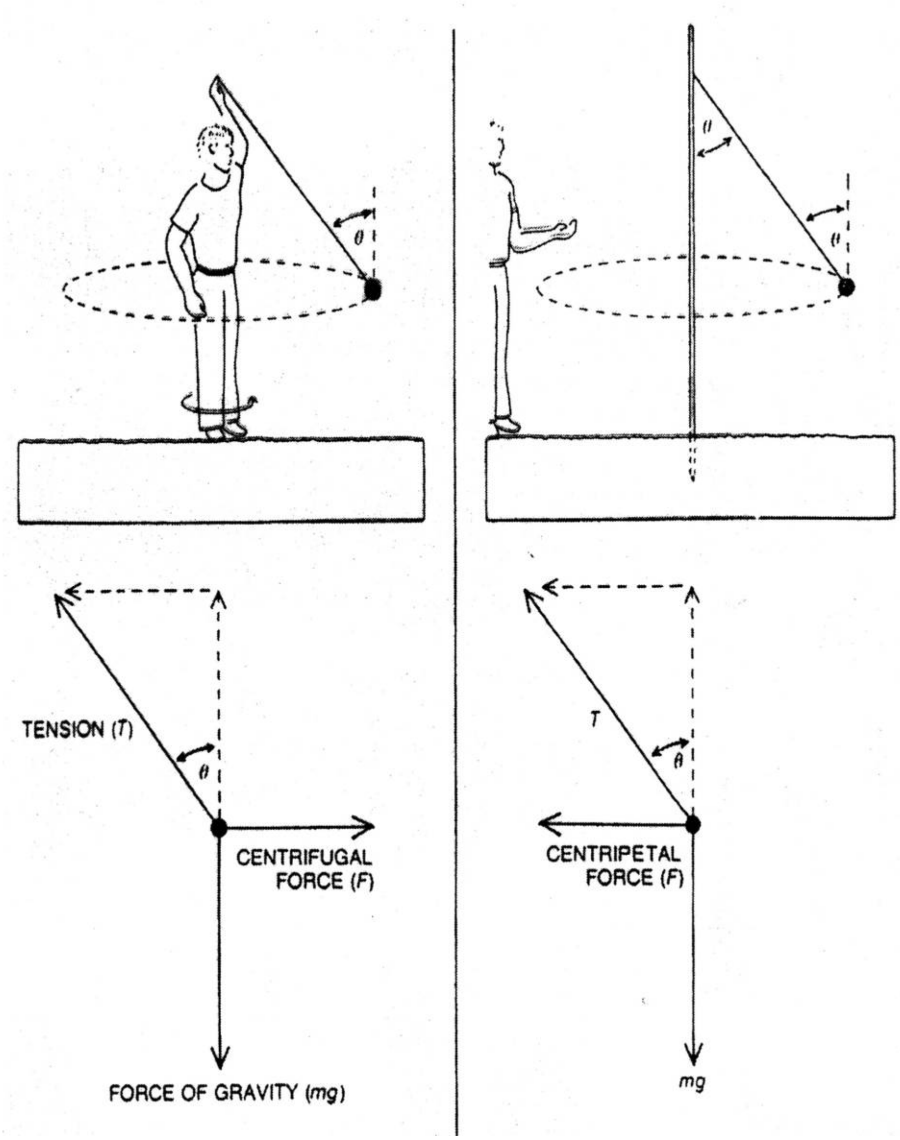



**Fig. 41: A Student Twirling a Ball Attached To a String**

Explanation of Fig. 41:

Top left: one student is twirling a pendulum, called a "conical pendulum". The student feels a force pulling out, i.e. A "centrifugal force" (center-fleeing force).

Top right: The other student is observing the motion. In this student's reference frame there is a "centripetal" (center-seeking force).

**More Interactive Applets on Centripetal Forces**

**IL 76** ** Misconception about rotation, a good picture to download

**IL 77** *** A good interactive applet (IA) for showing the forces on a carousel

**IL 78** *** An excellent IA to show the forces in rotations

**IL 79** *** An extensive collection of IAs for motion and force

**IL 80** *** An advanced discussion of the history of force

**IL 81** *** A comprehensive discussion of the history of force by A. Stinner

**IL 82** *** IA of Newton's "cradle": conservation of momentum

**The Study of Relative Motion**

Examples of Relative Motion

1. You are standing on the shore of a lake watching a ball being thrown up vertically by a man on a boat, as shown. The boat is moving with a velocity of 5 m/s.
   a. Describe the motion as seen by you
   b. Describe the motion as seen by the man in the boat
   c. What is the distance the ball moves, as seen by you, by the man on the boat?

