Conversations with great physicists about motion
(First Draft)

A Conversation with Aristotle

Imagine that you could go back in time and have a conversation with great physicists. Our first scientist is Aristotle. We are in Greece, in the fourth century, BC.

Aristotle appears. He walks back and fourth in deep thought. The student approaches him.

Aristotle:
Greetings my young friend. In anticipation of your visit I have been thinking about motion around us. The motion of a leaf falling, a javelin being thrown, the motion of a cart, etc…Motion in general is an inexhaustibly deep subject. I understand that you wish to discuss motion with me.

Student:
Yes, I do. It is bewildering, I know. But you have clearly categorized motion. Especially, you have separated the laws of motion in the heavens and those that govern motion on Earth, *terrestrial* motion and *celestial* motion.

Aristotle:
Yes. But let us only talk about motion on Earth only.
Aristotle takes a stone and a feather. He looks at the student and then asks:

Which of these will fall to the ground first, the stone or the feather?

Student:
I think the stone will fall faster… .

Aristotle:
Alright.
He drops the stone and the feather. As expected, the stone reaches the ground first. The student then takes a small piece of wood. He looks at Aristotle and says:

Student:
I have here a small piece of light wood. The stone is clearly many times heavier than the wood. Do you agree?
He gives these to Aristotle. Aristotle smiles and hands them back to the student. The student drops these and they seem to fall to the ground at the same time.

This simple demonstration suggests that all heavy objects fall at the same rate, don't you think?

Aristotle:
I am not convinced about that. I think if we went to a high tower and dropped these objects, then the stone would hit the ground first.

Student:
That may be so. However, you cannot say that if we had two objects, say two spheres made of different metals, but of the same size, and one twice as heavy as the other, the heavier one would fall twice as fast.

Aristotle:
Well, maybe not. But I have observed heavier than water objects fall through water."
He picks up two metallic spheres.

Let's place these in the water and allow them to fall.
He walks over to a glass container and lets the spheres fall through the water.

Now observe them as they fall through the water.

Student:
It looks like the heavier falls much faster.

Aristotle:
You see. Clearly, heavier objects fall faster in water.

Student:
Very impressive. But then, imagine an object falling toward the earth if there were no air. Don't you think that then a feather and a stone would reach the ground at the same time?

Aristotle:
No! That is impossible!

Student:
But why?

Aristotle:
Because if there were no air, we would have a vacuum above the earth. And…, I believe that vacuum cannot exist!

Student:
Aristotle, why do you believe a vacuum cannot exist?

Aristotle:
Because then any small force could make an object move at an infinite speed. And to have motion we need a force. Therefore, vacuum is impossible.

Student:
Yes, I can see that. But his is only true if we say ‘the greater the push force the greater the speed and also “the less the resistance force the greater the speed for a given push force.

Aristotle:
Exactly. The question then is: ‘What is the cause of motion of a freely falling object or a projectile like a javelin after it is thrown?’.

Student:
According to your physics, first, ‘for an object to move you need a force’ and secondly, there are two kinds of forces, *natural* and *violent*. A natural force is the force that pulls objects toward the center of the earth and a violent force is a force like the one that propels a javelin.

Aritotle:
Very good. So, a freely falling object needs no explanation but the motion of a javelin does.

Student:
Where does the motive force for the javelin come from.?

Aristotle:
Again we have to invoke the principle that vacuum cannot exist. As the javelin moves through the air, the air behind the javelin rushes in to fill the momentary vacuum produced. This action of the air provides the pushing force.

Student:
But, surely, there must be an air resistance that opposes this force, Aristotle.

Aristotle:
Yes. But the push force of the air rushing in is greater.

Student:
I would be interested to know what how you would explain this motion.
The student produces a pendulum and shows Aristotle how the attached mass moves back and forth.

Aristotle
He studies the motion and then smiles:

This is a very interesting motion. It seems to be a combination of free fall and constrained motion. Therefore I would say that it is partly natural and partly violent motion.”

Student:
Thank you very much, Aristotle. This was very illuminating.

Aristotle:

You are welcome. You must come and join us in my Academy. Perhaps you can continue to study of the motion of a , what did you…, the pendulum.

Student:

Thank you, I will do so very soon. Good bye.

A Conversation with Oresme.

Our student meets Oresme in his room at La Saint Chapelle, in 1363, where he was elevated to the post of dean of the Cathedral of Rouen.

Oresme:
I am looking forward to our discussion, young man. I understand that you have studied the physics of Aristotle.

Student:
Master Oresme, thank you for agreeing to have this discussion with me. Yes, I have studied the physics of Aristotle, especially his ideas of motion.

Oresme:
Wonderful. He was a great thinker in every field of study, especially in logic and biology. He smiles. But in physics, many of ideas were questionable. Especially those that had to do with motion.

Student:
Yes. I, too, was a little puzzled when Aristotle explains motion by way of his ideas of violent and natural motion. For example, his explanation of the cause of motion of a projectile is in my opinion, doubtful.

Oresme:
Actually, Aristotle's ideas about motion were first challenged about eight hundred years ago by John Philoponous (of?...) He rejected the Aristotelian law that the speed of an object depends directly on the force and inversely on the resistance. Specifically, he argued that speed is proportional to the force minus the resistance force.

