Unit 1
Movement and Force

1.1 Motion: A Regularity

Anu was at the dining table, reading a book. When she looked up, she thought she saw a lump of something at the far corner of the table. It looked like a ball of dirt. She didn't pay further attention, and went back to reading. Soon, while turning a page, she happened to look up again. The lump was now in a different place. She glanced at the spot again, decided that her memory was playing tricks, and went back to reading. When she looked up again a few seconds later, the lump was in yet another spot on the table.

Curious, Anu started looking at attentively at the lump. She found that it was moving, very very slowly. Amazing! How can that be? She called out to her brother Neel before realizing that he had gone out for basketball practice. So she phoned their friend Rafa.

Anu: Rafa, there is something on my table that looks like a dirtball, but it's moving! VERY slowly!

Rafa: Are you sure it is a dirtball? It could be some kind of creature.

Anu: No, I am sure it is not a living thing.

Rafa: Take a careful look, Anu. Do you have a magnifying glass?

Anu: Yes, I do. Wait a minute.

Anu got her magnifying glass from her desk drawer, turned on more lights, and looked at the lump. It had what looked like legs.

Anu: You were right, Rafa! Looks like it is indeed a creature.

Rafa: How do you know that?

Anu: It has legs! And it's walking on them. You know what? I was surprised earlier when I saw it move because I assumed it was not a living thing.

Rafa: You thought it was inanimate.

Anu: Mm-hm. And inanimate things don't move on their own, right? That's why I was puzzled.

Rafa: Is that ALWAYS so, what you just said about inanimate entities?

Anu: Come to think of it, it's quite regular. We can say for sure that:

"*Inanimate entities do not move on their own.*"

Rafa: Move on their own? What do you mean by that?

Anu: Take a stone. It moves only when something makes it move. But an ant or a bird can move even when there is nothing from outside making it move.

Rafa: Okay, *inanimate entities do not move on their own.* That sounds like a ***principle.***

Anu: What do you mean, principle? You're talking like a textbook, Rafa.

Rafa: Hey, you noticed a pattern; that certain things follow certain rules, ***all*** the time, with regularity. In this case, that inanimate things don't move on their own. And you stated that regularity. I think a principle is just the statement of a regularity.

Anu: Oh, okay. So, I noticed a pattern. And then I noticed something that didn't fit the pattern. That puzzled me.

Rafa: A ***counterexample*** to your principle, you mean.

Anu: I guess... I thought that the lump of dirt on the table was inanimate. There was no external push or pull acting on it, and yet it was moving. That puzzled me. But once I saw that it was a living thing, it was not a counterexample any more, so it wasn't puzzling.

Rafa: Great! Do you realize you're a budding scientist, Anu?

Anu was pleased. It wasn't often that Rafa paid her a complement.

Rafa: Listen, how about if we state the principle like this:

"*Inanimate entities move only when*
an external push or pull makes them move."

TASK 1.1

Rafa restated the **principle** that Anu first stated. Do you think the principle the way Rafa stated it is true?

Can you think of any **counterexamples**?

When Neel came home from basketball practice, Anu told him about her conversation with Rafa and the principle of motion they had formulated.

Neel: But Anu, there are so many counterexamples to that principle.

Anu: Like what?

Neel: A wristwatch is inanimate, right? But its hands move. The same with a toy car; if you wind it up and place it on the floor, it moves. What about rockets and robots? They are inanimate too, but they move without any external push or pull acting on them.

Anu: Agreed. But all your examples are of machines. They are manmade, not natural. The principle states a pattern we find in natural things.

Neel: Then the principle has to say so. The way you guys have stated it, does it say that it applies only to natural objects?

Anu: (after a moment's thought) You're right. What if I revise it like this?

Anu wrote a third version of her Principle of Motion in her notebook:

> *"Inanimate entities that are not manmade move only when an external push or pull makes them move."*

Neel: That might work.

Anu: So you accept that the statement is true?

Neel: No, no, no, I didn't say that. I just mean that for now, TILL we bump into counterexamples, let's TAKE THE PRINCIPLE TO BE TRUE.