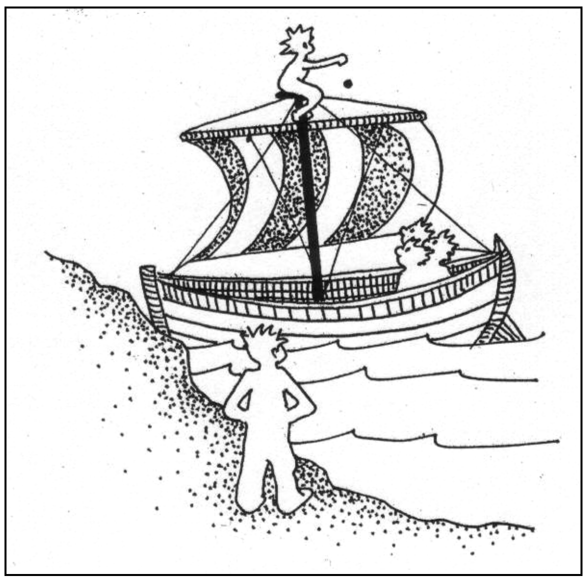


**Fig. 42: Galileo's Ship**

2. A physicist is performing experiments in a railroad car that is moving with a speed 10 of m/s in a straight line. Another physicist is watching from the ground and is making calculations. According to his frame of reference. Describe the following experiments from both points of view:
   a. A ball is dropped from a height of 1 meter.
   b. A ball is thrown horizontally at 10 m/s forward and then backward.
   c. A 25 cm long pendulum oscillates with a period of 1 second.
   d. A billiard ball collides with a stationary one.

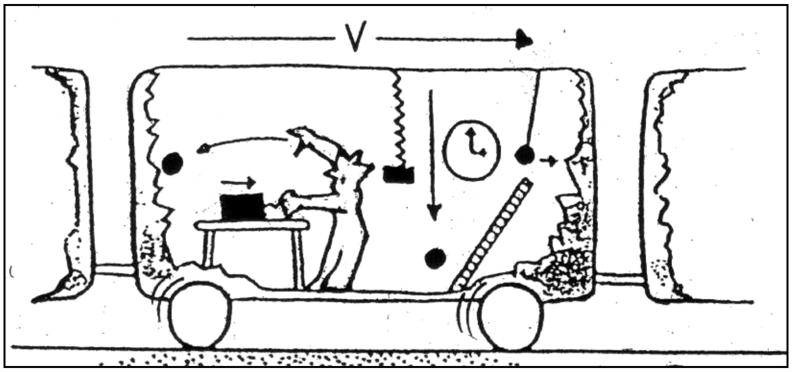



**Fig. 43: A railroad car moving with a constant velocity. Inside the car a physicist is testing the laws of motion**

3. Consider a fighter plane travelling at 500 m/s. It can fire rockets that leave the plane also at 500 m/s (relative to the plane). 1. Describe the path of the rocket, as seen by you on earth, and as seen by somebody in the plane, if it is:
   a. fired toward the front
   b. fired toward the rear of the plane
   c. fired vertically upwards

   (Note: Assume that the rocket has a very high acceleration and that it reaches a velocity of 500 m/s relative to the plane almost instantaneously, and that the air resistance has a negligible effect.)

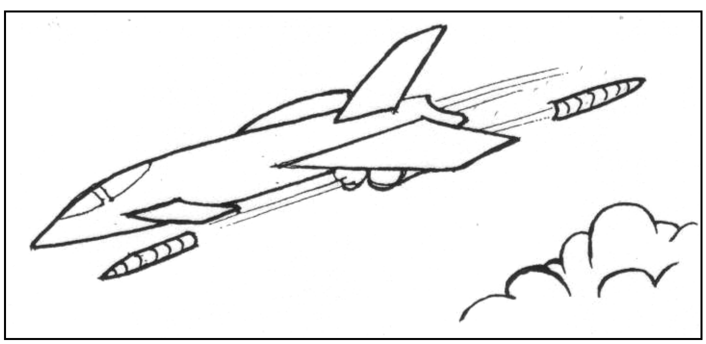


**Fig. 44: A Plane Flying and Shooting Rockets**

4. Consider the motion of the wheels on a car that is moving at 30m/s, or about 110 km/h on a level highway. Use the formula $F_c = V^2 / R$. (This formula will be discussed again in LCP2.)
   a. How fast is the centre of the wheel moving?
   b. How fast are points A,B, C, and D moving ?

c. Calculate the “centrifugal” forces on these points.

d. You will find that some of the forces are very large on . Why does the tire not explode?

