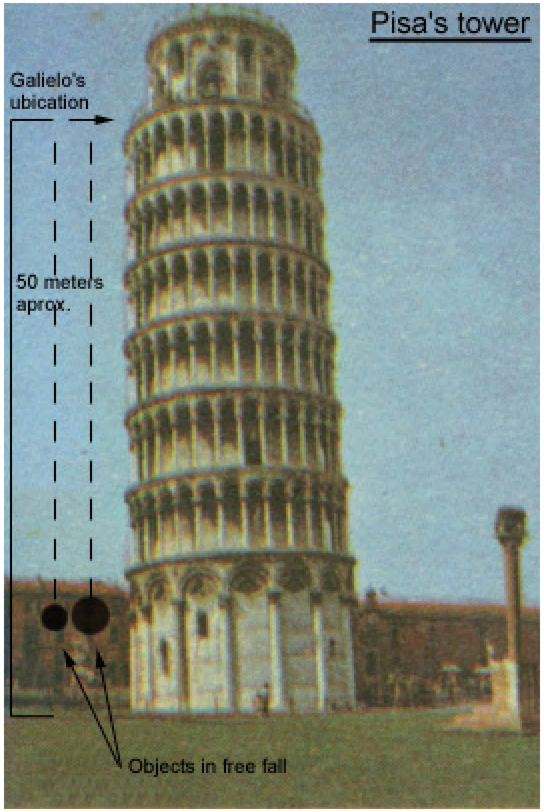
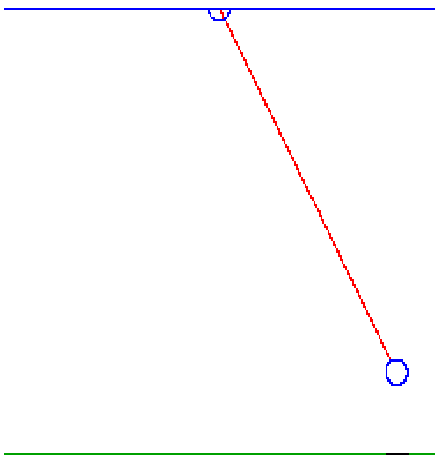
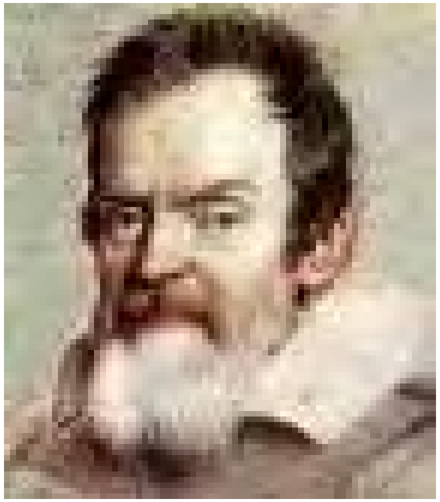
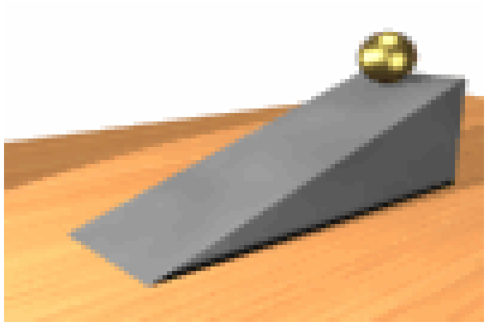






Motion and Galileo’s Inclined Plane



About motion: From his *Two New Sciences:*

- *My purpose is to set forth a very new science dealing with a very ancient subject.*
- *There is, in nature, perhaps nothing older than motion, concerning which the books written by philosophers are neither few nor small;*
- *nevertheless I have discovered by experiment some properties of it which are worth knowing and which have not hitherto been either observed or demonstrated.*

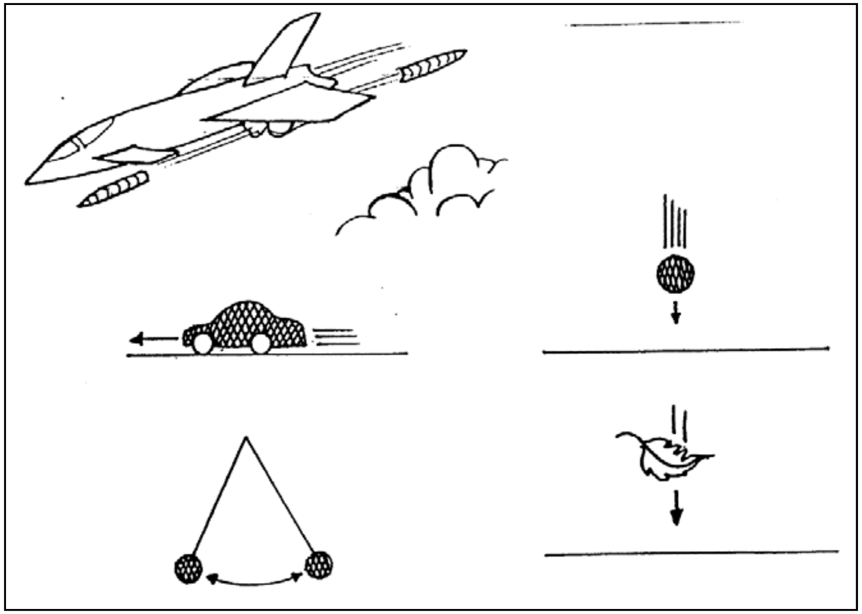
Galileo’s ’ Foundational Assumptions about Physics:

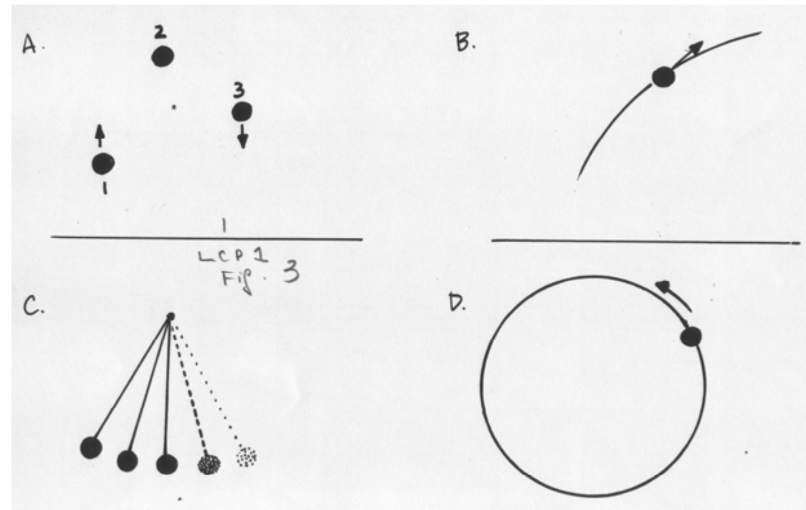
1. The world can be understood by rational thought.
2. The language of Nature is the language of mathematics (geometry).
3. The world must be studied only through primary (measurable) qualities of length, time, area, etc.

