UNIT 2
MOVEMENT AND TRANSFORMATIONS

2.1 Angle of Incidence

Neel was lying awake in bed that night, his mind on the principles of motion, when something struck him. *If we drop a rubber ball from a height, it falls perpendicular to the floor, hits the floor, and bounces up, again perpendicular to the floor. But if we throw the ball at an angle to the floor, it bounces up at an angle, not perpendicular to the surface.*

This reminded him of the term *angle of incidence*. He had learnt it as part of the lesson on the behaviour of light. When a particle of light falls on a mirror, it bounces off in such a way that the angle of incidence is equal to the *angle of reflection*. He tried to recall what he had learnt.

The ***angle of incidence*** is the angle between the perpendicular to the surface of the mirror, and the direction in which the particle hits the mirror.

And the ***angle of reflection*** is the angle between the perpendicular and the direction in which the particle bounces off the mirror.

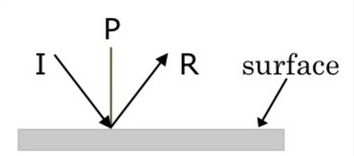


Figure 2.1

P: Perpendicular
I: Line of Incidence
R: Line of Reflection

Neel was excited. Perhaps this idea of bouncing of balls could be extended from mirrors to other surfaces. It might then help them to better understand the motion of colliding objects. He added a second part to PM 9, as PM 9b:

PM 9a *When a moving object M causes a stationary object N to move, N moves either in the same direction as the movement of M, or at an angle to that direction.*

PM 9b *When a moving object M collides with the flat surface of a body N such that M bounces off N, the angle of incidence is equal to the angle of its bouncing off.*

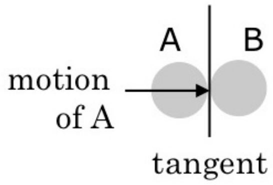


Figure 2.2

What would happen if both M and N (A and B in Fig. 2.2) were spheres, he thought. If the line of motion of A passes through the center of B, then the line of motion is perpendicular to the tangent of B. In that case, B would simply bounce off in the opposite direction.

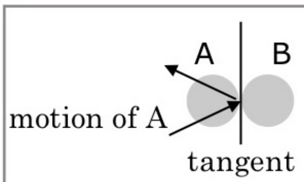


Figure 2.3

But what if A's motion is not perpendicular to the tangent. Then when it bounces off, the angle of the bounce will be the equal to the angle of incidence.

Neel was pleased with what he had figured out.

2.2 Displacement, Rotation, and Revolution

As Neel got out of bed the next morning, his thoughts went back to the principles of motion that he, Anu and Rafa had come up with. It occurred to him that perhaps the nature of motion depended on the size of the objects. He took out his note-book and started drawing pictures. Suppose A and B are both small beads (Fig. 2.4). If A moves towards B and collides with it, the collision would cause B to move. B would move in the same direction as A, not in any other direction.

Figure 2.4

But what if A is a small bead, and B is a big ball (Fig. 2.5)?

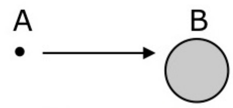
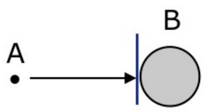
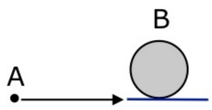
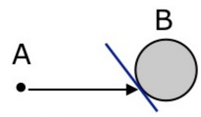


Figure 2.5

We have three possibilities:

I. The path of A, when extended, passes through the center of B.	II. The path of A is along the edge of B and forms a tangent to it.	III. The path of A lies between the center of B and its edge.
 *Figure 2.6*	 *Figure 2.7*	 *Figure 2.8*
B moves in the same direction as A.	B rotates in the same location; it does not change its location.	B rotates, and moves at an angle to the path of A.

These figures set Neel wondering. Suppose the scenario is reversed — A is a big ball, and B is a small bead. What would happen if A moved towards B and collided with it?

TASK 2.1

Can you help Neel figure out the answer to his question?

TASK 2.2

Now consider this scenario. What would be the result if both A and B are big balls, and A collided with B?

Neel was excited about the new questions that had emerged. He called out to Anu and told her about them.

Anu was excited too. She decided to test Neel's ideas and check the results. But she couldn't find any big balls at home that she could use for the experiment. "How about if we use disks instead of balls? In any case, measuring the angles is easier if A and B are disks, not spheres," she said. She took out their carrom board, and placed the striker at the center, since it was the larger object. She placed a carrom piece at the edge of the board, since it was smaller than the striker, and struck it. It moved and collided with the striker really fast. But it was too fast for them to see if the situation was as in the scenarios in I, II or III.