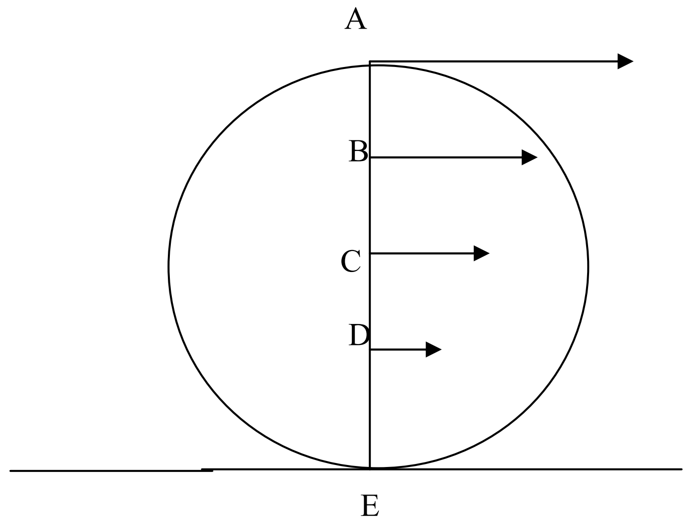



**Fig. 45: A Wheel of a Car in Motion. The velocity of the Car is v m/s.**

5. Now calculate the forces on the front wheels when the car is stationary, sitting on a lifting device so that and the wheels are made to spin freely at the same rotational speed. Now calculate the speed of the points and the forces. Comment.

Look at IL 83 for a good IA and explanation of the motion of a wheel

6. The sketch below shows a cross section of a railway wheel (not to scale). The flange around the rim of the wheel protrudes below the surface of the rail. Flanges inside the rails on both sides are what stops the train from leaving the tracks. Now the point of the wheel that touches the rail--the rolling surface--is instantaneously stationary, and the parts of the wheel above it, as with the bicycle wheel, are travelling forwards. But what about the part below the rail? The next animation in IL shows this.

(Note: We will discuss the cycloid again in LCP 2 in connection with the “least time” problem.)

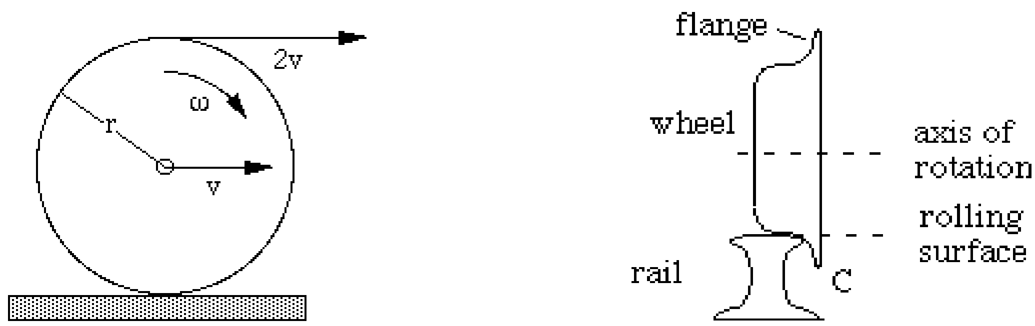



**Fig 46: Side View of Wheel of a Railroad Car**

IL 83 **** The physics of the motion of a wheel. Excellent discussion and good applets

IL 84 ** Motion of a wheel and the speed of a point on the rim of a wheel

IL 85 *** An excellent applet to show a cycloid by observing the motion of a bicycle.

IL 86 *** An excellent IA to show 2- D relative motion

IL 87 *** An applet to show frame of reference

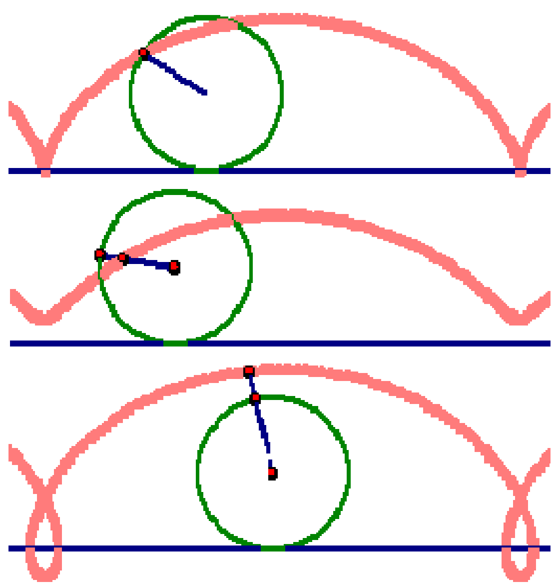


**Fig. 47: Generating a Cycloid**

**Exploring the Relationship between Newton's Second and Third Laws**

The following problems will lead us to a first understanding of motion in space.