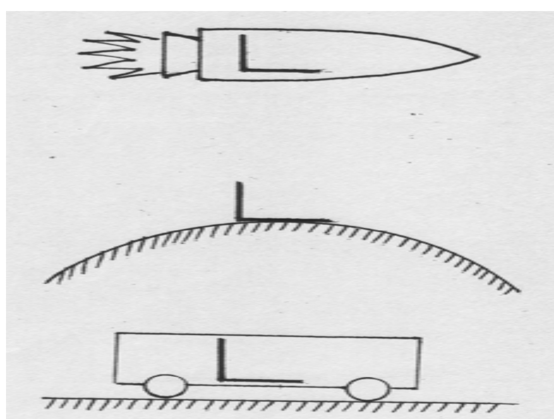
Galileo's questions about the physics of motion:

1. What is the mathematical law that correctly describes free fall?
2. How can we decompose complex motion, like the motion of a projectile, to simpler motions?
3. Can we describe such complex motion as the motion of a body through a resistive medium?
4. How can we describe the oscillation of a pendulum?
5. What are the primary qualities that allow us to describe motion quantitatively?

Examples of motion







Galileo: his categories of motion

I : Constant speed.

II : Constantly changing speed (uniform acceleration).

III : Complex motion, mathematically describable.

IV : Complex motion, mathematically not describable.

Examples of motion around us

1. The falling of a leaf.

2. The flight of a bird.

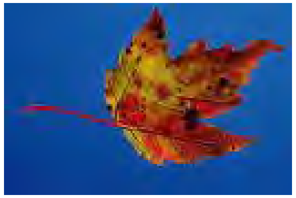
3. The running of a deer.

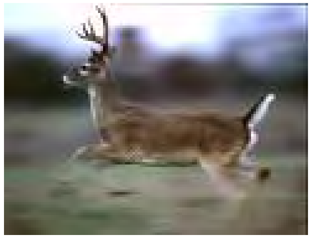
4. The free fall of a heavy object.

5. The motion of an artificial earth satellite.

6. Water skiing.

7. The motion of a space ship in deep space *without* thrust.





Examples of motion around us

8. The motion of a simple pendulum.

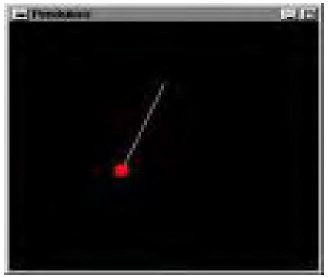
9. The motion of a point on the rim of an industrial flywheel.

10. The motion of a roller coaster.

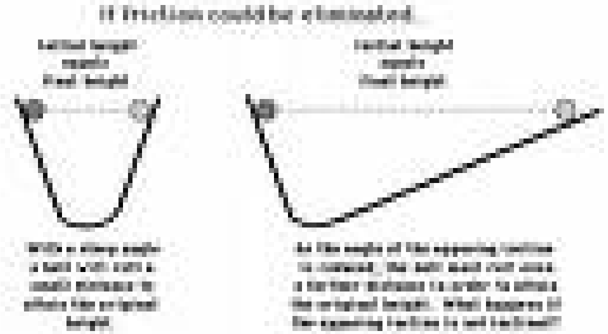
11. The motion of the Shuttle in orbit

12. The motion of a car

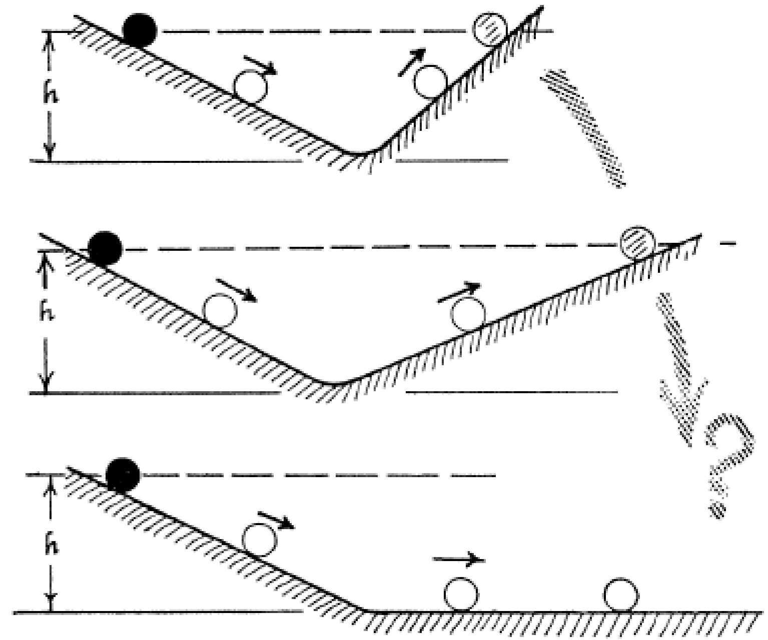
13. Suggest other examples and place them in their appropriate categories



?

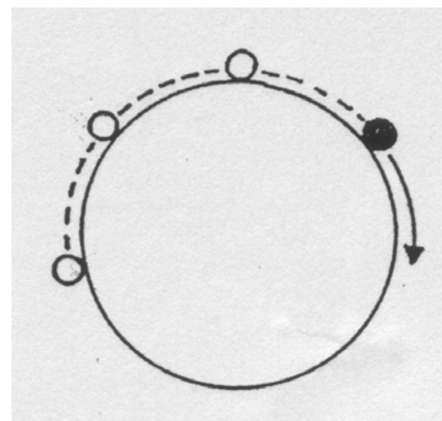


Galileo’s idea of inertia



- To illustrate the idea of inertia, Galileo first imagined a ball rolling down an inclined plane and then rolling up another one.