Student:
That of course neatly sidesteps the problem of the vacuum.

Oresme:
Yes, indeed. I agree with Philoposus. That means, of course, that motion in a void (vacuum) where there is no resistance, is possible.

Student:
But we still have the problem of the "cause of motion".

Oresme:
Philoposus went further and argued that it is not the air that provides the motive power to propel a projectile like a javelin, but an impressed force that he called impetus. The impetus, however, dies out.

Student:
Is there any text available that was written by Philoposus?

Oresme:

Yes, indeed.
He picks up a heavy book and looks for a passage.
Here we are.
The concluding words in his *Commentary on Aristotle's Physics* . sums it up well:

From these considerations and from many others we may see how impossible it is for forced motion to be caused in the way indicated. Rather is it necessary to assume that some incorporeal motive force is imparted by the projector to the projectile, and that the air set in motion contributes either nothing at all or else very little to this motion of the projectile. If, then, forced motion is produced as I have suggested, it is quite evident that if one imparts motion "contrary to nature" or forced motion to an arrow or a stone the same degree of motion will be produced much more readily in a void than in a plenum. And there will be no need of any agency external to the projector. . . .

Student:
He was certainly ahead of his time.

Oresme:
I agree. But my teacher, John Buridan, developed the impetus theory of Philiposus even further. He thought that an impressed force on a projectile was permanent unless acted on by resistances or other forces. I have been developing Buridan's ideas a little further. I believe that it is not possible to detect uniform straight-line motion.

Student:
Actually, that makes sense to me. When you are on a ship on a calm day, you are not aware of motion.

Oresme"
Exactly. This is why I believe that it may be the earth that is rotating and not the sun. But I have had problems with that idea because it against the teachings of the Church. Remember, I am a Bishop in the Catholic Church.
He hesitates and then continues

Here is an interesting idea, my young friend. Imagine a tunnel through the earth. Let me show you.
He draws a sketch in the sand

Now imagine a heavy object being dropped into the tunnel. Also imagine that there is no resistance offered to the motion. What kind of motion would you expect?

Student:
Let me think. If we assumed the earth as a perfect sphere, that is, the material distribution were the same throughout, the object should arrive at the other end and stop. Then the

motion should repeat itself. Why, the object would move like a pendulum.

Oresme:
Very good. Actually, this idea is not original with me.
Oresme opens a book and shows the student a passage.

My colleague Albert of Saxony discussed this idea first. Let me show you the text.

If the earth were completely perforated, and through that hole a heavy body were descending quite rapidly toward the center, then when the center of gravity (medium gravitatis) of the descending body was at the center of the world, that body would be moved on still further [beyond the center] in the other direction, i.e., toward the heavens, because of the impetus in it not yet corrupted. And, in so ascending, when the impetus would be spent, it would conversely descend. And in such a descent, it would again acquire unto itself a certain small impetus by which it would be moved again beyond the center. When this impetus was spent, it would descend again. And so it would be moved, oscillating (titubando) about the center until there no longer would be any such impetus in it, and then it would come to rest.

Student:
Wonderful. So now we have a better explanation of the motion of the pendulum than the one Aristotle gave us.

Oresme::
Indeed. The motion of the imaginary object falling through a tunnel then can be demonstrated by the motion of a pendulum.

Student:
But we still cannot make predictions about the time of oscillation involved for a given pendulum. For example, how many swings would a pendulum of length of 100 cubits make in given a time?

Oresme:
Maybe you will be able to do that when you become a natural philosopher.
I must go now. I hear the bells calling for vespers. Good bye.

A Conversation with Galileo

Our time traveler finds himself in Galileo’s laboratory in the year 1610. He looks around as Galileo suddenly appears. There is an inclined plane, pendula and many instruments on the table. One can see a water clock and a guitar. At the very front of the table there is a small telescope. Galileo is writing. He looks up.

Galileo:
Welcome to my laboratory, young man. I have just completed my manuscript *The Starry Messenger*, in which I describe the motion of the moons of Jupiter. A very revolutionary astronomical discovery. However, in your letter you said you are interested in the physics of terrestrial motion.

Student:
Well, if you have time we could also discuss your work on the motion in the heavens.

Galileo:
Well, we will see.
I am just working on an interesting problem.
He shows the student a pendulum, points to a very long inclined plane and a water clock.

I have shown that if a metallic sphere rolls down an inclined plane like this
He demonstrates the motion.

The distance covered is proportional to the square of the elapsed time.
So that if the sphere travels one cubit in one second, it will travel four cubits in two seconds, nine cubits in three seconds, etc.

Student:
How do you measure the elapsed time, Signor Galileo?

Galileo:
I have used my pulse at the beginning, but I found that a water clock gives the best result.
He points to a large cylinder

Student:
I see. So volume of water is equated with time.

Galileo:
Yes. ---

Student:
Did you just go ahead and measure distance traveled against time elapsed to arrive at this result?

Galileo:
Well, I could have done it that way. But that result would not have told me how speed and time are related. Can you see that?

Student:
I think so. But how many different ways could a ball roll as far as the relationship between time and speed is concerned?

Galileo:
At least three different ways. I called these my hypotheses about free fall.
Galileo stops for a moment and then continues.

Student:
But you are not measuring the free fall directly.