1. Two blocks are placed together on a frictionless surface and pushed as shown in Fig. 38.

   The student is to find the force of block A on block B and the force of block B on block A.

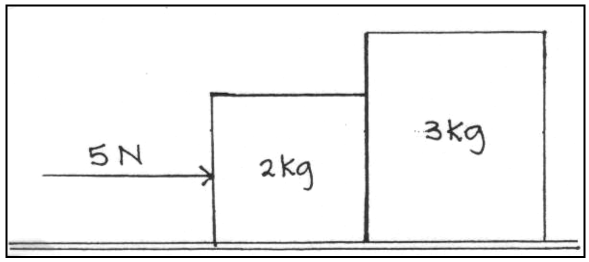



**Fig. 48: Two Blocks Being Pushed By a Force**

3. If two 1 kg masses are suspended at the end of two strings that are connected along the top of a table to a massless balance that reads in Newtons (see Fig.49) what will the balance read? Students are then to choose, without argument, between the following alternatives: a. 0N, b. 10N, c. 20N.

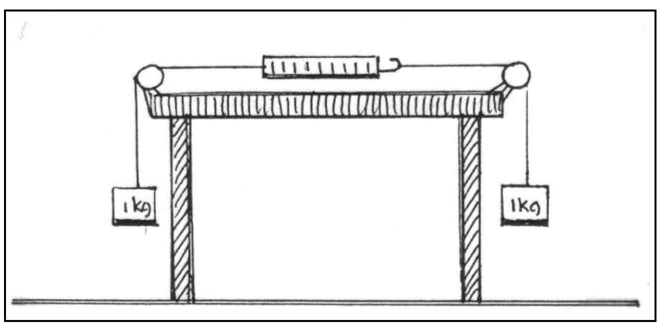



**Fig. 49: Two Masses Suspended From a Table**

4. A small car is pushing a truck on a level road (see Fig. 50). The mass of the truck is 5 times the mass of the car. The truck experiences an acceleration of 1 $m/s^{2.}$ What force does the small car exert on the truck? What is the force the truck exerts on the car? Discuss.

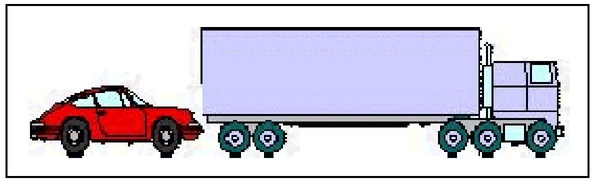


**Fig. 50: A Small Car Pushing a Large Truck**

**IL 88** ** Source of Fig. 39.

**IL 89** *** An excellent analysis of a car colliding with a truck

5. The relationship between the second and third laws can be illustrated by imagining two large masses in close proximity in deep space. Assuming that the gravitational attraction due to each other's mass is the only external force we can then calculate the acceleration (instantaneous) on the masses. Discuss.

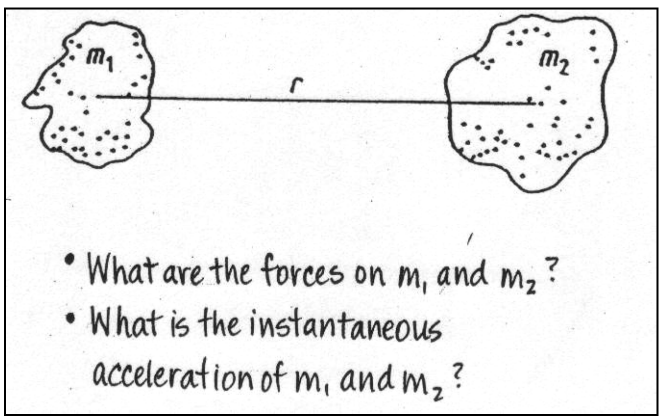



**Fig. 51: Two Large Masses in Deep Space**

**Inertial Frames of Reference (IFR)**

**IL 90** *** An advanced discussion of inertial frames of reference

**IL 91** *** IA for frames of reference

**IL 92** *** A fantastic collection of motions in space between 3 bodies

**IL 93** *** An advanced discussion of the physics of a rotating platform

A fundamental concept for understanding dynamics is the concept of an IFR. Newton was the first to describe these when he discussed his first law of motion. We have already discussed the motion of a railroad car on a level track travelling at a constant speed. When you are inside this car you are travelling in an If the motion of the car were completely smooth, and you could not see out of the car. There is no experiment that you could perform that would tell you that you are moving. In other words, we have what is known as an “equivalence principle” which says that you cannot distinguish between rest and constant velocity.