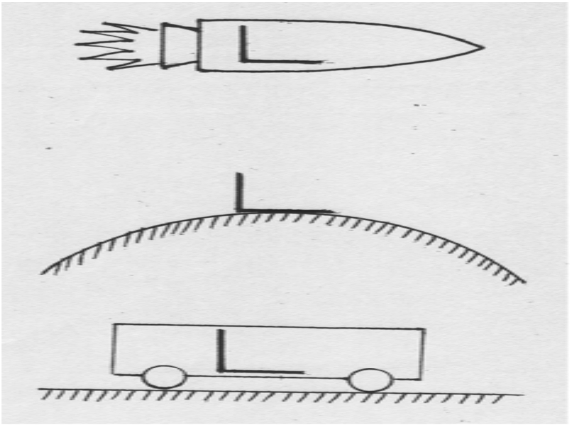
- He further argued that when the ball finally rolls on a level surface, in the ideal case when there is no resistance, it would roll around the earth and continue to do so forever.

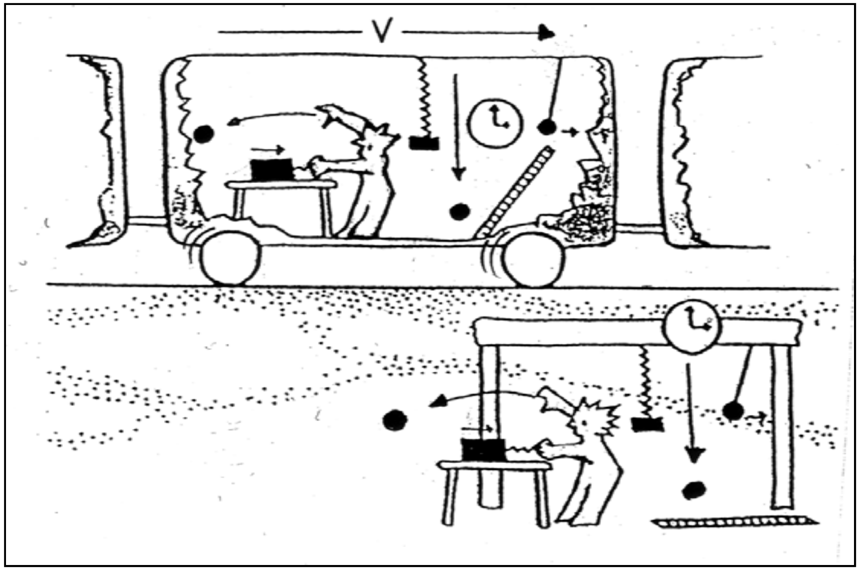


Galilean equivalence principle

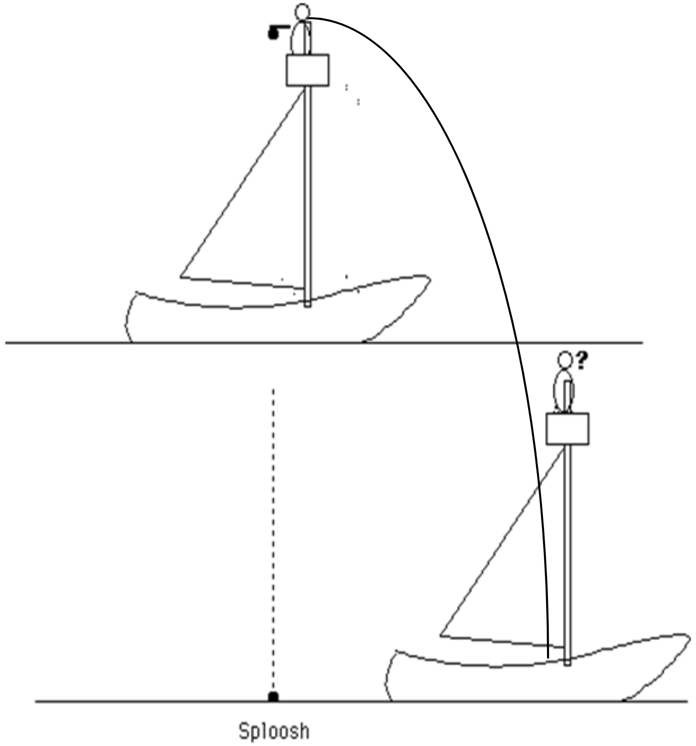
Galileo thus claimed that

there is no distinction between constant motion and rest.





- Galileo used a thought experiment to argue that you cannot tell the difference between constant velocity and rest.
- “If a sailor dropped a canon ball from the mast of a ship that was smoothly moving with a constant velocity, the cannon ball would fall directly below him.
- Whatever the sailor would do, he would not be able to tell that the ship was in motion if he confined his attention to the ship.



From his *Two New Sciences:*

Some superficial observations have been made, as, for instance, that the free motion of a heavy falling body is continuously accelerated;

but to just what extent this acceleration occurs has not yet been announced;

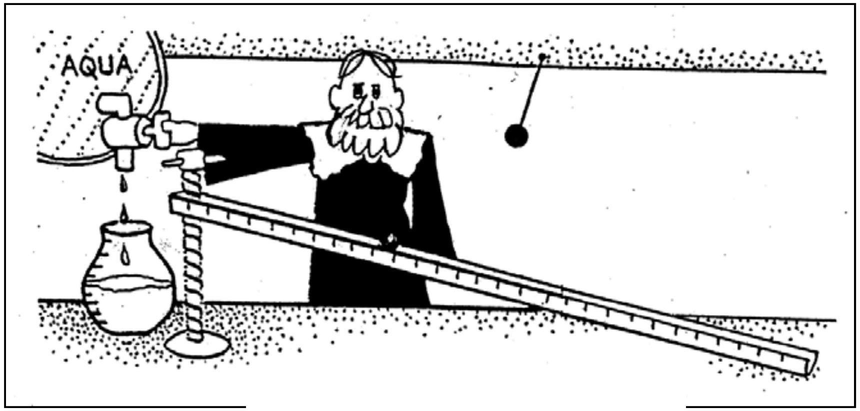
for so far as I know, no one has yet pointed out that the distances traversed, during equal intervals of time, by a body falling from rest, stand to one another in the same ratio as the odd numbers beginning with unity.