Galileo:
You see, I argued that I cannot measure the time elapsed in free fall directly, because of the small time interval involved….
He looks at the student..

Student:
Yes, I can see that. And then you extrapolate it to 90 degree vertical for free fall. Very Imaginative.

Galileo:
Thank you. However, I could measure the elapsed time for a freely moving sphere along an inclined plane. I then argued that free fall motion was the same as the motion along the inclined plane. I simply "diluted gravity", as it were.
They both laugh.

Student:
Very clever, Signor!

Galileo:
Thank you. ---To come back to our problem. Try to guess these three hypotheses of motion, young man.

Student:
Let's see. We could guess that the speed of a freely falling object varies according to the distance covered'.

Galileo:
Good. Unfortunately, this hypothesis leads to an absurdity. If you insisted, I could prove this . But let's ignore this one.

Student:
Thank you. The other hypothesis could be that motion is such that the speed varies according to time.

Galileo:
Very good. There is a third one but it turns out that it is really equivalent to this one.
He stops for a moment.

It is quite easy to show that if the speed varies as the time elapsed then the distance must vary as the square of the elapsed time.
Student:
I wish Aristotle and Oresme were here to hear this.

Galileo:
Well, Oresme would be impressed but I do not think Aristotle would be. I do not think he would have been interested in a quantitative measurement of motion.
Galileo walks over to the table and picks up an orange and grape.

But this may have baffled Aristotle.
He holds the orange about two cubits above the table and then drops then at the same time.

So, how would have Aristotle reacted to this simple demonstration, my young friend?

Student;
I don't know. He would probably have said that if you went to the top of a tall building and dropped these the orange would arrive first.

Galileo:
Well, we won't do that, even though the Leaning Tower is close by.---But let us return to the pendulum.
He makes the pendulum oscillate and looks at this motion, lost in deep thought.

As a young man, sitting in a cathedral during mass my thoughts drifted to other things. I noticed that identical chandeliers in a church swing with the same period, no matter what the amplitude is.
He explains the idea of a period, an amplitude and demonstrates it.

I also noticed that the mass of the chandelier doe not affect the period. I was convinced then and there that neither mass nor amplitude affected the period.
He smiles and then continues.

Of course, I used my pulse as a timing device.

Student:
That is very curious and unexpected. Actually, the discovery that mass makes no difference follows from the fact that all heavy masses fall at the same rate. But that the amplitude does not effect the period I find astonishing.

Galileo:
Yes, so did I. Next I wanted to find out how one can calculate the period of a pendulum on the basis of the length alone.

Student:
I would have guessed that if you doubled the length, the period would also double. But that must be wrong.

Galileo:
Yes, it is. ---I first argued using geometry and free fall-motion that the time it takes for a sphere to roll down any inclined plane that connects from the base point of a circle is the same as it would take a freely falling object to fall the distance equal to the diameter of the circle.
Galileo goes to the blackboard draws the appropriate diagram and explains.

Student:
This, too, is not obvious, Signor Galileo. But how is this connected to the period of the pendulum?

Galileo:
Well, it suggests that the period of the pendulum is proportional to the square root of the length. We can easily show this.
Galileo counts the time it takes for ten swings for a certain length. Then he doubles the length of the pendulum and repeats the experiment.
Galileo looks at the student

What length do we need to double the period?

Student:
That is easy. Four times the original length!

Galileo:
Bravo!

Student:
Thank you. Finally, I would like to have your opinion on something that Oresme suggested. Almost three hundred years ago he said:

A body falling through a well that has been drilled from one side of the earth, through the center, to the other end, would oscillate like a pendulum and eventually come to a stop at the center.

Galileo:
Yes. I, too, discussed this idea in my book
He brings a book and opens it.

> *… From this it seems possible to me... to believe that if the terrestrial globe were perforated through the center, a cannon ball descending through the hole would have acquired at the center such an impetus from its speed that it would pass beyond the center and be driven upward through as much space as it had fallen, its velocity beyond the center always diminishing with losses equal to the increments acquired in the descent; and I believe that the time consumed in this second ascending motion would be equal to its time of descent.*

Student:
Very interesting, Signor Galileo. This is very similar to the statement made by Albert of Saxony and then later endorsed by Oresme, almost three hundred years ago. Were you aware of these?

Galileo:
I really cannot remember. I probably was.

Student:
When you compare your statement with the one written by Albert of Saxony, you don't seem to mention the idea of impetus.

Galileo:
I have been thinking about the "cause of motion" rather than the description of motion. Therefore, I tried to understand how "impetus" could be quantified and measured. For example, I have done experiments with heavy objects falling into soft soil. I have found that if you double the speed of impact you will get four times the penetration effect. I called this quantity *velocitas,* which should not be confused with the velocity.

Student:
So you think that impetus has to do with a quantity you call *velocitas*, that is measured by the square of the velocity?

Galileo:
Yes. Clearly the force applied to an object accelerates that object. In this manner the force of gravity acting on a mass accelerates that object with an acceleration of free fall. What is mysterious is the fact that the acceleration is always the same for all heavy objects.

Student:
I see. Let me clearly understand what you are saying, Signor Galileo.
The student moves to one of the tables and lifts up a toy cart, places it back onto the surface and pulls on the string attached to it.