Neel said, 'What if instead of a carrom piece, we use a straight thin metal rod to hit the striker, so that we can control the angle at which the rod (A) hits the striker (B)? (Fig. 2.9) Then we can also control, with greater precision, the direction of the stick's movement, and where the stick hits the disc.

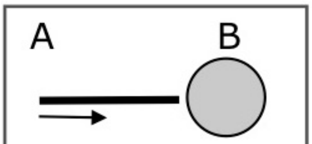


Figure 2.9

Anu used a metal rod to hit the striker, using all the configurations in Figs. 2.6, 2.7, and 2.8. She was careful. She made sure that that A and B collided; and that A didn't just nudge B. To their delight, they found that the results of the experiment were exactly as Neel had guessed. They couldn't wait to get to school to tell Rafa.

All three of them had arrived early that day, so they had a chance to talk before the school bell. When Neel and Anu told Rafa about their experiments with beads, balls and rods, Rafa raised a question.

Rafa: Good insights. I wonder though. Instead of a straight rod and a striker, what if A and B are both straight rods?

Anu: Hmph! We haven't tried that. Let me draw something and see how that goes. (Draws…) Okay, so this figure is somewhat parallel to Fig. 2.6, the first scenario with the sphere:

Figure 2.10

If A and B are both straight rods, and A hits B at the center, I think B would move in the same direction as A.

This figure is the counterpart of the second scenario, in Fig. 2.7:

Figure 2.11

If A were to hit B at one of the ends, B would rotate.

And this one is like the third scenario, in Fig. 2.8:

Figure 2.12

If A were to hit B at a point **between** the center and the edge, B would perhaps rotate and simultaneously move in the direction of A's motion.

Rafa: Wait a minute. Are you saying that if A hits B at an end, as in Fig. 2.11, B will rotate, but not move forward?

Anu: Well, the end that gets hit would move forward, but the other end would remain where it is. So, the object as a whole would rotate around that end. The entire stick doesn't move forward, but the center would move as part of the rotation.

Rafa: I'm not convinced.

Neel: We'll need to test this, but my intuition is that it will rotate around the center of the rod, not around the end that is not hit.

Just then, the bell rang.

Neel: Saved by the bell! Let's continue over lunch.

When they sat down to eat lunch, Rafa and Anu found that Neel had thought through the issue of a stick vs. a sphere or disk. He began in a professorial tone:

Neel: All this time, we have been talking about two kinds of motion. One is ***displacement***, and the other is ***rotation***. When a force acts on an object O, O is displaced from one location to another under certain conditions; it undergoes a ***change of location***. This is what happens to a tennis ball when a tennis racket hits it, or to a stone when you throw it.

Anu: And rotation is just ***change of orientation***, right? So when an object rotates, there is a change in its direction.

Rafa: I can see the change in direction when a stick rotates. But what about when it's a disk? A disk doesn't have a direction, does it?

Anu: You're right. But on a disk, draw a line through the center, and you can see the change in its direction when the disk rotates.

Neel: That's right. So an object rotates under certain conditions different from displacement. Rotating is what happens when the wind turns the blades of a windmill, or the turning on of a switch moves the blades of a fan.

Anu: And a pinwheel, when the wind blows!

Neel: That's right. A pinwheel has rotation, but no displacement.

> ### SOMETHING FUN TO DO
>
> If you feel like making a paper pinwheel, you can find out from these videos how to do it.
>
> https://www.youtube.com/watch?v=muywzgSIaqg
>
> https://www.youtube.com/watch?v=5KJPTb7Pg4o

Rafa: Nice, displacement has change of location, and rotation has change of orientation. That sounds like a good way to distinguish the two ideas. So now we have to ask. Under what conditions does something change its location, and under what conditions does it rotate?

Neel: That's exactly what we have to figure out.

Anu: It's possible for a body to do both at the same time, isn't it? Change location *and* orientation? As in the case of the wheels of a bicycle you are riding on. So we also need to find out under what conditions it does both.

Neel: Hmm! When you ride a bike, you're moving forward, changing location, and so is the bike. The hubs of each of the wheels is also moving forward, right? But what about the wheel itself?

Anu: Ah, I see. The wheel undergoes displacement *AND* rotation. But does it revolve? What *IS* revolution?

Neel: Revolution is displacement around a point, in a circle or ellipse.

Rafa: Great! Imagine an ant sitting on the edge of the bicycle wheel.

Anu: What about the ant?

Neel: I see what you're getting at, Rafa! Would the ant be rotating?

