Darshana Jolts

Cause of Unsteady Motion: Force

V V Raman

Hence no force, however great
Can stretch a cord, however fine
Into a horizontal line
That shall be absolutely straight.

– William Whewell

Force: *States of motion are affected by forces.*

When we consider the variety of motions a legitimate question that could arise is, what causes such variety? In other words, why do some bodies remain unchanging in motion, altering neither speed nor direction, while others – indeed most that we ordinarily observe – undergo changes now and again in a variety of ways?

In simple cases this is easy to see: The box sitting still on the floor can be made to change its state of motion by giving it a push, and the cart on the road by pulling it. We normally affect motions by imposing direct or indirect pushes and pulls. Pushes and pulls are collectively known as *forces*. By extension, whenever we observe acceleration (change in the state of motion), we say that some kind of *force* has come into play. Thus we may look upon forces as hypothetical entities subsisting in the roots of perceived reality, in terms of which we are able to describe, explain and even predict non-uniform motion.

Every time we observe non-uniform motion we may conclude that some force has come into play because force *is the cause of acceleration*. It is important to realize that the converse is not true; if there is rest or uniform motion it does not imply that no force is present at all. You may push a box in one direction and another person in the opposite direction, keeping the box stationary. In other words, forces may balance out and cancel each other's effect.

The philosopher David Hume said that a miracle is "a transgression of a law of nature by a particular volition of the Deity or by the interposition of some invisible agent[1]". In fact, the laws of nature themselves, rather than their transgression, are often due to invisible agents. Forces are

[1] David Hume, *An Inquiry Concerning Human Understanding,* Chap.1, p.537.

invisible agents: Except for our own muscular experience of exertion, forces cannot be seen, only their effects can be observed, What is interesting is that they can be precisely measured! There are countless instances of non-uniform motion, so it may seem that there are countless forces in the world. This is true and yet not true. There are indeed *countless instances* of forces, but there are only *a few kinds of* forces.

Measure of Force: ***The stronger the force on a body the greater the acceleration.***

When two forces come into play, as in a tug of war, the stronger overcomes the effect of the weaker. What we call strength and weakness are in effect measures of a force. The Latin proverb that the stronger always succeeds[2] is true in the physical world, if not always in the human realm. The stronger a force, the greater will be the acceleration it causes on a body. Give a greater push to the hockey puck, and the faster it takes off. On the other hand, the larger the body on which the force is applied, the smaller the acceleration it suffers: the toy cart is pulled more easily than the truck with the same exertion. These two facts of observation are formulated as a simple formula: $F = ma$. Known as Newton's second law of motion[3], it couches in it every instance, actual and conceivable, of motion that occurs in the universe. That such wondrous variety can be encapsulated in such beautiful brevity is a marvel in itself. With the aid of this simple-looking *mantra* of modern science we have been able to explain and understand much of the complexity in the world, whenever we know the particular forces that are involved in a given situation.

Using the formula above, one defines in the world of physics the intensity (or strength) of a force in precise quantitative terms[4]. In the course of the 19th century a convention arose by which units of physical quantities would be named after eminent contributors to the field, or, to put it in the more pungent language of Hogben, the fashion was set "for combing obituary notices of departed worthies to upholster names of physical units[5]." So the unit of force was named a *newton*: note that one does not use the capital letter in writing out the unit, as that would refer to a person. However, the abbreviation for the physical unit is given (by convention) by using capitals, like N for newton.

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[2] Titus Maccius Plautus, *Truculentus: IV.3.30*, *Plus potest qui plus valet*.

[3] Newton's original formulation of the second law in his *Principia* was as follows:
Lex II: Mutationem motus proportionalem esse vi motrici impressae, et fieri secundum lineam rectam qua vis illa imprimitur. LAW II: The alteration of motion is ever proportional to the motive force impress'd; and is made in the direction of the right line in which that force is impress'd.

[4] Thus a unit of force is that much force that can accelerate one kg of mass to 1 m/s^2.

[5] Lancelot Hogben, *The Vocabulary of Science*, New York, p.37, 1971.

Source and Target: ***Every force has a counter-force.***

You push the book on the table: the push is the force; you are the *pusher*, i.e., the *source* of the force; and the book is the *pushee*, i.e., the *target* of the force. The child pulls a string: the pulling is the force, the child is the source, and the string is the target. In every instance we can distinguish between these three entities: a force, its source, and its target.