If I pull a small cart with a given force, it will accelerate at a certain rate and if I doubled that force it would accelerate twice as much. So that if I applied the force for one second in both cases the cart would reach a velocity of twice this value for force which was doubled.

Galileo:
Very good. ----But now compare the distances moved and the velocities reached by the cart for the two cases.

Student:
Well, according to your formula that distance traveled for a constantly accelerating object is proportional to the square of the velocity. Therefore, the distance traveled for the second case is four times as much.

Galileo:
Exactly! So it seems that there is a quantity associated with the square of the velocity and the distance through which an object moves while a force is acting on it that will be important in the new dynamics. But I will leave this development to younger men, like yourself.

Student:
Thank you, Sir

Galileo:
Galileo walks back to the pendulum and slowly pulls the sphere away from its rest position.

Let's go back to the problem of an object falling through the Earth. You can feel that the force I require to pull the pendulum increases as I pull. That means that the acceleration itself must change.
The student tests this and nods.

Galileo:
Now things become interesting. We have a change of a change, that is, a change of acceleration is a change of a change of velocity.
He stops and thinks.

Student:
But how do we know that the change of acceleration is a uniform change?

Galileo:
Exactly! Even though I know that the period is proportional to the square root of the length of the pendulum, I do not know the exact motion of the mass as it moves.

Student:
But you know that the maximum velocity of a swinging pendulum will be at the lowest point.

Galileo:
Yes. And you also know that the oscillation will eventually stop. Again, it will be a future physicist that understands the dynamics of motion better than I who will be able to describe the motion exactly.

Student:
Maybe we can conclude by comparing the motion of a heavy object falling through the earth with the motion of a pendulum.

Galileo:
Good. We could argue that, as the object falls through the tunnel the force of gravity diminishes in the same way the force acting on a pendulum does.

Student:
I can see that. An obvious question would be: What length of a pendulum would produce a period equal to that of our object falling through the earth?

Galileo:
An interesting question. Let me see. Maybe the answer is that the length should be equal to that of the radius of the earth?

Student:
Using your formula we could figure that out by comparing to standard length that gives us a period of one second.

Galileo:
Yes. Well, I will let you work that out.
He hesitates and then continues.

But, young man, I would like to show you something that is not obvious.
He walks to the pendulum and pulls it out to a large amplitude.

Remember when we showed earlier that a ball will roll down any inclined plane
that connects the center of a large circle and a point on the circle in equal times?

Student:
Yes, I do. A very surprising result.

Galileo:
Well, I can show you something even more surprising. Imagine an inclined plane here, just as in our sketch earlier.
He points to the earlier sketch.

Now if I release the pendulum and the ball on the inclined plane at the same time, which one will arrive at the bottom first?

Student:
Well, common sense would tell me that the ball on the inclined plane will arrive first.
He hesitates and then continues.

But since you said it was surprising this must be wrong.
They both laugh.

Galileo:
Let's see. Come and help me with this so that we have the balls beginning to roll at the same time.
The student assists Galileo and the balls are released at the same time.

Student:
Amazing. But we can actually compare the times of descent to predict this.

Galileo:
Yes. I will leave this with you as home work. I must go now. I have an audience with one of the cardinals. He wants to look through my new telescope.

Student:
Do you think he will have the courage to look through your telescope?

Galileo:
We will see.

A Conversation with Christian Huygens:

Our student finds himself in the laboratory of the Dutch physicist and mathematician Christian Huygens, sometime in 1687. Newton's *Principia* was just published, but we assume that Huygens has not had time to study it.

The most important of Christian Huygens' written works was his *Horologium Oscillatorium* published in Paris in 1673. It discussed the mathematics surrounding pendulum motion and the law of centrifugal force for uniform circular motion.

The most obvious things noticed are a small billiard table, clocks, springs and several pendula. Huygens welcomes him.

Huygens:
Welcome, my young friend. What shall we talk about?

Student:
Thank you, Dr. Huygens.
The student looks around and smiles.

Do you play billiards?

Huygens:
Sometimes. But the reason for the billiard table in my laboratory is for experimenting with collision. I believe that we can test our ideas about dynamics best by studying the physics of impact and collision between billiard balls.

Student:
Later perhaps I want to know about these experiments. But now I am interested in finding out about your experiments and theory of the motion of the pendulum. I especially want to know what you have added to the findings of the great Galileo.

Huygens:
All right. Of course, Galileo has shown us many properties of this wonderful phenomenon we call oscillatory motion. But I have found new ones as well as shown that Galileo was wrong in some instances.

Student:
I have always thought that Galileo's insistence that the period of the pendulum is independent of amplitude must be wrong. Even in his time, the mathematician Mersenne claimed that he had experimental evidence to believe that the period changes significantly for angles over 20 degrees.

Huygens:
I can easily show you that Galileo was wrong.
He has a long pendulum oscillate for 10 swings using an amplitude of about 10 degrees. Then he increases the amplitude to about 30 degrees. The times are significantly different.

Student:
Very convincing. Surely, Galileo must have checked this.

Huygens:
Of course he did. But he believed so strongly in the isochronous property of the pendulum that he probably explained away the difference by suggesting that frictional effects contributed to the difference.

Student:
That makes sense.