Problems for the Student

1. If you were an astronaut in the Shuttle would you feel the force of gravity? Discuss. The Shuttle is generally about 300 km above the surface of the earth and orbits at about 30,000 km/hour in a circular orbit. How large would be the gravitational effect of the earth on the Shuttle as compared to the effect it has when the Shuttle is on the runway?

2. If you were and astronaut in the future, travelling to a nearby star (at a very velocity, of course) you would be travelling through space where the effect of gravity is essentially zero. Compare this situation with the one in the Shuttle.

3. Physics text books generally state that Newton’s first law of motion, his law of inertia, was already stated earlier by Galileo. Galileo illustrated inertia by imagining an object circumnavigating the world without resistance. The closest we can come to realizing this thought experiment is the motion of the Shuttle or a satellite in an orbit around the earth. Of course, the motion of the Shuttle is quite different because it moves with a very high speed. Compare these two motions.

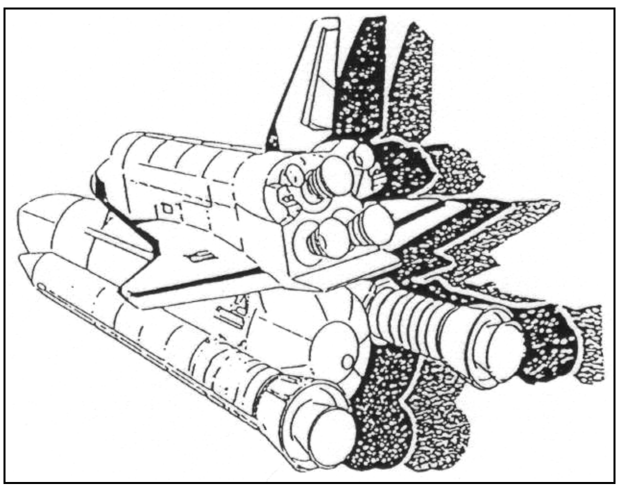


**Fig. 52: The Space Shuttle**

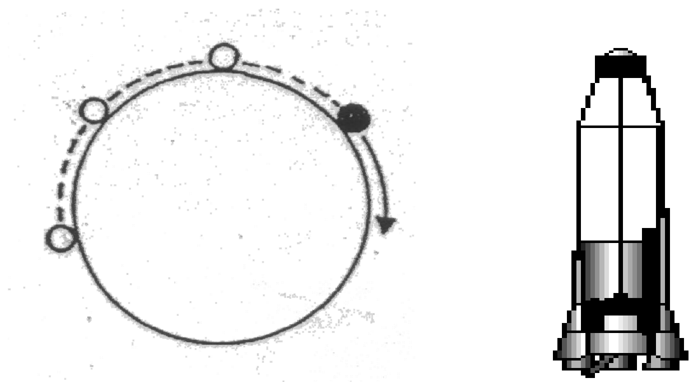
4. A Shuttle is moving at a constant speed in a circular orbit.
   a. Are the astronaut’s in an IFR? Discuss.
   b. Imagine that suddenly the earth's gravitational force is removed. What would happen to the satellite? Describe the motion of the satellite now.

c. Would the astronauts be in an IFR again?

d. You would now have an example of what Newton understood by the law of inertia, or his first law of motion. Discuss. Compare the two frames of reference.

e. State Newton's law of inertia *in your own words*.

5. We can understand Newtonian inertia by proposing the following thought experiment: Imagine an object moving in deep space where there is no gravity and the net force on the object being zero. Then the object will move in a straight line at a constant speed (relative to any other frame of reference that is inertial). What then is the difference between Galileo's understanding of inertia and that of Newton?



Galileo**:** An object circumnavigating the earth and encountering no resistance.

Newton: A rocket in deep space with the thrusters shut off.