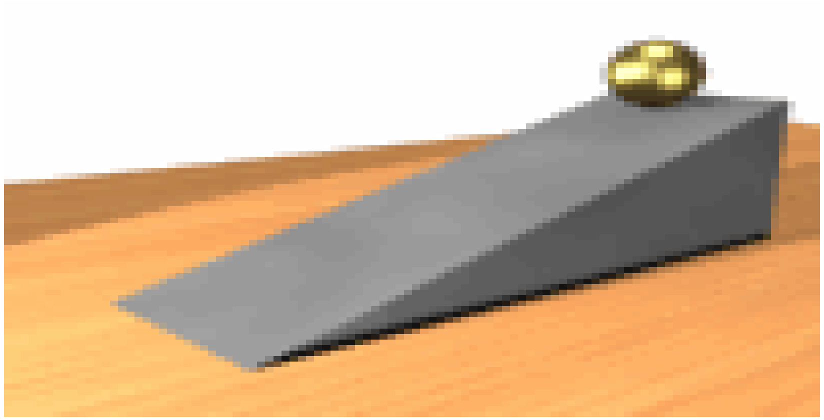
Galileo's inclined plane

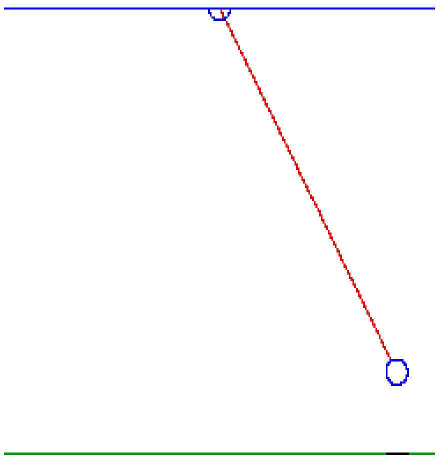
- The Galileo Room at the Deutsches Museum in Munich

The physics of the inclined pane

All of physics comes from the study of the inclined plane





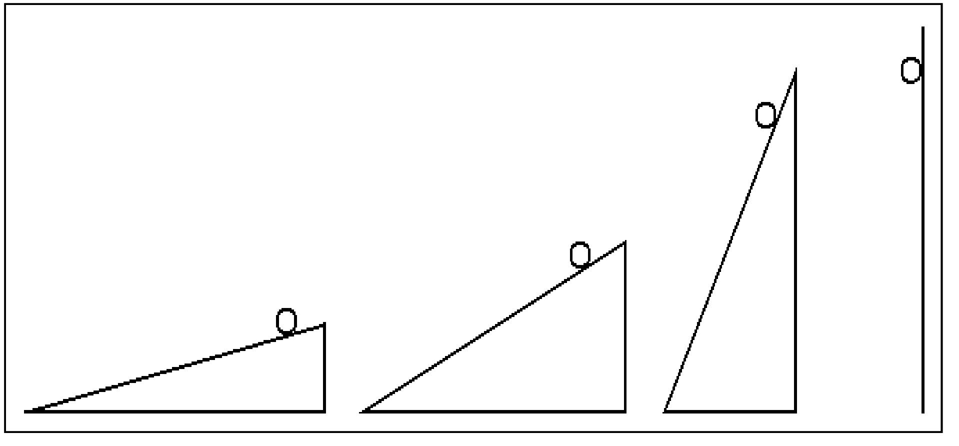


Galileo's inclined plane experiment

Textbooks generally describe Galileo's method for the inclined experiment this way:

Galileo was unable to measure the time of free-fall directly, so he "diluted gravity" and determined the time it took for a small copper sphere to roll down the incline a number of times. Record the time and distance and show that distance is proportional to the square of elapsed time.

extrapolation



An example of a textbook version

- Set up the ramp with h= 0.10 m above the table.
- 2. Starting with the cylinder at rest, use the stopwatch to measure the time to roll distance d = 1.0 meter down the ramp. See "Making Measurements", above.
- 3. Take 6 time measurements, record in data table A. Cross out the highest and lowest times and determine the average of the remaining four times. (Sum four times and divide by four to find the average.)
- 4. Repeat steps 2 and 3 for distances of 0.80 m, 0.60, 0.40 m (see data table A).

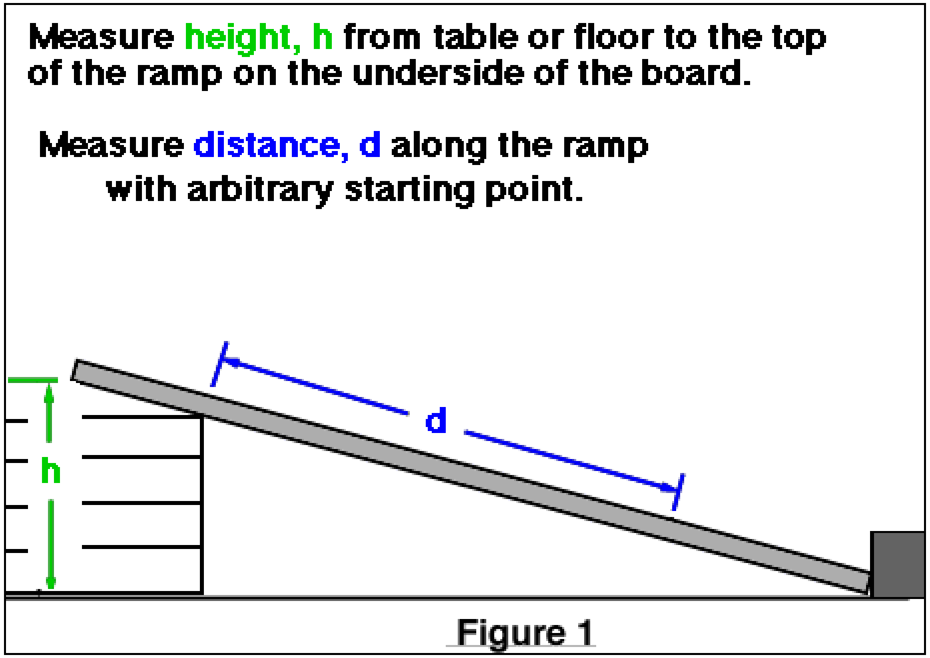
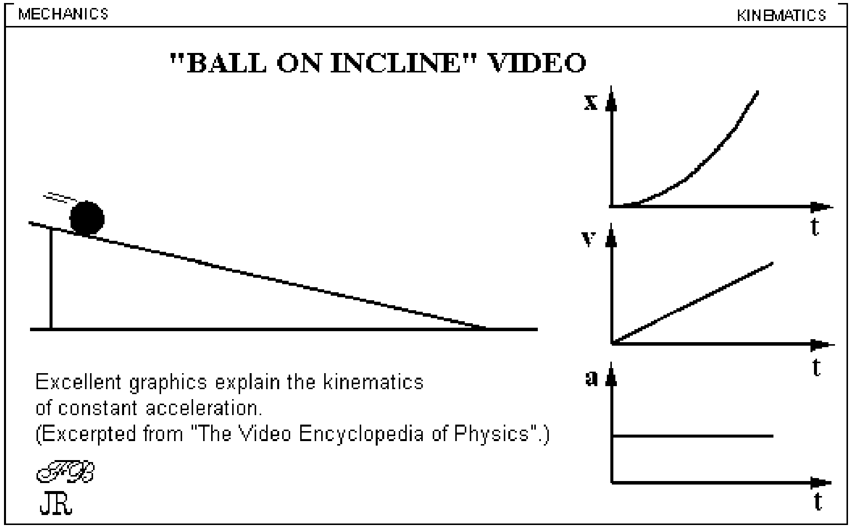


