CHAPTER 2

Free-Body Diagrams

A free-body diagram is a sketch of the system to which you will apply the laws of mechanics. The diagram shows all of the non-negligible external forces and couples which act on the system. The diagram tells what material is in the system and also what is known, and what is not known, about the forces. Mechanics reasoning depends on free-body diagrams. So, we give tips about how to avoid common, and often calamitous, FBD errors.

We also discuss two key related ideas:
1) Equivalent force systems; and
2) Center of Gravity (or, Center of Mass)
On a free-body diagram, systems of forces are often replaced with 'equivalent' forces, a special important case of which is a weight force at the center of gravity. The center of gravity is also the Center of Mass, a key concept in Dynamics.

First, a language issue. Traditionally in mechanics, like in Newton's and Shakespeare's times, a system, or object, was often called a *body* (as in 'heavenly bodies'). When such a system is conceptually isolated it is *free*, as in *free* from its surroundings. So, translating to modern language, A *free-body diagram (FBD)* is a sketch of an isolated system and of the external forces, from outside the system, which act on it.

The laws of mechanics use the forces shown on a free-body diagram, and no other forces. Thus, as we can't repeat too much (but will attempt to), drawing good free-body diagrams is essential for both statics and dynamics. The skills for drawing these diagrams are presented in the following sections.

Some basic mechanics assumptions

Isolated systems. One way to understand something is to isolate it, see how it behaves on its own, and see how it responds to various stimuli. Then, when the thing is not isolated, you still think of it as isolated, but think of the effects of all its surroundings as stimuli. Reversing the point of view, we can also see the system's behavior as causing stimulus to other things around it, which themselves can be thought of as isolated and stimulating back, and so on.

This reductionist approach is used throughout the physical and social sciences. A tobacco plant is understood in terms of its response to light, heat flow, the chemical environment, insects, and viruses. The economy of Singapore is understood in terms of the flow of money and goods in and out of Singapore. And social behavior is regarded as being a result of individuals reacting to the sights, sounds, smells, and touch of other individuals and thus causing sights, sounds, smell and touch that the others react to in turn, *etc.*The concept of an isolated system is central in most of the reductionist sciences①.

①**Closed systems in thermodynamics.**The isolated system approach to understanding is made most clear in thermodynamics courses. A system, usually a fluid, is isolated with rigid walls that allow no heat, motion or material to pass. Then, bit by bit, as the subject is developed, the response of the system to certain interactions across the boundaries is allowed. Eventually, enough interactions are understood that the system can be viewed as isolated even when in a useful context. The gas expanding in a refrigerator follows the same rules of heat-flow and work as when it was expanded in its 'isolated' container.

The "*free-body*" is a closed system. As in elementary thermodynamics, we only consider here so-called *closed* systems. A (closed) system, in mechanics, is a fixed collection of material. You can draw an imaginary boundary around a system, then in your mind paint all the atoms inside the boundary red, and then define the system as being the red atoms, no matter whether they later cross the original spatial boundary markers or not②. Mechanics, as used by engineers, depends on bits of matter as being durable and non-ephemeral. Violating the theory of relativity:

A given bit of matter exists forever, has the same mass forever. A given bit of matter is either in a given system, or out of that system, for all time.

Mechanics is based on the notion that any part of a system (*i.e.,* a subsystem) is itself a system . And we assume that all interactions between systems or subsystems have certain simple rules, most basically:

② **Open Systems.** The mechanics of *open systems*, where material crosses the system boundaries, is important in fluid mechanics. Such open fluid systems are first seen in some elementary dynamics problems (like rockets), where material is allowed to cross the system boundaries. But the equations governing these *open* systems are deduced from careful application of the more fundamental governing mechanics equations of *closed* systems. So we have to master the mechanics of closed systems first.

Force is <u>*the*</u> *measure of mechanical interaction.*

Thus a person can be moved by forces, but not by the sight of a tree falling towards them or the attractive smell of a flower. Sights and smells may cause, by rules that fall outside of mechanics, forces (on the feet, *etc.*) that move a person. When a person moves towards a flower or away from a falling tree she is moved by the force of the ground on her feet not by sight, sound, smell or fear. Finally,

The principle of "action and reaction": what one system does to another, the other does back to the first.

When a person accelerates away from a falling tree because of the force on the ground, her feet push equally hard on the ground the other direction. Of course, when you think of this you think the other way around. To start running, you make a quick action, pushing on the ground with your feet. The *reaction* force accelerates you. But, what causes what is not the issue. Rather, if system A is pushed by B then B is pushed back equally by A. In kindergarten talk, 'it doesn't matter who started it.'

The rules above, which we call the zeroth[3] laws of mechanics, imply that all the mechanical effects of the outside world on a system can be represented by a sketch of the system with arrows showing the forces of interaction. If we want to know how the system, in turn, affects some part of its surroundings, we draw the opposite arrows on a sketch of that outside part.

[3] Why do we awkwardly number the most basic laws as zero? Because they are really more of an underlying assumption, a background concept, than a law. As a law they are a little imprecise since force has not yet been defined. You could take the latter two of these zeroth laws as an implicit and partial definition of force. The phrase "zeroth law" means "important implicit assumption". The third of the zeroth laws is usually called "Newton's third law."

Every single atomic force? OK, it is not practical to show every force from every atom that acts on a system. We cluster the forces, add them up and replace them with a single 'equivalent' force. 'Equivalent forces' are described in the next section. A special case of an equivalent force is the replacement of the billions of gravity forces acting on all the atoms in a system with a single force acting at the center of gravity, as shown in the next section.

Draw good free-body diagrams. The final two sections of this chapter tell you how to draw free-body diagrams. Draw a good free-body diagram and then well-use the vector skills of Chapter 1 and you have near-guaranteed success at doing mechanics problems.