Huygens:
It is interesting that Galileo also rejected Kepler's work in astronomy. He always

believed that the motion of planets must be circular, despite strong evidence for the motion of Mars to be elliptical.
He stops for a moment

But let's continue. As we have already mentioned, Galileo believed that the motion along an arc of a circle is isochronous. But I have shown that it is the cycloid that guarantees isochronous motion. Let me show you.
Huygens shows a pendulum whose motion is guided along a cycloid. Makes the pendulum oscillate. He measures the time take for 10 swings for different amplitudes

Student:
Very convincing. Could you then use this principle to make clocks that are more accurate? Sailors could use a good clock that keeps accurate time over long period to establish the longitude of their position.

Huygens:
Yes, indeed. Latitude is easily measured by simply finding the angle to Polaris but to measure longitude requires a complicated astronomical observation, using the Moon or the moons of Jupiter.

Student:
Yes. I have studied this a little. I believe that if you had a reliable clock that is accurate to a few seconds a day you could then find your latitude, to a good approximation, degrees measured East or West of Greenwich I believe, by observing the time of passage of the midday sun.

Huygens:
Very good. But we still cannot do this. I have built a marine clock as early as twenty years ago. But it did not survive rough seas. I am personally convinced that it will not be a pendulum driven clock to accomplish this but a mechanical-spring driven clock. I had some success with such a device that I built over 20 years ago. But I do not think this will happen in my lifetime.

Let us continue with the pendulum. I have studied the conical pendulum and using my formula for centrifugal force been able to find a formula for the period of the pendulum. that is superior to the one that Galileo found.

Student:
Galileo showed that the period of the pendulum is proportional to the square root of the length.

Huygens:
Yes. But he was not able show that the strength of gravity varies on the surface of the Earth. In my formula. The gravity is part of the expression. That means that I am able to find the acceleration due to gravity for various places on Earth.

Student:
Can you show me please?

Huygens:
I would be glad to explain it and show you with a simple demonstration.
He goes to the table and picks up a pendulum. He rotates the ball in a circle.

I can show that the rotation period for a small angle is the same as the period of oscillation of a pendulum with a length equal to the vertical distance.
He draws a picture on the black board and explains and derives the formula for the pendulum.

Using the expression $\mathbf{T = 2\pi\sqrt{(l/g)}}$ I can now find the value of gravity in terms of free fall.
He stops for a moment band then continues.

But that is not how we compared the gravity of various locations on Earth.
We determined the strength of gravity by finding the length of a one-second pendulum for a given location.

Student:
But how do you determine the value of this length for various places.? You must have standard against which you measure.

Huygens:
Yes, Indeed. In 1672 the astronomer Richer found that the length of the seconds pendulum that was calibrated in Paris was shorter on the equator than in Paris, as measured in Cayenne, South America. The values found were about 3/100 different.

Student:
This difference must be due to the centrifugal force produced by the rotation of the Earth.

Huygens:
Yes, exactly.
But you must remember that an ordinary simple pendulum like this one is not good enough to detect the difference for the value of g for various locations.
He walks to his table and picks up an apparatus that looks complex but resembles a modified pendulum.

This is a compound pendulum where the center of mass can be mechanically adjusted. This pendulum can be seen as a research instrument to determine the value of gravity with a high accuracy and precision.

Student:
What are you working on right now, Mr. Huygens?

Huygens:
Well. First of all, I must look at Isaac Newton's *Philosphiae Naturalis Principia Mathematica,* which has just been published. It is written in Latin so that all scholars can read it. I am sure this work will occupy me for some time.
He smiles and then continues
Perhaps you can back in a few months to discuss the *Principia,*

Student:
Yes, that would be nice.

A Conversation with Sir Isaac Newton

Our student finds himself in Newton's Laboratory. There are instruments, chemical apparatus (alchemical), a globe, several large prisms, as mall reflecting telescope and pendula. Newton is working on a manuscript, he is indicating with his hand that the student sit down. It is summer time in the year 1712. Newton has been Master of the Mint since 1699, was elected president of the Royal Society, after the death of Robert Hooke. The Royal Society commission , under Newton's direction, investigates the competing claims of Leibniz and Newton to having developed the calculus. The commission decides in favor of Newton.

Newton:
Sit down please. Ordinarily I do not give interviews. They are a waste of time for me. But you come highly recommended as someone who has studied the history of natural science deeply, especially the physics of motion.
Well, we will see.
He gets up and moves to a chair close to his guest.. He points to his desk.

Young man, do you recognize the items on my desk?

Student:
Yes, I do, Sir Isaac. I recognize the prisms, the telescope, the globe, and especially the pendula. I have studied your Optiks and have tried to work my way through the less intimidating parts of your *Principia*.
Newton nods with approval.

I know that you constructed a reflecting telescope as a young man after your studies of optical phenomena. You argued that refracting telescopes were subject to color interference and therefore argued that they were outdated. I also recognize some containers that suggest that you are doing chemical experiments.

Newton:
Very good. But why are you especially interested in pendula?

Student:
Well, I have been following the use of pendula in understanding motion. Aristotle was puzzled by the motion of a pendulum, Oresme used pendula to illustrate motion, Galileo found them very useful in his studies of free fall and used them as a timing device. Recently Huygens investigated the motion of pendula in his *Horologium Oscillatorium.* I believe that pendula were very important in your work in discovering the laws of motion.