1.2 More Regularities: When Objects Collide

The next day at school, Anu and Neel told Rafa briefly about their revision of the principle of motion that Rafa and Anu had stated earlier. Rafa, as usual, listened carefully. He was silent for a while, and then got up.

Rafa: Let's go back to the classroom.

Neel: But why? There's a lot of time before the bell.

Rafa: We might need the whiteboard.

Neel: Oh, okay.

Rafa: What makes inanimate objects move? If I swing my leg, and my foot hits a ball, the ball would roll away, right?

Neel: That's right. So your foot hitting the ball is the external push that makes the ball roll away.

Rafa: And if that ball hits another ball as it rolls, the second one would also start rolling.

Neel: So the moving ball hitting the stationary ball is another external push.

Anu: This means we have another principle to state:

> "*When a moving object M collides with a stationary object N, M serves as the external push to make N move.*"

Rafa: Right. Also, the faster I swing my leg, the faster the ball would roll. Right?

Neel: Hmm! I hadn't thought of that. So there are other regularities in the way motion happens.

Anu: So we'll need to state more principles of motion.

They were in the classroom now. Anu picked up a whiteboard marker.

Anu: Let me write down the principles we already have. We'll call them PMs for Principles of Motion.

She wrote:

> **PRINCIPLES OF MOTION (PMS)**
>
> PM 1 *Inanimate entities that are not manmade move only when an external push or pull makes them move.*
>
> PM 2 *When a moving object M collides with a stationary object N, A serves as the external push to make B move.*

Neel: Nice! As we explore, we'll have more principles. All related to motion. When we have a cluster of related principles like that, we might end up with a *THEORY* of motion!

Anu: So that's what a theory is?

Rafa: Let's not worry about theory now. Let's first figure out the patterns and state the regularities as principles.

TASK 1.2

Can you think of counterexamples to PM 2 above?

A *COUNTEREXAMPLE* here would be an example where a moving object M collides with a stationary object N, but N does not move. If there is indeed such a case, you need to revise the statement, or add another statement, so that there are no counterexamples.

1.3 Force as a Cause of Motion

As Rafa rode his bicycle to school the next day, he was preoccupied. Something was bothering him. He was glad to see that Anu and Neel were already there.

Rafa: Remember the principles of motion from yesterday?

Neel: Of course.

Rafa: I am concerned about the second principle. It may not work.

Neel: How so?

Rafa: If the moving object is light, and the stationary object is really heavy, the stationary object won't move on collision. Suppose a moving table tennis ball hits a big iron ball that is stationary. The iron ball is not going to move. If a moving bicycle collides with a stationary truck, the truck is not going to move.

Anu: True that. Oh, drat! So the principle has to specify when the stationary object would move and when it wouldn't move.

Rafa: Exactly.

The bell rang just then, and they had to go to their class. All morning, Anu's mind was on the principles of motion. This kept her from paying attention to what was happening in class. As soon as the bell rang for the break, she ran out to talk to Neel and Rafa.

Anu: Listen, when I want to open a bottle, if the lid is closed tight, and I try to turn it, it doesn't move. But Neel can open it easily. He is stronger than me, so he can use more force than me to twist the lid off.

Neel: So? What's your point? Why are you saying this?

Anu: (cutting him off) Patience. Suppose we assume that the tight lid resists change. If I understand it, this is what is called inertia in our textbook.

Rafa: Okay, Anu! So inertia is resistance to change. Now what?

Neel: Sorry, Anu, you are right. Inertia is what keeps me from getting out of bed early in the morning, unless there is the pull of a game of basketball.

Rafa: So force causes change, and inertia resists change, a kind of opposing force. When we pull, push, twist, or lift something, we are using force.

Anu: Right. I'm going to add two more principles to the ones we have.

Anu wrote on the whiteboard, starting with the principles they already had.

