Chapter 0: Mechanics Defined

MOTIVATION:

This text is an outgrowth of many years and much advice from students and teachers alike. We wished to organize and grow the material in a “cycle” approach to learning; the usual textbooks were difficult to use for this purpose. Our reasons for cycling are many. They include providing reflection time to digest new concepts and new calculations, and to help remember what was learned. We’ll talk more about these motives at the end of this chapter.

We do recommend acquiring a standard textbook for supplementary reading; they are full of beautiful examples for you to study. While in the past most students have not made frequent use of these supplements, they are still valuable references for future coursework, and for those who desire additional reading.

SYNOPSIS:

If we had one sentence to write about this course’s purpose, it would be to identify what interactions (i.e., forces) are present in any physical system, and figure out how the system will change in time as a result of those interactions. If there’s one piece of advice we would be allowed to give you, it is this: **please try to figure out ALL the forces that are acting on a system, draw pictures of those forces, and then use the equations coming from Newton’s laws to figure out what is going to happen to the system now and in the future!**

DEFINITION OF THE TITLE OF THE COURSE:

MECHANICS: The Motion of Bodies and how the Motion Depends on the Forces Acting on those Bodies

DEFINITION OF THE WORDS IN THIS DEFINITION:

- WHAT IS A **BODY**? For this course, we usually refer to blocks of wood, cars, air particles, planets, and (!) people, as bodies. A body is something fairly solidly held together (even rigid) so that when we talk about its position, we have some idea of where the body is. If it isn’t solidly bound together, that makes it more difficult to describe its position. For example, the location or position of a blob of ink spilled onto the floor is harder to describe, although we will talk about flexible bodies like ropes before long (and short ropes before long ones ☺).

- WHAT IS **MOTION**? To understand what motion is, we start by thinking about the body’s **position** and how it changes in time. That means we need the **velocity** (the time rate of change of position), and, because of Newton's laws described below, we also need the **acceleration** (the time rate of change of velocity) of the body.

- WHAT IS **FORCE**? Well, a body **accelerates** (changes its velocity, as we said) because there is some **interaction** between it and another body (some influence on its motion due to another body). Why? Well, this is what is behind Newton's laws. We think a neat way to start this introductory physics course in mechanics is to show you Newton's three laws straightaway. Why? Well, because everything we do in this course can be explained, and can be derived, from them.

REASSURANCE TO THE READER:

We will be going over the above definitions and concepts in detail throughout the text. This is especially true for the following discussion. The goal of this chapter 0 is to introduce the words and the foundations together with the promise we will come back and say the same things again!

VECTORS AND THEIR COMPONENTS ARE A VITAL MATH LANGUAGE:

When we begin to express our laws in a mathematical language, a crucial word of this language is "vector." We can describe the strength and direction of the interactions (that is, forces) by "numbers" that are called "vector components." That is, in our full three-dimensional (3D) world, there are three components needed for each force, which together represent the three directions (for example, F_x, F_y, F_z are the force components in the x, y, z directions). Each component is a positive or negative number. (In 2D, we have two components and in 1D, one component.)

For that reason, we love to speak the language of "vectors." (We will have a more detailed discussion of vectors as we move along.) The force vector corresponding to the set of numbers or components of the interaction is denoted by $\vec{F}$. $\vec{F}$ is a nice notation reflecting the fact that the 3 numbers (the force "components" in three dimensions) can be alternatively and equally described in terms of a direction and a magnitude. Hence the arrow over the F implies it has a direction. Similarly, we often use $\vec{r}$, $\vec{v}$, $\vec{a}$ for the position, velocity, and acceleration, all of which are vectors, too.

NEWTON'S THREE FAMOUS LAWS

1) Newton's First Law

If there is no acceleration, there is no net (by "net" we mean the total sum) force, and conversely, if there is no net force, there is no acceleration

$$\vec{F}_{net} = \sum \vec{F}_{individual} = 0 \;\Leftrightarrow\; \vec{a} = 0$$

By the way, the symbols $\Rightarrow$, $\Leftarrow$ mean "implies" in the indicated direction. The symbol $\Leftrightarrow$ means "implies" both ways. The idea that a body does not accelerate unless there is some interaction on it is understood better, when we discuss the second law.