Newton:
Yes, indeed. Well, I am impressed by your general knowledge of natural philosophy. Let me see.
He gets up and paces around, stopping to pick up a pendulum.
Student:
It is puzzling to me that you were able, by yourself, to find the underlying laws of motion.

Newton:
The laws of motion did not come from divine revelation.
They both laugh.

Many people seem to believe that they were self-evident to me, or came full-blown to the mind of the great Newton, shortly after an apple fell on his head.
Again, Newton laughs.

To come back to your original question. I think I have been able to do much because I keep the subject constantly before me and wait until the first dawnings open slowly, little by little, into full and clear light.
He looks reflective and then continues.

But let us go back to pendula. I have used pendula extensively for the confirmation of my laws of motion. Let's start with the first law. Perhaps you can state this law.

Student:
Yes., I can. I memorized your laws straight from the *Principia*. But, of course, that does not mean I understand them.
Newton smiles and nods.

Why don't I state all three of them?

Newton:
All right then. You can state them first and then we can discuss them.

Student:
The first law states that
An object at rest or traveling in uniform motion will remain at rest or traveling in uniform motion unless acted upon by a net force.

The second law says that:
The rate of change of momentum of a body is equal to the resultant force acting on the body and is in the same direction.

The third law makes a very general statement:
For every action there is an equal and opposite reaction.

Newton:
Good. But as you said just because you can recite them does not mean that you have a good understanding of them.
Let us look at them one by one.

The first law is really just a statement of Galileo's law of inertia. Galileo stated this law and his mental picture was an object moving on a perfectly frictionless surface of the Earth. So he saw the motion that can be thought of as 'the unimpeded circumnavigation of the Earth'.

Student:
Yes. I can see that.

Newton:
But my mental picture is this: "motion in deep space where gravity is negligibly low. That is 'unimpeded constant speed in a straight line in deep space'.

Student:
How can this law be confirmed?

Newton:
Well, it really can't be experimentally confirmed. One can only make a mental picture of it. You could call this a "thought experiment".

Now the second law can be illustrated by analyzing the motion of a pendulum.
He goes to a long pendulum and attaches a spring to the hook that is seen in the large wooden sphere. Newton pulls the sphere a little to a certain small displacement and then pulls it to about twice the original displacement.

My friend Robert Hooke showed (before the *Principia* was written) that when a spring is pulled, the extension of the spring is proportional to the force applied. This law applies here.

Student:
I see. A pendulum oscillates like a spring.

Newton:
Exactly.
He demonstrates this with a pendulum and a spring oscillating with the same period.

Now I can use the second law and show that the period of a pendulum is given by the very formula that Huygens derived about thirty years ago. He did this by analyzing the motion of a conical pendulum and using the formula for centrifugal acceleration that he found.
Newton stops for a few seconds.

You should notice that Huygens did not use dynamical laws, he only used kinematics.
Newtons suddenly seems to remember.

Actually when he derived his expression for centrifugal acceleration he did mention the idea of force.

Student:
But does Hooke's law apply for all displacements?

Newton:
Unfortunately, no. You can easily show that after about 10 degrees of displacement from the vertical we will have problems. In fact, as Huygens showed, the period of a pendulum becomes larger as you increase the amplitude. You would find that the period of a pendulum for a displacement of 90 degrees is about 17/100 longer than the period for small displacements..

Student:
Clearly this is why Huygens had to find the curvature of motion that produced a tautochronous motion, that is motion such that the time of oscillation is constant for all displacements. He showed that a cycloid was that curve.

Newton:
Exactly. Galileo believed that along the arc of a circle a sphere would roll down to the lowest point in the shortest time and that it also provided the curve for a tautochronous motion.

Student:
So he was wrong on both counts.

Newton:
Yes. And it is interesting that Huygens did not realize that the cycloid is also the curve along which a ball descent in the shortest time.

Student:
This gives me a chance to ask you about the challenge that the famous Swiss mathematician Johann Bernoulli sent to all the leading mathematicians of Europe, 1697, I believe.

Newton:

Oh, yes. The challenge was, something like:

Given two points A and B in a vertical plane, what is the curve traced out by a point acted on only by gravity, which starts at A and reaches B in the shortest time.

I remember (I think it was in 1696). I cam home from the Mint, in the midst of the hurry of the great recoinage, did not come home till four in the afternoon from the Tower very much tired, but did not sleep till I had solved it, which was by four in the morning.

Student:
That is an incredible story of the power of concentration on a difficult problem, Sir Isaac.

Newton:
Well, you know, I do not love to be pestered and teased by foreigners about mathematical things ...

Student:
I have heard the story that when Johann Bernoulli looked at your proof, after it had been published anonymously, he said: " I recognize the lion by his print".
Newton smiles.

Student:
Your solution of the problem was based on geometric reasoning only, whereas Leibniz, and the Bernoullis solved it by the analytical method using algebra and the Calculus.

Newton:
Well, you know algebra is for bunglers.
He smiles and then continues.

But in a more serious vein, the challenge of the problem implied that it could only be solved by those who knew the secrets of Leibnizian calculus. I wanted to show them that geometry is still king in computing such things.

But, my young friend, we have strayed from the discussion of the three laws of motion.

Student:
Yes. Well, the third law seems to be the most general. The simplest form of the law is:

> *For every action there is an equal and opposite reaction.*

Newton:

I think this is the law that most people seem to intuitively understand,--at least most can state it.