Figure 1



<u>What Galileo really did…Taken from his *Two New Sciences*</u>

- *A piece of wooden moulding or scantling, about 12 cubits long, half a cubit wide, and three finger-breadths thick, was taken; on its edge was cut a channel a little more than one finger in breadth,…we rolled along it a hard, smooth, and very round bronze ball.*

- *Having placed this board in a sloping position, by lifting one end some one or two cubits above the other, we rolled the ball along the channel, noting the time required to make the descent. We repeated this experiment more than once in order to measure the time with an accuracy such that the deviation between two observations never exceeded one-tenth of a pulse-beat.*

What Galileo really did…

- *We now rolled the ball only one-quarter the length of the channel; and having measured the time of its descent, we found it precisely one-half of the former.*
- *Next we tried other distances, comparing the time for the whole length with that for the half, or with that for two-thirds, or three-fourths, etc..*
- *In such experiments, repeated a full hundred times, we always found that the spaces traversed were to each other as the squares of the times, and this was true for all inclinations of the plane.*
- *We also observed that the times of descent, for various inclinations of the plane, bore to one another precisely that ratio which, as we shall see later, the Author had predicted and demonstrated for them.*

What Galileo really did…

- *For the measurement of time, we employed a large vessel of water placed in an elevated position;*
- *to the bottom of this vessel was soldered a pipe of small diameter giving a thin jet of water, which we collected in a small glass during the time of each descent, …the water thus collected was weighed, after each descent, on a very accurate balance;*
- *the differences and ratios of these weights gave us the differences and ratios of the times, and this with such accuracy that although the operation was repeated many, many times, there was no appreciable discrepancy in the results.*

Galileo's inclined plane experiment

- http://www.ngsir.netfirms.com/englishhtm/Incline.htm

Inclined plane on the internet

- http://www.ngsir.netfirms.com/englishhtm/Incline.htm

Galileo in history

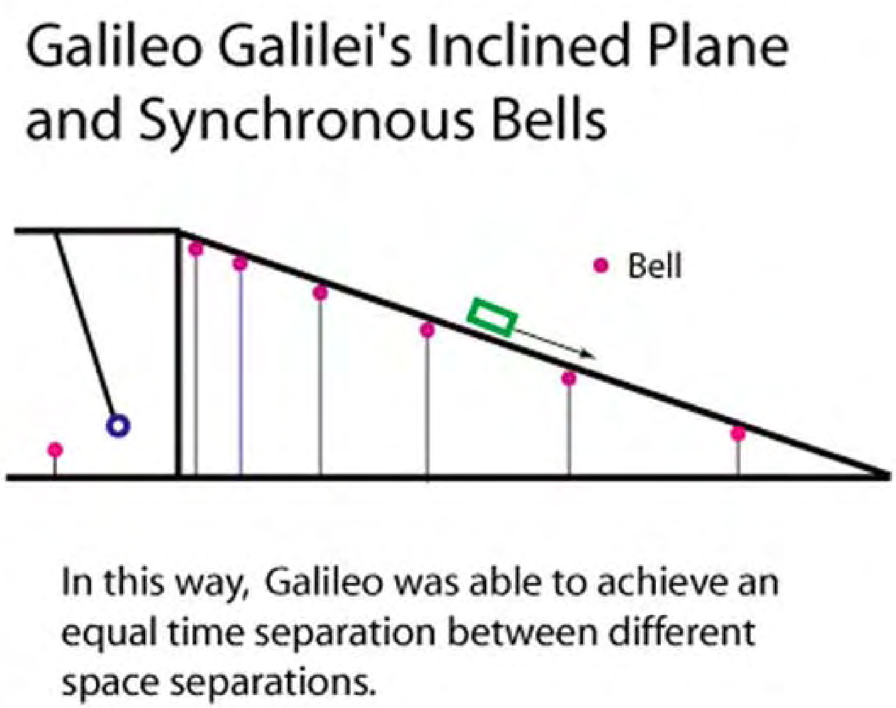
- In this Florence museum, there are many scientific instruments which Galileo used to formulate his physical ideas. Of course, one of the most important items is his inclined plane.

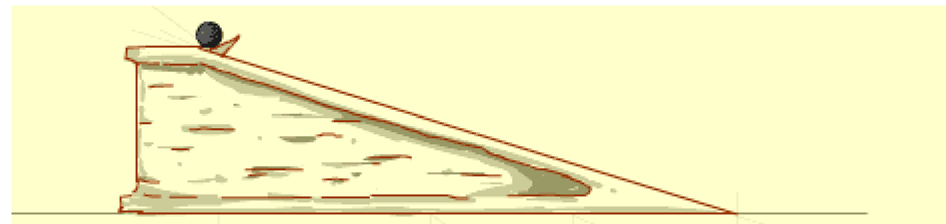
One physics teacher, who discovered the importance of the historical context says:

- *One of the most neglected museums is the History of Science Museum in Florence. In this museum, there are many scientific instruments which Galileo used to formulate his physical ideas. Of course, one of the most important items is his inclined plane.*

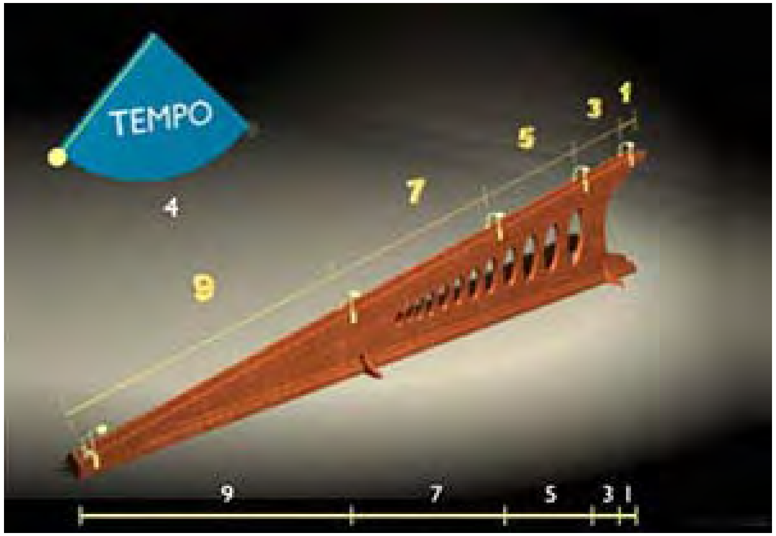
- *After seeing it, I realized how I used to be stupid when I was teaching physics. When I drew inclined planes to illustrate gravitational acceleration in the past, I never included Galileo's clock attached to the plane. You will note that* ***the inclined plane without the clock*** *looks very dumb. Without the time dimension, physics is meaningless.*

Florence Museum





The inclined plane



The ratios of the distances increase by odd numbers.
1,3,5,7,9...
This progression is always the same for any angle.