2) Newton's Second Law

If there is acceleration, then the net force is not zero and is proportional to that acceleration at each instant in time: $\vec{F}_{net} \propto \vec{a}$. The proportionality constant measures how hard it is to move the given body, and it makes sense that this constant is the mass M

$$\boxed{\vec{F}_{net} = M\vec{a}}$$

Incidentally, we put a box around this last equation because it is the heart of the course. If we can find out how to satisfy it for any situation of interest to us, then we have "solved" many problems and can "predict the future" for the system. There will be short cuts we can take, however, for such predictions.

The idea that a body accelerates if there is some interaction on it can be rephrased in two equivalent ways:

VECTOR STATEMENT:

The vector force $\vec{F}$ causes (or drives) the vector acceleration $\vec{a}$.

COMPONENT STATEMENT:

That is, F_x, F_y , F_z cause (or drive) the accelerations a_x , a_y , a_z , respectively.

The mathematics behind the phrase "force causes acceleration" is the famous equation, $\vec{F}_{net} = M\vec{a}$.

3) Newton's Third Law

If the force on body 1 is due to body 2, then body 2 feels an equal and opposite force due to body 1.

$$\vec{F}_{\text{on 1 by 2}} = -\vec{F}_{\text{on 2 by 1}}$$

Here, we are *always* comparing one force on one body with another force on **another** body.

> ***These laws are rich***
> ***- everything we do in mechanics can be derived from them!***

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UNITS DIGRESSION:

All of our quantities for a mathematical description of nature have units, and all of these units can be related to the three primary units of length, time, and mass. We will primarily use SI units of **meters m, seconds s, and kilograms kg for lengths, times, and masses** (SI $\equiv$ System Internationale where we will often use "$\equiv$" to mean "defined by" or "equivalent to" or "means"). The littler length and mass units come in the "cgs" system and are centimeters cm, seconds, and grams g (1 m = 100 cm, and 1 kg = 1000 g).

For force, the SI unit is the Newton **N** as a short-hand for $\text{kg}\cdot\text{m}/\text{s}^2$.

That was the good. Now for the bad and the ugly. Even though in this country we comfortably use feet **ft** for length, and pounds **lb** for force (libra is the Latin word for pound), many respectable physics books avoid them. That way they don't have to deal with the unit of mass in the "U.S. Customary Units;" namely, the **slug**! BUT you will certainly want to know this on your future and frequent travels to the (only) other countries in the world that use them, Myanmar and Liberia, so we'll give the conversions here:

1 ft = 0.3048 m
1 lb = 4.448 N
1 slug = 14.59 kg

(We haven't even touched ounces, inches, pints, and other fun stuff.)

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GOAL FOR MUCH OF MECHANICS: GIVEN AN INITIAL SITUATION, WHAT HAPPENS LATER?

If a baseball is hit at some angle and speed, where does it end up 3 seconds later? How fast will a teeter-totter rotate through some angle with one kid heavier than another? What is the final speed if (shudder) one car crashes head-on into another car and they stick together?

There are also situations where we can **predict** whether something will stay put. Will it stay balanced? For example, is there enough friction to stop a ladder from sliding, given a certain angle of recline?

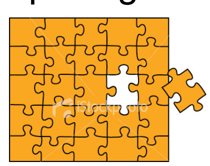
Using the wonderful approach of "Newtonian dynamics," as defined by Newton's laws, and knowing how to model the interactions by forces, we can figure out what will happen in the future. We can put our **forces into Newton's laws** and we will get an equation that, if we can solve it, the future is ours!

By "happen," we refer again to **what motion will occur,** including the situation where there is no motion at all. We may have an "equilibrium" where the system is stable and nothing moves. And by system, we mean the body or collection of bodies referred to before.

Hmmm ... did you actually read everything up to this point? We're not worried if you didn't (of course, if you didn't, who in the world are we talking to here?), since we are revisiting everything in this course. We will discuss briefly the cycle approach to revisiting at the end of this chapter.

GOAL FOR MOST OF MECHANICS STUDENTS: DOING HOMEWORK PROBLEMS THE NIGHT BEFORE THEY'RE DUE!

To help you so that you can wait until the last minute* to do your homework, we would like to emphasize that there are two general things we are trying to do in our problem solving: "completing the puzzle" and "predicting the future."