Student:
But it is not clear how to interpret it when considering dynamics. How do you understand this law?
For example, when I push against a cart the force the cart “feels” is the same force that I feel, except that it is in the opposite direction.

Newton:
Good. This is so no matter how you move the cart. Now if you look in the *Principia,* volume 1, you will find a sketch of colliding pendula.
He picks up two very long wooden pendula, one about twice as large as the other.

I experimented with the collision of these two pendula. What I found was that the motion before collision, as measured by the quantity of mass times velocity was the same as it was after collision. In other words the quantity mass times velocity is indestructible, as it were.

Student:
This result is certainly not obviously contained in the general statement of the law.

Sir Isaac, could you briefly summarize the role pendula played in establishing these three laws of motion?

Newton:
Good. Very few people understand that I struggled to establish force as a unifying concept. As a young man I believed in the impetus theory of Oresme. I also believed in the idea of transfer, the idea that one body may give up some of its force to another during impact.

Student.:
I also believed these things before I studied the *Principia*, Seems like I am in good company.

Newton:
Yes, you are.
Eventually I understood the idea of inertial mass and now it was possible for me to think of motion without force. I first investigated the idea of force as far Galileo’s law of free fall is concerned.
He says emphatically:

But the notion of force had to be reconciled with how it was used in two other senses.
He looks at the student and asks:

Can you think of these two other senses of force in dynamics?

Student:
Well, I suppose the force between two colliding wooden balls would be another sense of force.

Newton:
Very good. And the third?

Student:
I can't think of it.

Newton:
Let me give you a hint.
He walks to the table and pick up one of the pendula. He then makes the wooden ball circle.

Student:
Of course, centrifugal force!

Newton:
I had great difficulty in getting rid of the idea of centrifugal (center-fleeing) force in describing the force on a body in circular motion. It was difficult for me liberate myself from this idea, believed by Descartes as well as Huygens. Finally, I understood that the force in the case of a conical pendulum must be understood as a center-seeking or centripetal force.

Student:
I see. So when we consider the revolution of the moon around the earth, what produces this centripetal force is the gravity between the two bodies.

Newton:
Exactly. And remember, the gravitational force of the Moon on the Earth is the same force as the gravitational force of the Earth on the Moon, but in opposite directions.

Student:
Yes. Could you summarize these forces?

Newton:
Yes. For linear motion we have force in terms of rate of change of momentum given my $\mathbf{m\Delta v / \Delta t}$, as demonstrated by the oscillation of a pendulum; for collision we have the quantity $\mathbf{m\Delta v}$, as demonstrated by the collision of two pendula, and for centripetal acceleration we have the quantity $\mathbf{m\,v^2 / r}$, as demonstrated by the conical pendulum.

Student:
Thank you, Sir Isaac. I have learned a lot today.

But I have a last question.

Newton:
Please. There is some time left, before I have to go to the Mint.

Student:
Keeping with the ubiquitous pendulum, I remember that Nicole Oresme in the fourteenth century suggested that if we could dig a tunnel through the earth an object falling through this tunnel would oscillate like a pendulum. Later, Galileo investigated this, what we may call a mental experiment. It seems to me we could use your laws of motion to investigate this problem.

Newton:
Actually I have thought about this problem some time ago.
He goes to the blackboard and makes a sketch of the Earth, a tunnel through it and a mass falling through it. He also draws a picture of a mountain with a cannon.

You see, the force on the mass falling through the Earth decreases linearly because it is governed by Hooke's law. Do you know why this is so?

Student:
I think so. In the *Principi*a you showed that if you descended into the Earth with a constant density the gravitational effect on the descending mass would be due only to the mass of the Earth underneath it.

Newton:
Very good. That condition guarantees that the gravitational force acting on the descending mass is linear.

Student:
I see, Therefore the motion must be an oscillation like that of a mass on a pendulum.

Newton:
But there is more. The period of a cannon ball being shot out from a cannon high above the Earth (I am assuming no friction due to the atmosphere) will be the same. What is more, an imaginary pendulum that has a length of the radius of the Earth would also have the same mass.

Student:
Incredible, Sir Isaac.
But I have a final question: What would be the period of an object falling through a tunnel that connects any two points on the surface of the Earth?

Newton:
That would be a good question for you to answer. I think I know the answer.
But I must go now to the Mint. See you in a few days.

A Conversation with Leon Foucault

We are in the laboratory of the French physicist and engineer Loen Foucault.It is a summer day in 1851. Just a few months ago in the spring Parisians flocked to Foucault's 67 m long pendulum in the dome of the Pantheon. The pendulum swung for about six hours and the swing plane had veered, as expected, about 70 degrees clockwise, showing that the Earth was revolving counterclockwise. The experiment caused a sensation and Foucault became an instant international Celebrity.

His lab is cluttered with instruments of all kind. We see his famous rotating mirror that he used to show that the speed of light is lower in water than in air. A large lathe is in the middle of the table and beside it we see what looks like a copper sphere. At the edge of the able we see mount with a gyroscope. There is a small reflecting telescope that Dr. Foucault built in preparation for the large reflecting mirror telescope he built for the astronomer Le Verier who used it for the discovery of Neptune.
Dr. Foucault is seen adjusting the gyroscope. He looks up and points to a chair for his guest to sit down.