**Fig. 53: Comparing the Idea of Inertia of Galileo and Newton**

**IL 94** ** Simple explanation for above problem

**IL 95** *** Forces acting on a shuttle - free falling objects

**The Relationship between Acceleration and Gravity:**

1. One day Isaac Newton received a letter from Robert Hooke. In this letter, Hooke outlined the mathematics governing how objects might fall if dropped through hypothetical tunnels drilled through the Earth at varying angles. Though it seems that Hooke was mostly interested in the physics of the thought experiment, an improbable yet intriguing idea fell out of the data: a dizzyingly fast transportation system.

See:

IL 96 *** for details

Also see:

IL 97 ***

The complete history and the solution to the problem can be found in these links.

a. Imagine a tunnel through the earth, as shown below. Drop a heavy object at A and describe the motion.

b. Now imagine a pendulum, with the length of the radius of the earth. Describe the motion of the pendulum.

c. Finally, find out the period of a satellite in circular motion, just above the surface of the earth. Compare the times for the three motions and comment.

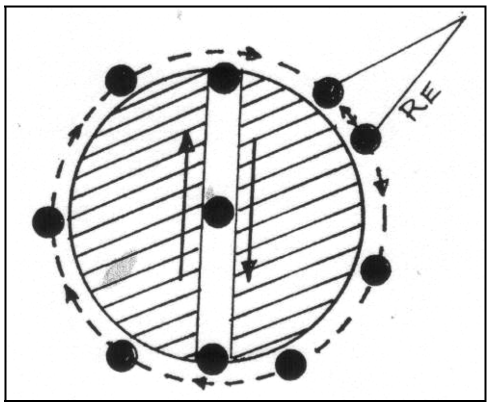



**Fig. 54: Earth with a Tunnel Through It**

**IL 96** ** Discussion of gravity powered transportation – through earth tunnels

**IL 97** *** Detailed discussion of gravity train – earth tunnel travel

**IL 98** ** Brief discussion of gravity train – earth tunnel travel

2. To further illustrate the relationship between gravity and acceleration consider the following demonstration:

   A balloon containing helium is attached to the floor of a car and a pendulum from the ceiling of the car. The car accelerates as shown. Which way will the balloon and which way will the pendulum move?

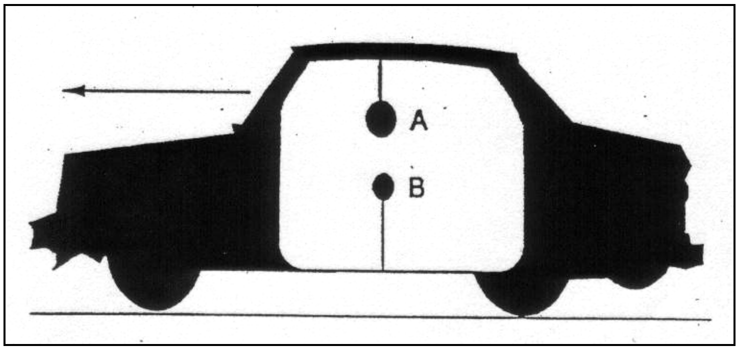



**Fig. 55: A Car with a Balloon and a Pendulum Accelerates**

3. Imagine standing in an elevator with a balloon in your hand. The cable holding the elevator is cut and you find yourself in free fall. Predict the motion of the balloon.

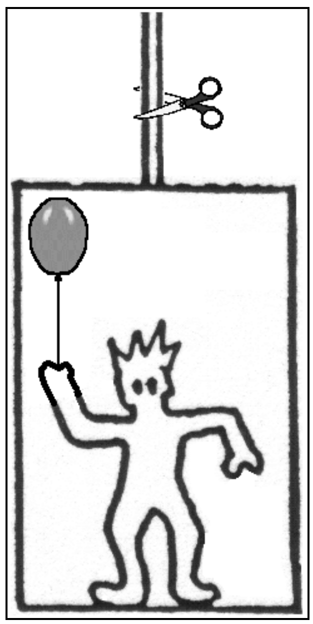


**Fig. 56: Standing In an Elevator with a Balloon, Before the Cable Is Cut**

4. Now imagine the elevator in deep space where there is no gravity. What would happen to the balloon? To a burning candle?