Time	Total Distance Covered
1	1
2	1 + 3 = 4
3	1 + 3 + 5 = 9
4	1 + 3 + 5 + 7 = 16

Total distance covered is proportional to the time squared.

$$d \sim t^2$$

Time	Total Distance Covered	Time Squared
1	1	$(1)^2 = 1$
2	4	$(2)^2 = 4$
3	9	$(3)^2 = 9$
4	16	$(4)^2 = 16$

Straight line motion on the internet

- http://www.ngsir.netfirms.com/englishhtm/Kinematics.htm
- http://www.walter-fendt.de/ph11e/acceleration.htm
- http://www.ngsir.netfirms.com/englishhtm/Kinematics.htm

A famous theorem by Galileo

Galileo proved that the time of descent of an object (on a frictionless surface) along an incline represented by any chord is the same and is equal to the time it would take for an object to fall through a distance of twice the radius.

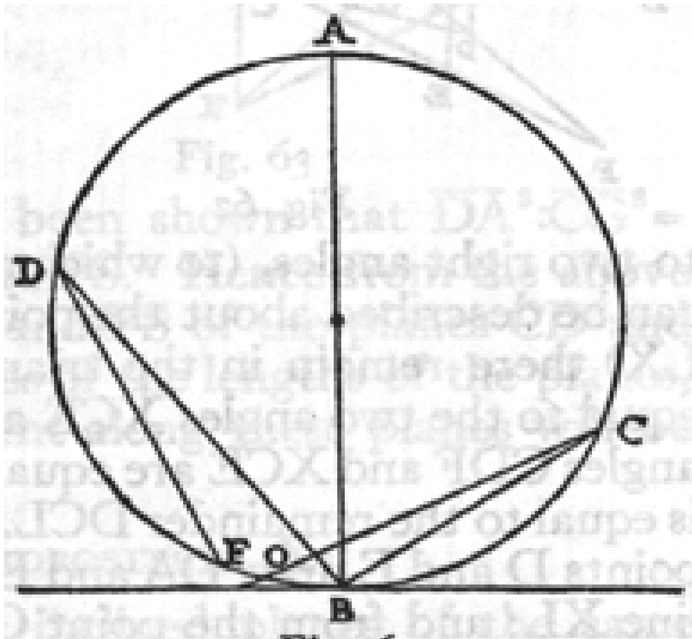
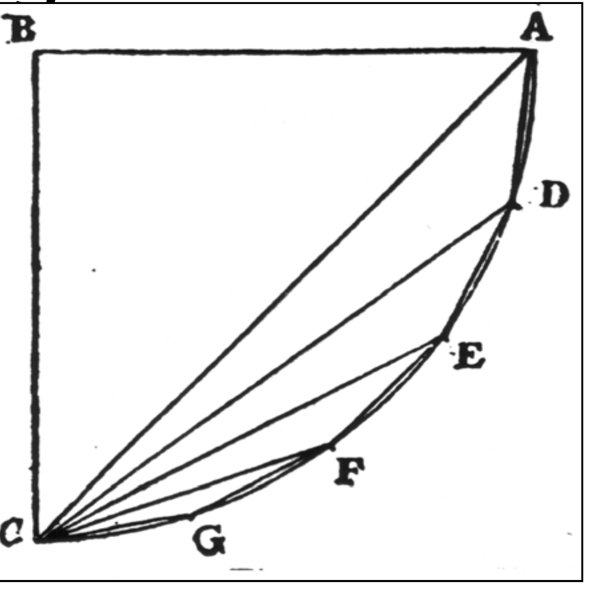
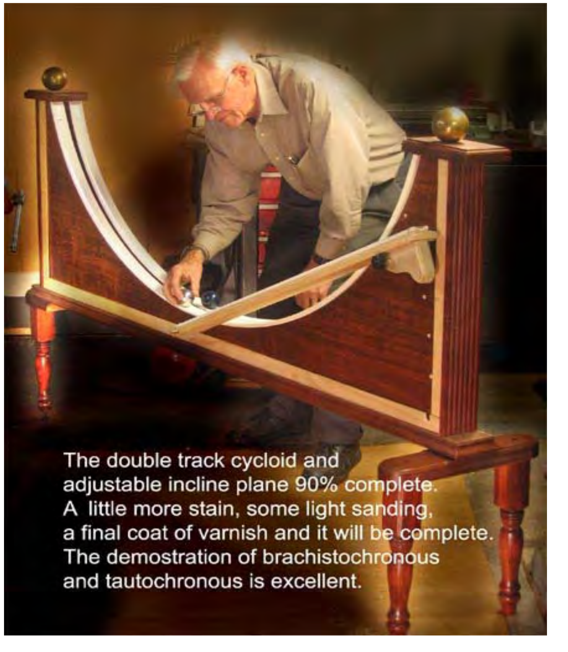


Fig. 61

Galileo and the "least time proble (brachistochrone)