PRINCIPLES OF MOTION (PMS)

- PM 1 *Inanimate entities that are not manmade move only when an external push or pull makes them move.*
- PM 2 *When a moving object M collides with a stationary object N, M serves as the external push to make N move.*
- PM 3 *All objects have inertia; inertia is the resistance to change.*
- PM 4 *The degree of force applied to an object to make it move needs to be greater than its inertia.*

Rafa: That sounds good, Anu! So are you assuming that heavier objects have more inertia than lighter ones?

Anu: Mm-hm, I am assuming that. But it is not just a matter of heavy and light. It also depends on the kind of movement. So take a really heavy suitcase. It is easier to push it horizontally than to lift it. So the suitcase has greater inertia against upward motion than against horizontal motion.

Neel: I like the way you're going, Anu.

Anu: Another example is a lid on a bottle. A lid that is tightly screwed on has more inertia than the same lid loosely screwed on. And it is more difficult to twist off. So, the tighter the fit, the greater the inertia.

Rafa: You've really been thinking about this, haven't you?

Anu: Mm-hm. So inertia is just resistance to change. The greater the inertia of something, the greater the force required to change it. That may of course depend on many factors. So pushing the heavy suitcase across a smooth floor takes less force than pushing it across a rough floor. And if the suitcase has wheels, it takes even less force to move it.

Neel: Rafa, you had an example earlier of a moving table tennis ball colliding with a big iron ball that is stationary.

Anu: Well, the iron ball doesn't move because its inertia is much greater than the force of the moving table tennis ball.

Neel: But how do you find out what the inertia of a stationary object is, and what the force of a moving object is? If we don't have a way to find that out, we can't tell if the principle holds.

Anu: I don't know, but let me try. I think there are three parts to this. The first has to do with weight; the heavier an object, the greater its inertia. The second has to do with a moving body M causing the movement of another body N. The greater the weight of M, the greater the force with which it acts on N. And the third point is, the faster the motion of M, the greater the force on N.

Neel: Let's write this so that we don't forget. (Writes.)

1. The heavier N is, the greater its inertia.
2. The heavier M is, the greater the force on N.
3. The faster the motion of M, the greater the force on N.

Rafa: Point 1 is fine. The heavier something is, the harder it is to move it. But how would you test Points 2 and 3?

Neel: I have an idea. Imagine three solid balls of the same size. One is made of lead, another of wood, and the third of stone. Suppose we roll the lead ball and make it hit the wooden ball. And then we make the stone ball hit the wooden ball at the same speed. According to point 2, since the lead ball is heavier than the stone ball, it would hit the wooden ball with greater force.

Rafa: That sounds reasonable. But how do we know if the lead ball has hit with greater force? We can't perceive force. Does hitting with greater force result in something that we *can* perceive? What would the consequence of 'greater force' be?

Anu: One consequence of greater force would be greater speed. When you watch a game of golf, you can see that the greater the force with which you hit the golf ball, the faster it goes.

Neel: We should add that as a fourth point. (Writes)

4. The greater the force on N, the faster N moves.

Anu: So one consequence of greater force is greater speed. We can perceive it, and also measure it. When the lead ball and the stone ball hit the wooden ball, since the lead ball is heavier, it should result in the wooden ball moving faster. IF that is what happens, we must conclude that the lead ball hits the wooden ball with greater force than the stone one, right?

Rafa: Great!

Neel: Suppose we hit the wooden ball with the lead ball several times, changing the speed of the lead ball. By point 3, the greater the speed with which the lead ball hits the wooden one, the faster the wooden ball should move. If this turns out to be true, then we know that point 3 is on the right track.

Anu: This must be why when a moving vehicle hits another vehicle, the greater the speed of the moving one, the greater the damage to the other one.

Neel: So going back to the three balls, our statements in points 1 to 4 predict that the wooden ball should move faster when hit buy the lead ball than when hit by the stone ball. If it happens the other way round, our statements are false.

Rafa: Wow! That is like a mathematical proof. Cute. But I need to go through it myself to make sure that the prediction does follow.

Neel: Nice! We have three more principles now. I think that's enough to call it a theory of motion.