5. The elevator is now accelerated in deep space with an acceleration of 1g (about 10 $m/s^2$). Describe the motion of the balloon now

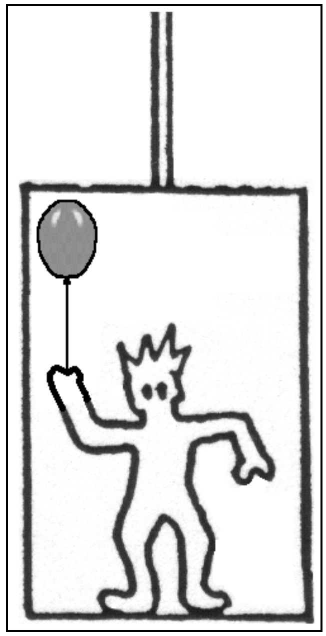


**Fig. 57: Holding a Balloon in an Accelerating Elevator in Deep Space**

**IL 99** ** Discussion of explanation of general relativity

What these examples illustrate is Einstein's equivalence principle, which says that "there is no difference between gravity and acceleration". The balloon behaves in this unexpected fashion because "the balloon cannot differentiate between gravity and acceleration".

**Newton Thinks about Satellite Motion**

In his *Principia* (published in 1687) Newton anticipated satellite motion in orbit around the earth.

**IL 100** *** Complete description of orbits, including historical and mathematical

The following is taken from the website above:

As an illustration of the orbit around a planet (eg. Earth), the much-used cannon model may prove useful (see image below). Imagine a cannon sitting on top of a (very) tall mountain, which fires a cannonball horizontally. The mountain needs to be very tall, so that the cannon will be above the Earth's atmosphere and we can ignore the effects of air friction on the cannon ball.

If the cannon fires its ball with a low initial velocity, the trajectory of the ball will curve downwards and hit the ground (A). As the firing velocity is increased, the cannonball will hit the ground further (B) and further (C) away from the cannon, because while the ball is still falling towards the ground, the ground is curving away from it (see first point, above). If the cannonball is fired with sufficient velocity, the ground will curve away from the ball at the same rate as the ball falls — it is now in orbit (D). The orbit may be circular like (D) or if the firing velocity is increased even more, the orbit may become more (E) and more (F) elliptical. At a certain even faster velocity (called the escape velocity) the motion changes from an elliptical orbit to a parabola, and will go off indefinitely and never return. At faster velocities, the orbit shape will become a hyperbola.

**IL 101** *** An excellent IA using Newton's cannon.

In later LCPs the physics of space will be discussed in detail. For now we will consider simple problems involving travelling in space.

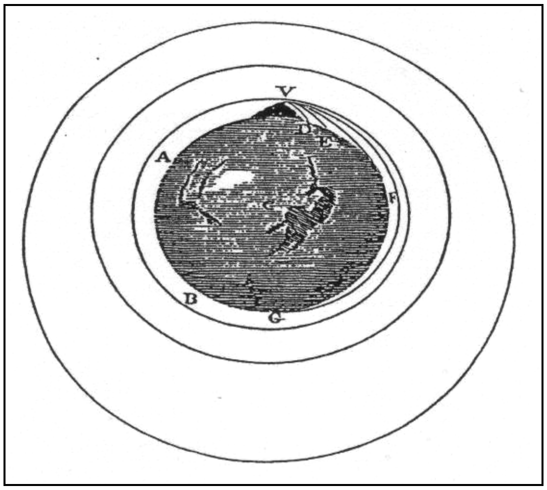



**Fig. 58: Newton's Cannon**

Questions Newton Could Have Answered About Satellite Motion

Use IL  for answering these.

(Note: You can obtain a qualitative and some quantitative understanding of satellite motion using this interactive program. Below we will discuss a quantitative approach, using Newton's own calculations.).

1. Use the program in IL to find the velocity required to place a satellite into a circular orbit, not far above the surface of the earth.
2. Notice that velocities lower and higher than this velocity describes a motion that looks like an ellipse.
3. Find the escape velocity of an object from earth, the velocity necessary to escape the gravity of the earth.

**IL 102** *** An advanced discussion of escape velocity

**Fig. 59: Starship Enterprise**

**Into Space: Toward "The Physics of Star Trek"**

In the last LCP "The Physics of Star Trek" will be discussed. The following is just a little hint of what will be presented there.

The TV series Star Trek has captured the imagination of generations of students since it was introduced in the late 1960's. The original was later replaced by a new one in the series "Star Trek, the New Generation". However, those who have grown up with the original series seem to prefer it, as attested by the fact that the new series is run concurrently with the old one.

The episodes of Star Trek concentrate on speculating on the personal and social interaction in a galactic society of the twenty third century. For such a society to be able to interact at all we must postulate a high technological achievement, indeed. The level of technological and scientific achievement is indicated by having the Star Ship Enterprise travel at a speed faster than that of light, and making the teleportation of the crew from the surface of a planet to the Enterprise seem plausible.