1) COMPLETE THE PUZZLE

We are given some combination of forces or motion information and we want to find out more about the motion or the forces. For example, if we know a body of mass m is going in a circle with radius R and speed v at a particular time, we will learn how to calculate the component of the acceleration pointing inward and toward the center of the circle. As another example, if we are given a plot of a position component for an interval in time, we can use its slope to find the velocity component.

* But please don't wait until the last minute!

2) PREDICT THE FUTURE

We can directly predict the future for constant force at any time, because we know how to handle constant acceleration. It's easy. We also can do that for non-constant force systems like springs.

But much of freshman physics revolves around using short cuts for more general motion. The short cuts are "conservation of energy, momentum and angular momentum." For example, we can quickly predict the speed at some lower position for a block sliding down a complicated but frictionless track, using energy conservation.

In solving problems, we often step back and ask what happens in words and in pictures, especially regarding the forces acting on the system or subsystem of interest. Over and over and over and over, we ourselves will draw pictures showing all the forces acting on a given body (the "free-body diagrams" FBD) and we will ask you to do the same.

THE CYCLE APPROACH TO LEARNING

The three-cycle approach to learning is as follows. For the first five weeks we lightly cover all the subject matter. In the next five weeks we go over it again with more sophistication and connections. In the final five weeks, we'll go over it again with the final desired level of mastery, while paying special attention to any area where the class may have had troubles. The top ten reasons **(*and perhaps what might be a reader's response* ☺)** for doing this are:

10) It helps students remember what they've learned. **(*But we don't want to!*)**

9) It provides an early picture of the whole course. **(*But then there's nothing to look forward to at the end!*)**

8) We won't have three months between the material at the beginning of the course and the final exam, and we won't get overwhelmed when the hardest material appears for the first time at the end of the course. **(*But it is better to spend less time on the hard stuff, if it's that hard!*)**

7) It is a natural fit into a three-exam schedule and what is really great is the possibility that your lecturer may decide that your overall grade for the three hour exams can be what you got on the third exam or the average, whichever is higher. This is because each exam covers all the material. **(*Well, why not replace it with the grade I got in physical education?)***

6) We now have a natural mechanism for returning to areas of difficulty. **(*If we didn't like it the first time, then we'd certainly rather not see it again!*)**

5) It is completely compatible with other new methods of teaching, such as "group homework." (***We don't like these methods, either!***)

4) It offers a natural cure for the "post-exam syndrome" where a student who does poorly on an exam feels bad because we"re moving on to new material before he/she has mastered the previous work. (***After an exam, I don't want to ever look at it again!***)

3) It is supported by psychology research that says we learn better by "layering" information rather than by a "continuous" approach. (***If I wanted to learn psychology, I wouldn't take physics classes!)***

2) It is supported by some previous CWRU experiments in a comparison with a "control" group. (***Who was in the control group? A bunch of "control freaks?" ☺)***

1) Former students who have been out of school for a few years feel this would have made a big difference for them. (***Sure, because they don't have to take any more courses!***)

Topics of Mechanics by Chapter for the Three Cycles
(each section of a chapter corresponds to a different cycle)

Ch 0: INTRODUCTION TO FORCES AND MOTION (cycle 1 only)

Ch 1: ZERO FORCE
- **1 (cycle 1): Constant and relative velocity in one dimension (1D)**
- **1+ (cycle 2): Relative velocity and right angles in two dimensions (2D)**
- **1++ (cycle 3): Relative velocity with general angles**

Ch 2: CONSTANT FORCE IN 1D
- **2: Acceleration, mostly constant force in 1D**
- **2+: "Catch-up and throw-up," intersections, graphical analysis**
- **2++: Problem solving ploys, drawing graphs of intersections**

Ch 3: CONSTANT FORCE IN MORE DIMENSIONS
- **3: Constant force in any dimension; 2D trajectories**
- **3+: More 2D constant-gravity trajectories and intersections**
- **3++: CM and relative motion in 2D trajectories**

Ch 4: GRAVITY FORCE
- **4: Newton's gravity and g, Kepler's laws introduced**
- **4+: Kepler's circular orbits, kinetic energy and potential energy**
- **4++: More KE and PE for orbits, escape velocity**

Ch 5: CONTACT FORCES (friction introduced later)
- **5: Pushes/pulls in 1D, ideal ropes and tension, third law examples**
- **5+: Strings of blocks and massive rope**
- **5++: Tension changes along a tug-of-war**