In this context, observations reveal a most interesting symmetry in the roots of perceived reality: whenever a force (which invariably has a source and a target) comes into play, another force of equal magnitude appears also in which the source and target are precisely the reverse of the first force. In other words, here the source of the first force becomes the target and its target becomes the source. Thus, when you push an object with your hand exerting a certain force, the object pushes back your hand with an equal amount of force. We usually refer to one of the forces as *action*, and the other as the *reaction*. Like cousins, action and reaction are always reciprocal. If we consider one as the action, the other becomes the reaction and vice versa. The existence and equality of action-reaction pairs of forces in opposite directions is known as (Newton's) third law of motion[6].

In the eighteenth century a paradox arose in the context of the action-reaction principle. When a horse (source) pulls (action) a carriage (target), then the carriage (source) must pull (reaction) the horse (target) with an equal force. If that is the case, one argued, then how does the carriage move? The answer to this is that the horse and carriage do not move with respect to each other, but with respect to the road. Indeed all motion on any surface occurs from the operation of the principle of the action-reaction principle. When we walk, we kick the road back, and the road kicks us forward. That is what wheels do too. For ages human beings have been walking without recognizing this root of perceived reality.

Another paradox that arose in this context was how any change in motion is possible at all if all forces come in equal and opposite pairs. Should they not cancel one another out, leaving no net force to cause changes? The paradox is resolved if we remember that the action force and the reaction force *act on different bodies, never on the same body*. That is why changes in motion of different bodies is possible.

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[6] In Newton's words: *Lex III: Actioni contrariam semper et æqualem esse reactionem: sive corporum duorum actiones in se mutuo semper esse æquales et in partes contrarias dirigi:* Law III: To every action there is always an equal and opposite reaction: or the forces of two bodies on each other are always equal and are directed in opposite directions.

The Law of *Karma* and the Third Law of Motion: *Linking metaphysical tenets to physical principles is neither useful not necessary, and dishonors both*.

The law of *karma* is an insightful metaphysical tenet in the Hindu framework which holds that ever consequential action that a human being performs will have an effect on the performer. In simple terms, if you do something good, something good will happen to you, and if you do something bad, you will experience something bad also. This is not unlike the Biblical statement (Galatians VI): Whatsoever a man soweth, that shall he also reap.

It is important to recognize these are morally inspiring perspectives. However, contrary to the claims of scientific-sounding exponents of religious philosophies, Newton's third law of motion has nothing whatever to do with good and bad behavior, rewards and punishments, heaven and reincarnation. The third law is a quantitatively precise statement on force-pairs acting on mutually interacting bodies, with utterly no moral implication or connotation. Attempts to formulate or proclaim religious truths in terms of modern scientific principles may sound convincing to those who have little understanding of science, but they do little to enhance the substance or significance of metaphysical notions like *karma* and the reaping of the fruits of one's behavior. In the rich tradition of such thinking there is a book which has been described as "a powerful force that combines the highly predictable 3rd Law of Physics … with the notion that what goes around comes back around, in order to stop you from being miserable, even around those who should have known better[7]."

Weight: *The earth exerts a force on every mass in its vicinity.*

We live in an age when many people are conscious of their weight. Weight watching is a national concern in many over-consuming countries. It has given rise to health foods, obsession for low calorie diet, attempts at fasting, jogging, visits to the gyms, etc. But not one in a hundred may be able to tell what exactly one means by *weight*. People may laugh if told that by merely flying to the top of a mountain one can lose some weight[8].

But this is true, because weight (on earth) is simply the force with which the earth pulls a body towards its center. The farther we are from that center the less is that force. We note right away that being a force we must measure weight in newtons and not in kilograms[9]. What the 'overweight' individual is trying to accomplish is to lose *mass*, not weight. The distinction between mass and weight was not possible without the notions of force and of planetary bodies

[7] Gretchen Schauffler, *Karma Physics*, Inkwater Press, 2001.

[8] The acceleration due to gravity (in m/s^2) is 9.78 at the equator and 9,83 at the North Pole. Thus one would weigh more at the North Pole than at the equator.

[9] Weight may be expressed in pounds (lbs) because pound is a unit of force.

(including the earth) pulling other bodies towards their center: ideas which were not clearly formulated until the seventeenth century[10].