However, here we will begin with "baby steps" before discussing the physics of Star Trek in the last LCP. In LCP 6 we will travel to the Moon and investigate the kinematics, dynamics on the Moon, as well as look at the physics of building in low gravity and an atmosphere-free surface. In LCP 7 we will find out how a trip to Mars will be possible, all in preparation for the physics of Star Trek.

Travelling to the moon requires an initial velocity of a little over 8 km/s. Newton did not consider the problem of sending a canon ball to the moon. We will discus the physics of sending a space craft to the moon in a later LCP. This trip is relatively quick. It only takes a few days.

Problems for the Student

1. How would Newton have arranged the position of his canon, when and in which direction would he have shot the canon ball so that it would land on the moon?

2. We will also study the physics of travelling to Mars. To get to Mars, the cannon ball would be underway for about 7 months. Make a simple calculation to confirm this

approximate travel time assuming that the space craft leaves the earth at about 11 km/s.

3. How long would it take the canon ball to travel beyond the solar system? We will show later that the escape velocity of the earth itself from the solar system would be 42.3 km/s. We know that the escape velocity from the earth is 11.2 km/s and we also know that the earth is revolving around the sun with a velocity of 30 km/s. It can be shown (we will do that in a later LCP) that the escape velocity from the earth and the solar system (travelling in the same direction as the motion of the earth around the sun, of course) would then be 23.6 km/s.
    a. At that speed how long would it take to travel beyond the solar system? Assume the solar system is about 100 AU, or astronomic units in diameter (1 AU = 1.5 x $10^{11}$ m.)
    b. How long would it take for space craft to travel to the nearest star? The nearest star is about 4 light years away, or the distance that light would travel in 4 years.

5. These calculation should convince you that, using space travel capabilities we have today will never get humans to Pluto and back, not to speak of travelling to the nearest star. Let us make one last desperate attempt. Imagine that we had enough fuel/energy propelling system to accelerate the space craft to a speed of 10% of l\the speed of light, or $3x10^7$ m/s.
    a. Assume that it is possible to maintain an acceleration of the space craft of 10 $m/s^2$, how ling would it take to reach the "cruising speed"?
    b. How long would it take to get to the nearest star, assuming that the space craft is also able to decelerate at 10 $m/s^2$ ?

We will explore the question of travelling to the stars and galaxies, in the last LCP that deals with the physics of Star Trek.

These simple calculations should convince you that it is not possible, using today's physics and technology to travel to the nearest star, much lees than to another galaxy. perhaps a new technology and a new physics will allow us to do so. We will find out in LCP 10.

**IL 103** *** Detailed discussion of escape velocity.

## CONCLUDING REMARKS

We have come a long way since considering the general problem of trying to understand motion around us. We began our study by classifying motion into four categories and found that it was very difficult to identify motion that we were able to describe mathematically. Our intuitive (common sense) understanding of motion and forces, when measured by "physicist's understanding", was found inadequate. The path from intuitive understanding of motion and forces to scientific understanding is often difficult.

First, it was claimed that understanding motion and forces in general was made more accessible by using contextual and historical settings. Secondly, we presented motion, using the sequence of verbal definition, graphical representation, symbolic or/and mathematical representation, followed by a simple example to illustrate the concept, and finally having the student connect to one or more selected Internet connections, often by way of an interactive applet. This sequential approach, moving from a qualitative to a quantitative understanding of motion, was introduced to ensure that students don't just memorize formulas, definitions and algorithmic procedures, but are able to gain a high level of conceptual understanding.

The discussion of motion and forces continued with the study of kinematics and dynamics, emphasizing both qualitative and quantitative understanding. Galileo's kinematics of free fall and projectile motion were followed by discussing Newton's laws of motion and applying them to our examples that were used to test our intuitive understanding. We concluded with Newton's thought experiment that investigates the possibility of satellite motion, taken from the *Principia*, using a very excellent interactive applet. The LCP concluded with some exotic examples of motion that foreshadow the content of LCP2, as well as the study of the physics of Star Trek in LCP10.

In the next LCP we will continue to discuss these laws by following the history of our understanding of forces and motion, using the pendulum as the central idea. In LCP 2 we will recapitulate (re-discover) the concepts we discussed in LCP 1. However, these ideas will be discussed in a richer context and on a more sophisticated level.

Additional interactive applets:

**IL104** *** IA of Newton's third law

**IL105** *** IA of Newton's third law

**IL 106** *** An excellent IA for projectile motion

**IL 107** *** IAs for motion and other physics concepts and laws

**IL 108** *** IAs from all of physics

**IL 109** *** IAs for motion for motion in general