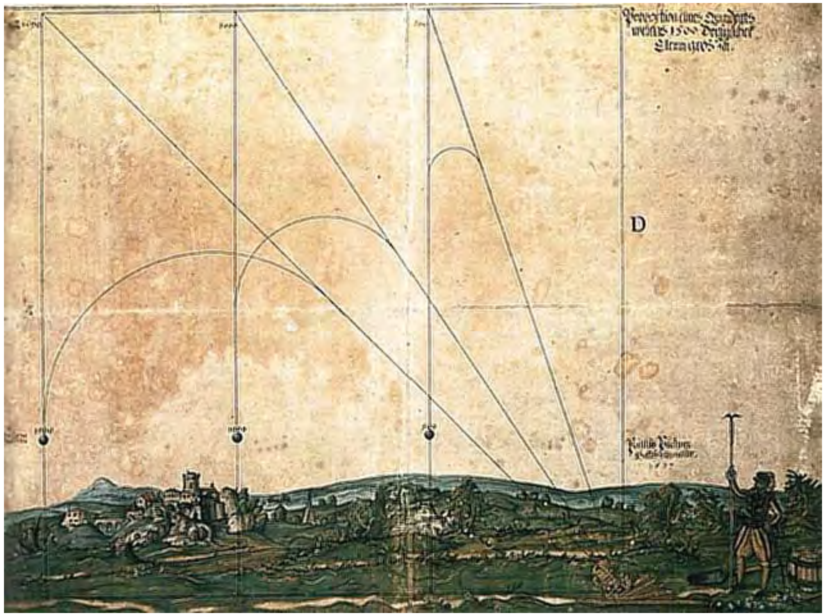
- Galileo believed that the arc represented the least time (brachistochrone) of an object descending along a frictionless path in a vertical plane.



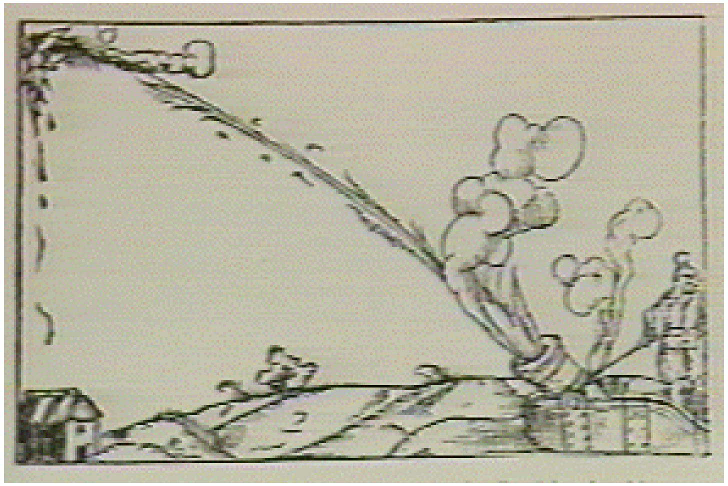


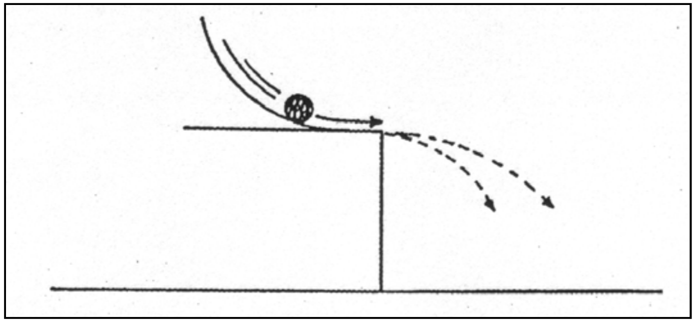
Trajectory motion: From his *Two New Sciences*

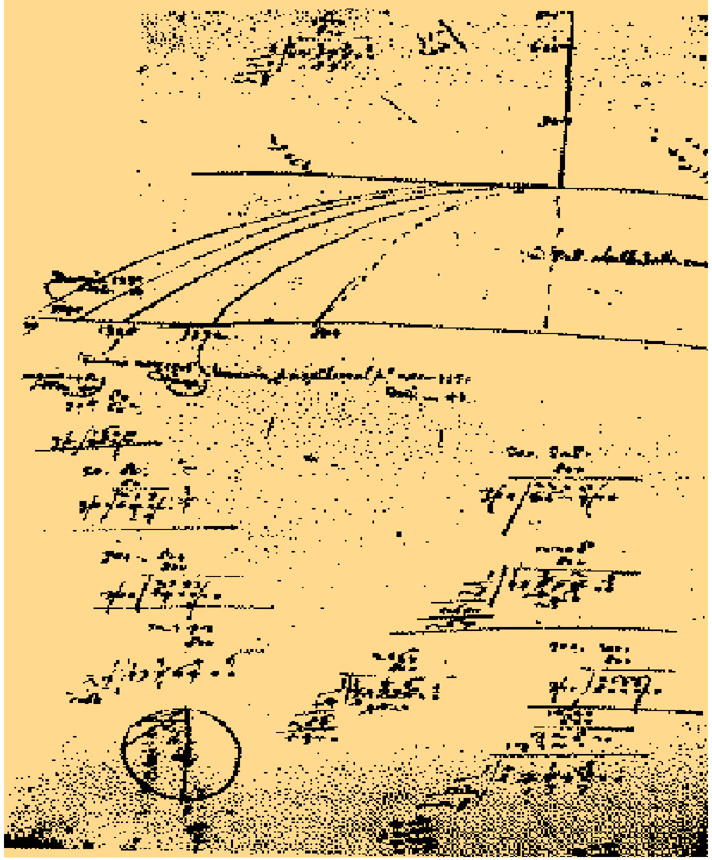
It has been observed that missiles and projectiles describe a curved path of some sort, however no one has pointed out the fact that this path is a parabola.