Everybody in the vicinity of the earth experiences this force which is generally referred to as gravity. If one is sufficiently far away from the earth, this force becomes negligible. When one is close enough to any other celestial body (the moon, another planet, the sun, etc.), one will experience similar pulls. Depending on the mass of the pulling body, a body's weight would be less or greater. On the moon one would be much lighter than here below[11], but if transported to Jupiter a body will be glued tight to the ground. Weighing incredible tons, it will be impossible for a person to even stand up on that very massive planet.

It is weight that causes things to fall to the ground; but for this force, things would hang in thin air. It is weight therefore that keeps us here on earth; without it, we would be flying all over space. If we are on earth it is because of the force of weight. It enchains us to this speck in the universe, but in doing so it provides us with the security of a home in the cosmos. Again, weight is also the force that holds on the mantle of air that is hugging the planet. If the earth's hold were too slight (as in the case of the moon), all air will fly away and there will be no atmosphere. Indeed, many gases are escaping from our atmosphere continuously.

Friction: ***The force that opposes motion and is needed for locomotion.***

When an object is given a push on a table top, it soon comes to a stop. What made its motion change? When we exert a force on a heavy box on the floor, it does not easily move. When a wheel is spun on an axle, it eventually comes to a stop. Whatever caused these changes in motion? Why is there no change in motion even when we push (apply a force on) a huge truck?

Such phenomena are explained when we recognize the existence of another kind of force called (the force of) *friction*. Friction is a commonly occurring force whose principal property is to prevent or stop motions on surfaces. With solids, friction prevents the start of motion itself, and with liquids and gases it comes into play after motion has begun. In all instances it is because of friction that moving bodies slow down and halt when they are in contact with surfaces, and it is because of friction that turning wheels rotate slower and stop. Friction causes the wear and tear of materials. It is to minimize these that one uses roller bearings and lubricants. Friction

[10] It should be pointed out that though the modern concept of weight and its relation to gravitation arose only much later, already in the *Arthashástra* of Kautilya (Chapter xix) there are discussions of weights and measure which were useful for practical purposes. See in this context, K M Viyayalakshmi Sharma and H C Bhardwaj, Weighing Devices in Ancient India, *Indian Jour. Hist. Sc*., 24.4, 1989.

[11] In this context one may read H G Wells' *The First Men in the Moon* in which Dr. Cavor and Mr. Bedford go to the moon and tell the Selenites (moon people) how earthlings could lift many heavy things on the moon.

invariably results in the dissipation of energy as heat. In other words, when friction slows down a moving body, the body loses some energy.

Though friction seems to be a nuisance in the context of motion, ironically friction is also helpful, indeed indispensable, for locomotion. If frictional forces do not come into play between feet and ground, we cannot walk. That is why we slip on ice and oily surfaces where friction is very small. One may think that it is the turning of the wheels that causes a car to move. Rather, it is friction that makes this possible: that is why the car will not move with bald tires on an icy road. We cannot lift an object with our fingers, nor can we play the violin or the cello, were it not for frictional forces.

The mathematical physicist Charles Eugène Delauney (1816 – 1872) calculated with the utmost precision the motion of the moon, and found some minor discrepancy between his results and the data of observation. He suggested one possible cause of this: the slowing down of the earth's rotation as a result of the friction arising from the motion of the tides[12]. The vast masses of ocean waters are in continuous motion through waves and tides. They rub against the ocean floors and splash on the coastal surfaces. All this means friction and dissipation of energy. The net effect of it is to slow down the earth's rotation. This would cause a lengthening of the day. It turns out that this loss is negligibly small in the span of human history: barely 0.016 s in a thousand years. It is not the amount that is significant in a case like this, but our being able to become aware of a process like this that makes science exciting. Who could have thought that the earth is slowing down in the course of thousands of years, and days are getting longer, without careful observation, precise calculation, and ingenious concepts?

Although the bare effects of friction have been known since a very long time, it was the detailed experimental studies of Charles Coulomb (1736–1806) in the course of the eighteenth century that we have come to know a good deal about various aspects of friction as a commonly occurring phenomenon. His contributions to the science of friction were exceptionally great. Coulomb is credited with the founding of the science of friction.. "Without exaggeration," noted two scholars, "one can say that he (Coulomb) created this science[13]".