Foucault:
Please sit down, young man. I am just making a final adjustment on this instrument. I will be right with you.
His guest looks around with fascination. Foucault leaves the table, comes over to his guest and shakes his hand.

Student:
Thank you, Dr. Foucault, for allowing me into your lab. I realize that you have done important work in photography as well as in physics. I have just read your publication about how you and the physicist Fizeau have experimentally confirmed that the speed of light is lower in water than in air.
The argument

Foucault;
Thank you. That was a nice experiment. But do not believe that all physicists now believe that light is a wave phenomenon. It will take some time. Newton's dominating authority (as you know he defended the particle theory of light) is still with us.

Student:
Yes. I am acquainted with the dispute between Newton, defending his particle theory of light, and Hooke and Huygens who argued for the wave theory.

Foucault:

Well, as far as Fizeau and I are concerned, this was the crucial experiment that should settle The great physicist Arago, whose idea the experiment actually was, also believes that we have established the nature of light as a wave phenomenon.
He stops and looks sad.

Unfortunately, Arago is now blind and was unable to see the actual procedure.

Student:
That is sad.
But, Dr. Foucault, I would like to talk to you about the role of the pendulum in physics in general and in your recent dramatic demonstration of the rotating Earth in the Pantheon.

Foucault:
The pendulum has been an important, if not an indispensable tool, for developing ideas about motion in general, from Galileo to Huygens to Newton

Student:
And now to Foucault:

Foucault:
Thank you. But I don't think I can be mentioned along with those giants of physics.

Student:
I disagree.
How did you get the idea for constructing your now famous pendulum? I think this is one of those demonstrations, which in retrospect, seems obvious.

Foucault:
I agree.
The idea of finding a direct and publically understandable demonstration to confirm the rotation of the Earth around its axis was always in the back of my mind.

Student:
Since the time of Galileo people have been aware

And now to the direct demonstration that the Earth rotates.

Foucault:
I was inspired to do this experiment when, working in my lab, I happened to twang a steel rod that was clamped in the chuck of a lathe. I noticed that although the rod rotated with the chuck , the plane of vibration remained the same.
He goes to the table and the lathe He demonstrates this effect.

Student:
Wonderful. I find it absolutely surprising.

<u>Foucault:</u>
Yes. Everyone, without exception, finds it so.

<u>Foucault:</u>
Interesting is that once you see it, you can then explain it. But it would have been difficult to predict it.
Well, young man , why do you think is the explanation?

<u>Student:</u>
The explanation must be in Newton’s first law: ”inertia keeps objects in the same state of motion unless they are they are disturbed by an external force.

<u>Foucault:</u>
Very good. I think Galileo and Newton would have had the same inspiration had they seen this phenomenon.

<u>Student:</u>
Yes. It is puzzling that no one before you tried this demonstration.

<u>Foucault:</u>
But let me continue with my story.
I was convinced that if I had a very long and heavy pendulum I could demonstrate that the pendulum would veer slowly in a counterclockwise direction. Thus the clockwise rotation of the Earth would manifest itself to an observer on Earth, in Paris, for example.

<u>Student:</u>
This sudden insight that you gained immediately after looking at the rotating lace and the twanged rod could be compared to the sudden insight of the young Galileo when he noticed that chandeliers of different swing had the same period of oscillation.

<u>Foucault:</u>
The difference of course is that he made a crude measurement right in the cathedral.

<u>Student:</u>
O yes. He used his pulse. But you could not and did not need a measurement.

<u>Foucault:</u>
True. Well, as you can imagine I started working on constructing such a pendulum immediately. I went to the cellar of my mother’s house and there I observed the swing of a pendulum that was two meters long and had a brass ball of about 5 kg..

<u>Student:</u>
Did a short pendulum like that veer that could be noticed?

<u>Foucault:</u>

Well, first of all, the wire snapped at first try. But I managed to construct another pendulum several days later. I could clearly identify a swinging plane.
Later the physicist Arago urged me to build a longer one and I manged to study the swing of an 11 m pendulum at the Paris Observatory.

Student:
When did you have a public demonstration?

Foucault:
I first was allowed to make an announcement at the Academy of Sciences. There I made the assertion that the pendulum's swing plane would seem to veer by 360 degrees a day on the North pole but elsewhere it would veer slower, that is inversely according to the sine of the latitude of the location.

Student:
I see. That means that on the equator ther would be no veering.

Foucault:
Exactly. It is then easily predictable that in Paris the pendulum would rotate counterclockwise 360 degree in about 32 hours.

Student:
I see. But were you able to have the pendulum oscilltate that long?

Foucault:
Actually. When we demonstrates this phenomenon to the public in the spring of 1851, we had a endulum 67 m long and a mass of 28 kg.

Student:
Amazing.

Foucault:
Indeed. We managed to have this giant pendulum swing for almost 7 hours. It veered by about 70 degrees. This was expected.
Of course air resistance would slow down the swing.

Student:
Yes. I understand that this experiment was soon repeated around the world.

Foucault:
Yes. In Rio de Janeiro, which is south of the equator, the swing plane moved counter clockwise, as expected.
He moves to the table and picks up a pendulum.

Student:,,,**To be completed…**

\