Rafa: That's right! The principles we have are connected, and they explain what we observe. When we put them together, their logical consequences match what we observe. So yes, a theory is taking shape.

Neel: We should write down all the statements together, so that the connections become explicit. Let me do that.

A THEORY OF MOTION

PM 1 *Inanimate entities that are not manmade move only when an external push or pull makes them move.*

PM 2 *When a moving object M collides with a stationary object N, the collision serves as the external push to make N move.*

PM 3 *All objects have inertia; inertia is the resistance to change.*

PM 4 *For an object to move, the degree of force applied on it must to be greater than its inertia.*

PM5 *The greater the weight of an object, the greater its inertia.*

PM6 *The greater the weight of a moving object M, the greater the force with which it acts on a stationary object N.*

PM7 *The greater the speed of a moving object M, the greater the force with which it acts on a stationary object N.*

PM8 *The greater the force with which M acts on N, the faster N moves.*

1.4 The Direction of Force and of Movement

On his way home, Rafa was still thinking about the theory of motion that was emerging through their discussion. The second principle said:

PM 2 *When a moving object M collides with a stationary object N, the collision serves as the external push to make N move.*

But was that precise enough? he asked himself. *What about the direction of motion? Suppose a moving ball M collides with a stationary ball N. Would N move perpendicular to the direction in which M was moving? No! Would it move in the opposite direction? No! So what was missing in their statement? We need yet another principle!* he thought.

Just as he got home, a statement popped up in his mind. He pulled out his notebook and wrote:

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

He called Anu and Neel to tell them about the new PM. The three of them spent a long time looking for counterexamples, but couldn't find any. So they decided to accept the principle as true till they found evidence to show that it was false.

But the next day, Neel pointed out a problem with PM 9.

Neel: Look, Rafa, your point was that when M hits N, N does not move either perpendicular to M's motion or in the opposite direction. I agree, that's a good generalization. But your principle says that N moves in the same direction as M. Isn't it possible that it moves at an angle to the direction of M?

Rafa: Is that possible?

Anu: I think so. Imagine a wooden equilateral triangle. Suppose we place it flat on a table, and hit it at the center of one of its sides with a thin straight stick such that the line through the stick, when extended, passes through the centre of the triangle. The stick would be perpendicular to the side of the triangle. The triangle will move in the same direction as the stick, right?

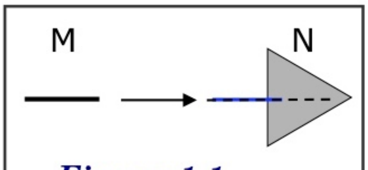

Figure 1.1

Rafa: Yes.

Anu: But if the stick hits the triangle off center (Fig. 1.2), still perpendicular to the side, would the triangle move in the same direction as the stick?

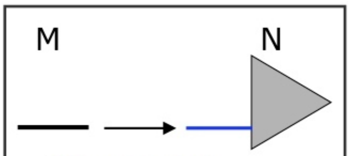

Figure 1.2

Rafa: I think I see what you mean. It would either move off at an angle, or it might rotate a bit.

Anu: Shouldn't we revise the principle like this?

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

Neel: I think that would work.

Here is the theory of motion that Anu, Neel and Rafa have come up with so far:

A THEORY OF MOTION

PM 1 *Inanimate entities that are not manmade move only when an external push or pull makes them move.*

PM 2 *When a moving object M collides with a stationary object N, the collision serves as the external push to make N move.*

PM 3 *All objects have inertia; inertia is the resistance to change.*

PM 4 *For an object to move, the degree of force applied on it must to be greater than its inertia.*

PM 5 *The greater the weight of an object, the greater its inertia.*

PM 6 *The greater the weight of a moving object M, the greater the force with which it acts on a stationary object N.*

PM 7 *The greater the speed of a moving object M, the greater the force with which it acts on a stationary object N.*

PM 8 *The greater the force with which M acts on N, the faster N moves.*

PM 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.*

TASK 1.3

Can you find counterexamples to the set of Principles of Motion 1-9?