Tension: *Strings exert forces when pulled.*

The chandelier is hanging from the ceiling, attached to a chain. We know that the earth is pulling the lamp through the force of weight. But there is no change in the state of motion (rest) of the lamp. We have to conclude that an equal and opposite force is pulling the lamp in the upward

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12 David Edgar Cartwright, *Tides: A Scientific History,* Cambridge University Press, p.146, 1999.

13 I V Kragelskii and V S Schedrov, in *Development of the science of friction – dry friction,* pp.51–69, Moscow, 1956.

direction. This force must be exerted by the chain to which the lamp is attached. We call this the *tension* (force) exerted by the chain. This is another type of ordinarily occurring forces on our scale.

Any rope or string, chain or rubber band, exerts tension when it is attached to an object and stretched. In our technological world, therefore, there are a great many contexts in which tension forces appear. In belts connecting wheels, in suspension bridges, in lamps hanging from ceilings, in transmission wires, in elevators cables, in pulleys and cranes and children's jump-ropes, we find countless instances of tension.

While weights and friction forces occur more generally in nature, we do not observe tension forces in natural phenomena, for there are no ropes hanging from cliffs, no wires stretched across valleys, nor strings in nature's wilderness. But in the biological world, tension forces do come into play, as in cobwebs and in tendons connecting joints.

When we stretch a string, there is only so much tension it can bear. Hanging a massive rock from a slender fiber is not a wise idea. Materials have a finite tensile strength, we say: if stressed beyond, they break. Even columns of liquid have tensile strengths. It is not easy, for example, to break a long column of water because its tensile strength is considerable.

Many key insights of modern physics had occurred, if not in as clear and final a form, to some ancient thinkers also. A case in point is the role of the tension force in the equilibrium of bodies which was studied and analyzed in remarkable detail by Leonardo da Vinci in the 16th century[14].

Normal Contact Force: *Reaction forces enable us to stand and sit.*

When you are standing on the floor, you know that your weight is pulling you towards the center of the earth. But there is no change in your state of motion. One has to conclude that another force is balancing your weight. This is a force exerted by the floor on you. Indeed, because of your weight you are pushing the floor downwards. Because of your (source) push (action) on the floor (target) in one (downward) direction, the floor (source) is pushing (reaction) you (target) back in the opposite (upward) direction. Such a force which a surface exerts on any body that is impressing upon it is called a *normal contact force*. Thus we see that normal contact forces are direct consequences of the law of action and reaction. Like all forces, these too cannot be seen save through their effects.

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[14] For details, see C Truesdell, *Essays in the History of Mechanics,* New York, pp.1–83, 1968.

Normal contact forces are what prevent the rude penetration of bodies into surfaces. It is because of these that objects can rest on tables, we can sit on chairs, and ladders can lean on walls. What this means is that such ordinary things we do, like standing and sitting, reclining and lying on bed, are possible only because of the so-called third law of motion. The roots of perceived reality have the most unsuspected aspects.

At this point let us stress the difference between a force and the experience of a force. When we press against a wall, we can experience the push of the wall against us. Similarly, we must distinguish between our weight and the experience of weight. That experience becomes available only when we are standing on a surface. That feeling is totally absent when we take a dive or if we happen to fall. Then we feel we are weightless. When we are in an elevator which is accelerating downwards, the floor is pressing on us with less than the force of our weight, and we feel lighter as a consequence. If the downward acceleration of the elevator is equal to that caused by the weight (the acceleration due to gravity), then we will feel no weight at all. This is precisely what happens to astronauts in earth satellites. The orbiting satellites are in free fall, and so the astronauts experience complete weightlessness.

Buoyancy: ***When a body enters water, upward forces come into play*.**

When we enter a pool we begin to feel lighter. We have not lost our weight, the downward pull; but an upward push by the body of water cancels out a part of the weight. This is the property of all fluids: to gently push in the upward direction anything and everything that is immersed in it. We call this the *buoyant* force. But for it, ships can't float, nor swimmers swim, for we need forces to counterbalance the earth's pull downwards.

A wooden plank floats and a metal sphere sinks. The upward thrust of water depends on how much a body is immersed in the water. If the buoyant force exceeds the weight of a body, then the body will not sink, but rather would be pushed to the surface. If the buoyant force is less than the weight of the body, the body will go right through and sink. If the two forces are equal then the body can remain pretty much anywhere within the fluid.