Anu: Of course not!

Neel: Would it be revolving?

Anu: Oh yes! Revolving around the hub. Cool!!!

Rafa: Nice! So let me see: a white spot on the edge of a rotating wheel would also be revolving around the hub.

Neel: Exactly. Just like when a merry-go-round rotates, its seats revolve around its hub.

Anu: And suppose my bicycle goes around a tree in a circular path, about ten feet from the tree. The wheels would be rotating, and also revolving around the tree, right? Just like the earth going around the sun.

Rafa: Great example, Anu! One that has rotation *AND* revolution. So when the earth rotates and revolves around the sun, are we revolving around the center of the earth? And are we also rotating?

Neel: After lunch!

Rafa: Sure, But this is fascinating! Ties in with what our science textbook says about the earth both rotating and revolving. A twirling sphere going around a burning sphere in a curved path! (laughs. Neel and Anu join in the laughter.)

TASK 2.3

Can you answer Rafa's questions?
State your reasons for your answer.

After lunch, they continued the conversation.

Anu: I have a question. Suppose we place my bicycle upside down on the table. If we push on one of its pedals, the back wheel would move. It would rotate, but it wouldn't move forward. But if the bicycle wheels are on the ground and we push down on the pedals, the bicycle moves forward while the wheels rotate. My question is, how does the downward movement of the pedals cause the wheels to rotate, and how does the rotation cause its forward motion?

There was silence. Everyone was contemplating. Neel was the first to speak.

Neel: To look for an answer to that question, Anu, I think we need to understand the relation between rotation and displacement.

Rafa: Cool! Great question, and an awesome way of clarifying it. We'll need some time to figure out the answer.

TASK 2.4

Can you answer Anu's question? First, you will need to build a theory of bicycles.

2.3 Identifying the Essentials

On his way home on his bicycle, Rafa was in deep thought. As soon as he got home, he ran to his mother, Samira.

Rafa: Mom, there's something I want to talk to you about.

Samira: I'm all ears, Rafa.

Rafa: Anu posed a question today. If we place a bicycle upside down with the wheels up in the air, and push on the pedals, the wheel would rotate, but the bycicle wouldn't move forward. But if the wheels are on the ground and we push down the pedals, the bicycle moves forward while the wheels rotate. How does the movement of the pedals cause the wheels to rotate, and how does the rotation cause its forward movement?

Samira: Hm! Good question. To engage with it, to respond to it, you would need to construct a theory of bicycles.

Rafa: Neel pointed out that we need to first understand the relation between rotation and displacement. And to understand that relation, I want to first simplify Anu's question a bit. What are the conditions under which displacement causes rotation? And under what conditions does rotation cause displacement?

Samira: That's a good start!

Rafa: I am going to focus on wheels and surfaces for now, and not worry about the bicycle pedals and chains.

Samira: Yes, focus on what is essential to what you want to understand, and eliminate all the irrelevant details. It's a good strategy.

Rafa: Are you okay, Mom? You're not pointing out flaws; you're paying me a complement!

Samira: [smiling] Come on, Rafa! I know when to point out flaws, when to challenge, and when to nurture.

Rafa: Okay, okay! The question. Suppose we have a wooden board with edges A, B, C and D, with four legs that have wheels, like this. (He drew a diagram on a piece of paper.) It looks like a cart, so let's call it a cart.

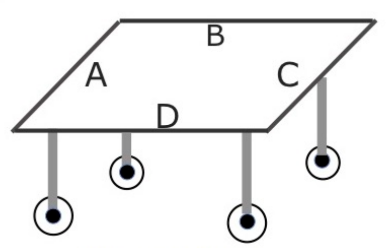


Figure 2.13

If the board is small enough, say, two feet by three feet, and we hit edge B with a cricket bat, the board will move forward, with side D in front. It will move in the same direction as the movement of the bat. The wheels would also be rotating. It wouldn't matter whether you hit the edge of the board, the leg, or the wheel. The result would be the same. There will be displacement of the entire object, and rotation of the wheels.

But if the cart is placed upside down on the floor, and you do the same thing, there might be displacement of the cart, but no rotation of the wheels. Why?

Samira: Good question!

Rafa: I think it has to do with the wheel being in contact with the floor. Suppose we place the cart on a carpet and push it. The pushing would cause the wheels to rotate. And the rotation would cause displacement of the cart. But if we pull the carpet out from under the cart while we hold the cart, the carpet is displaced, but the cart doesn't move forward. But the wheels are in contact with the carpet, and so they move, resulting in rotation.