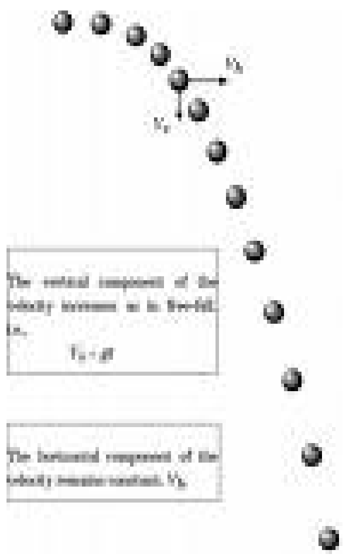
Projectile motion…

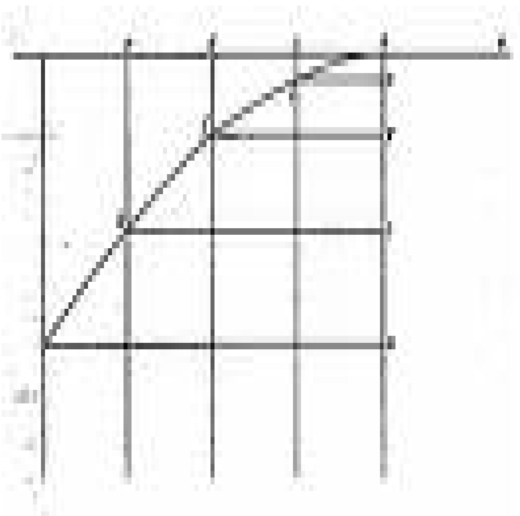


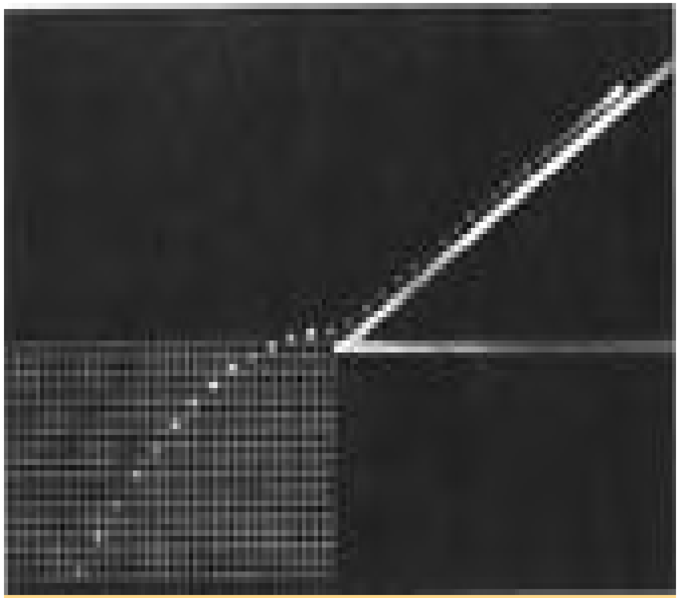


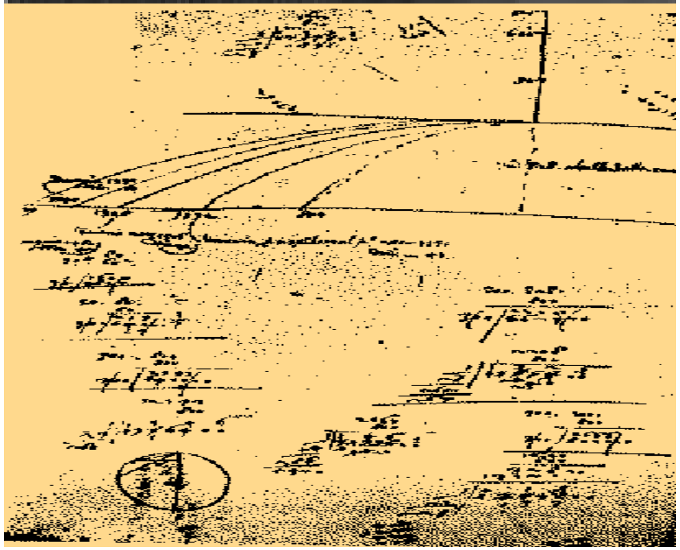


Projectile motion…





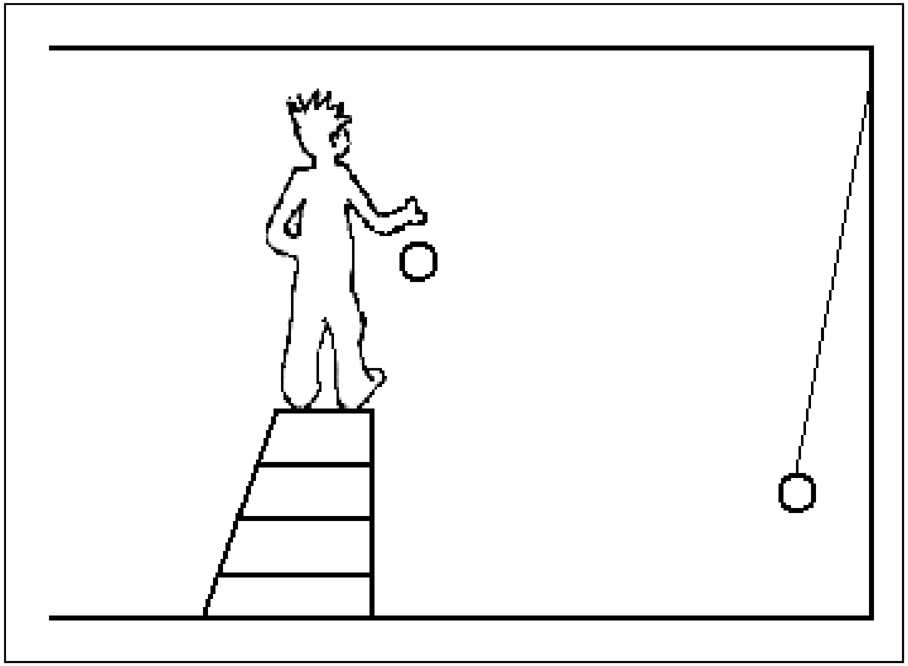


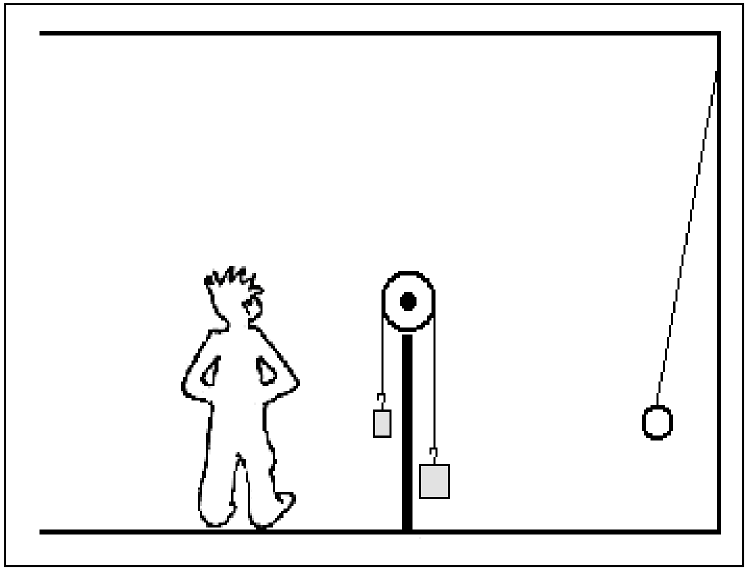


Projectile motion on the internet

- http://galileoandeinstein.physics.virginia.edu/more_stuff/Applets/ProjectileMotion/enapplet.html
- http://www.ngsir.netfirms.com/englishhtm/ThrowABall.htm

Galileo also used a pendulum to calculate the acceleration due to gravity <u>directly</u>





A discrepant event

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.