The buoys near lands where boats and ships come to anchor are meant to warn the pilots of rocks, cables, and the like. These floating objects and their name suggest that buoyancy is essentially a property of liquids. In fact, gases (and air) also display buoyancy. In other words, gases also exert an upward force on solids immersed in them, thus diminishing the net downward pull or weight. It is because of the buoyancy of air that balloons float in air.

That water exerts a buoyant force should be a matter of simple observation for anyone who was gone into a pool or even into a bathtub. Per a legend in science history, the principle of buoyancy came to Archimedes of Syracuse in a flash one day while he was in a public bath. In his great excitement, we are told, he ran stark naked into the streets screaming "Eureka! Eureka!," which in the language of the day is said to have meant, "I have found it! I have found it![15]" This story and cry have come to symbolize the joy of discovery[16].

Then again, consider the fact that much of the continental land mass is high above the sea level, enabling us to live on ground. Here too buoyant forces are at play: The granite and basalt rocks which constitute the continents are lighter than the material of the earth's rock mantle which lies underneath. The lands literally float up above, so to speak. This phenomenon is referred to as *isostasy*. What an unexpected revelation? Archimedes' buoyancy in the bath-tub and the drift of the continents on the earth's mantle are in fact related! Here is another root of perceived reality that is utterly hidden from our normal view[17].

Change of Forms: *Bodies change forms as a result of forces.*

We see bodies of various forms and shapes. Why are they not all the same? How can their forms be changed? Here again forces are involved. Forces not only cause acceleration, they can change the forms of bodies. When you press on a balloon or pinch a cheek, you are causing deformation: rather the force you are applying is causing deformation.

Deformation is possible because most solids are compressible. A body that is not so is said to be rigid. Rigid bodies suffer no change in shape even under great pressure, but there is no body that is perfectly rigid. From the bouncing ball to strong steel, everything is deformable. When you sit on a cushion or place you head on a pillow you are deforming the body because of the force you are exerting. When a child is playing with play-dough or a sculptor is shaping clay, substances are deformed. When the *roti*-maker rounds the mass of moist flour (dough) and flattens it to shape, we see what the deforming power of force can accomplish.

The deforming effects of forces may be seen not just in the compression of balloons or in the strokes of the blacksmith, but in the transformation of the world at large.

Then again, when we speak of evolution it is of species that we think. But ordinary matter too is evolving in shape and form, under the action of the many forces that are acting. The sun and

[15] For more on Archimedes and his work, see E J Dijksterhuis, *Archimedes*. University Press, Princeton, 1987.

[16] Though scholarship has debunked the charming "Eureka!" legend, metaphorically speaking, the word still stands for the Aha! experience of scientists and of others too. See in this context, Arthur Koestler, *The Act of Creation*, 1964, Penguin, 1990.

[17] For a technical and historical overview of isostasy, see A B Watts, *Isostasy and Flexure of the Lithosphere*, Cambridge University Press, 2001.

the stars were not always the same, nor the earth and its mountains and valleys. Eons from now, when you and I and our species will have gone for good, sun and moon will all look different, if on-lookers there still are, but the fundamental forces will never cease to act. Such, at least, is the worldview of current physics.

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Previous Parts: The World Above: Vol.15, No.10, pp.954–964; No.11, pp.1021–1030, 2010;
The Physical World: Vol.15, No.12, pp.1132–1141, 2010; Vol.16, No.1, pp.76–87, 2011;
On the Nature of Heat: Vol.16, No.2, pp.190–199, 2011;
Sound: The Vehicle for Speech and Music, No.3, pp.278–292, 2011;
Light: The Revealer of Chromatic Splendor, No.4, pp.359–371, 2011;
More on Light, No.5, pp.468–479, 2011;
Matter: The Stuff the World is Made of, No.7, pp.670–681, 2011;
More on Matter, No.8, pp.784–793, 2011;
Restless Motion: Its Variety and Relevance, No.10, pp.987–998, 2011.

V V Raman is Emeritus Professor of Physics and Humanities at the Rochester Institute of Technology, Rochester, New York 14623, USA. He is available for giving Skype lectures in Indian universities.
Email: vvrsps@rit.edu
http://en.wikipedia.org/wiki/Varadaraja_V. _Raman