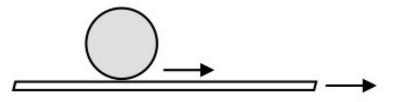


Figure 2.14

So we should conclude that it is the linear motion of the wheels relative to the carpet that makes the wheels rotate. They rotate whether we push the cart on the carpet, or pull the carpet from under the wheels. Am I making sense?

Samira: I can follow your reasoning, you're clear.

Rafa: Good. What I just said, I'm going to state it as a principle:

PRINCIPLE OF ROTATION:

When a wheel is in contact with a surface, the relative linear motion of the wheel with respect to the surface causes the wheel to rotate.

Samira: Good. You should write it down. Can you also write down the principle you wanted to talk to me about? I'd like to check it.

Rafa wrote both principles on a piece of paper:

PM 9a *When a moving object A causes a stationary object B to move, B moves in the same direction as A.*

Samira: Your principle doesn't say anything about the contact between A and B.

Rafa: Oh yea! Let me add another principle:

PM 10 *For a moving object A to cause a stationary object B to move, there must be contact between the two bodies.*

Samira stared at the two principles, and was silent for a while.

Samira: That might work. But I should tell you this, Rafa. You are referring to your statements as 'principles'. In Physics, these statements would be called 'laws'. So perhaps you could call them laws.

Rafa: But laws are to be obeyed, right? Like traffic laws.

Samira: In this context, 'law' means something else. It is the statement of a regularity in nature.

Rafa: Oh! So a law is the same as what we call a principle!

Samira: Alright, I have to get to work. Good luck with your laws. See you later.

Rafa was ecstatic. He called Anu and Neel immediately, and reported to them his discussion with his mother, and told them about the new principle. He also told them about the idea of laws of nature.

Neel: That's good.

Anu: Cute! So the bicycle and the cart can rest now.

2.4 Theory as a Configuration of Laws

The next day, Anu, Neel and Rafa hurried through lunch and were at the whiteboard in the classroom. Rafa spoke excitedly, but was somewhat disorganized. So Neel took charge. He went to the whiteboard, and drew a vertical line down the middle.

Neel: So we now have a theory of motion with a number of connected principles, or I should say, laws. In the column on the left, let's write down what we want to explain — our observations. And in the column on the right, let's write the laws that explain what's on the left.

What the theory seeks to explain	Laws that yield the explanation
...	...

Let's put all the laws we have in one place.

Neel wrote, with Rafa and Anu dictating the laws from where they were written:

A THEORY OF MOTION: Laws that yield the explanation

Law 1	*Inanimate entities that are not manmade move only when an external push or pull makes them move.*
Law 2	*When a moving object M collides with a stationary object N, the collision serves as the external push to make N move.*
Law 3	*All objects have inertia; inertia is the resistance to change.*
Law 4	*For an object to move, the degree of force applied on it must to be greater than its inertia.*
Law 5	*The greater the weight of an object, the greater its inertia.*
Law 6	*The greater the weight of a moving object M, the greater the force with which it acts on a stationary object N.*
Law 7	*The greater the speed of a moving object M, the greater the force with which it acts on a stationary object N.*
Law 8	*The greater the force with which M acts on N, the faster N moves.*
Law 9	*When a moving object M causes a stationary object N to move, N moves either in the same direction as the movement of M, or at an angle to that direction.*
Law 10	*For a moving object M to cause a stationary object N to move, the two bodies must be in contact.*
Law 11	*When a wheel is in contact with a surface, the relative linear motion of the wheel with respect to the surface causes the wheel to rotate.*

Neel: Okay, so that goes on the right. On the left, let's list our observations, all the phenomena that we need to explain.

When they were done, this is what they had on the board:

PHENOMENA: What our theory seeks to explain

A. When a carrom striker moves and hits a carrom piece, the piece moves.

B. When a stick A moves and hits the center of another stick B perpendicular to it, B moves in the same direction as A. If A hits B at an end, B rotates.

C. If a cricket bat hits a not-so-heavy cart on wheels, the cart moves in the same direction as the bat, and the wheels rotate. But if we turn the cart upside down, and hit it with the bat, the cart moves in the same direction as the bat, but the wheels do not rotate.

D. If we hit the cart with greater force, it moves faster.

E. If a moving ball A hits a stationary ball B, and B moves, the greater the speed of A or the greater the weight of A, the faster the speed of B.

Anu: (disappointed) We explain five things with that many laws?

Rafa: Don't worry, Anu. As we develop our theory further, we'll find more and more things to explain. And we may not need all the laws, so the laws will be fewer. At least, that is what we need to try to do.