AIR COMMAND AND STAFF COLLEGE

STUDENT RESEARCH REPORT

THE FREE-BODY DIAGRAM REVISITED

2500-80B

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THE FREE-BODY DIAGRAM REVISITED

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The purpose of this article is to review and hopefully revive interest in a procedure - the use of the free-body diagram - which is useful to students in an introductory mechanics course. This article provides a detailed discussion of the free-body diagram with examples and integrates the free-body diagram in to the problem-solving process.

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PREFACE

The establishment of general procedures is important in assisting a student in the study of any field. The purpose of this article is to review and hopefully revive interest in a procedure - the use of the free-body diagram -- which is useful to students in an introductory mechanics course. The author has used this procedure three years teaching introductory mechanics in the Department of Physics at the United States Military Academy. As Tipler indicates in his textbook Physics, the main problem, which students have in applying Newton's Second Law is identifying the proper mass and the forces acting on it. The free-body diagram emphasizes just this point. This article provides a detailed discussion of the free-body diagram with examples and integrates the free-body diagram in to the problem-solving process.

This article has been submitted to The Physics Teacher for consideration.

THE FREE-BODY DIAGRAM REVISITED

Michael T. Toole

THE FREE-BODY DIAGRAM REVISITED

INTRODUCTION

Students in introductory physics courses need sound problem-solving techniques to use with basic principles in solving problems. Many students experience difficulties in problem-solving because they attempt to memorize solutions rather than to apply basic principles in conjunction with effective problem-solving techniques to arrive at logical conclusions. For example, they memorize different methods for solving such specific types of problems as static equilibrium, centripetal force, motion on an incline, connected-body problems, free falling bodies, and projectile motion. They should learn, instead, to use a free-body diagram in conjunction with Newton's Second Law to solve these and many other problems.

This discussion describes a procedure for using the free-body diagram to solve problems involving Newton's Second Law. The procedure is not new, but both students and teachers agree that it is not sufficiently stressed in most schools. The Department of Physics at the United States Military Academy has used the procedure for a number of years in a core introductory physics course for approximately 1,000 students each year.

THE FREE-BODY DIAGRAM

The study begins with a review of steps in the problem-solving process and then describes the role of the free-body diagram in problem solutions. Problem-solving in physics involves the following step-by-step process:

1. READ: Read the problem and note the essential elements of the problem
2. GIVEN: List given data
3. FIND: List the data you are required to find
4. PICTURE: Draw a figure or diagram
5. PHYSICS: Write down the physics principles or laws involved and analyze the problem mathematically
6. SOLVE: Solve the algebra. Substitute the numerical data into equations and complete the numerical solution
7. CHECK: Check numerics, units, and dimensional consistency (Is the answer reasonable?)

The free-body diagram enters the problem solution in Step Four and involves the following procedure:

1. Isolate the body by removing all external constraints, such as ropes, cables, flat surfaces, or hinges that support the body.

2. Reduce the body to its simplest form, such as a point or a rod as appropriate.

3. Draw and label all forces given as "known" forces.

4. Replace all external constraints with forces in the proper direction. Some fundamental examples are

a. rope, cable, etc. (replace with a tension).

b. flat surface (replace with a normal force).

c. hinge (replace with two perpendicular forces).

5. Draw and label coordinate axes.

We can use the hanging mass shown in Figure 1a to illustrate the above procedure. Students should first isolate the body as shown and reduce it to its simplest form, in this case, a point. They now draw the "known" force, the weight of the mass, on the figure. They next replace the external constraint of the rope with a tension and, finally, they draw and label a coordinate system. (Figure 1b-d shows three other examples.) If the students can draw complete and proper free-body diagrams, they can complete the problem solution by writing Newton's Second Law in each of the component directions.

The instructor should emphasize the following dos and don'ts associated with free-body diagrams to prevent common student errors.

• The free-body diagram is not a picture in the sense that objects resemble their actual physical form. The body must be isolated and drawn in its simplest form, such as a point, a line. This is to insure the student understands which mass is being considered.

• Only forces are drawn on a free-body diagram. Acceleration and velocity vectors do not belong on a free-body diagram. This is an especially difficult problem for students attempting to solve problems which involve centripetal forces such as a car proceeding around a flat curve. Based on their experiences with cars, students commonly believe that an outward force should be shown on the free-body diagram. They fail to recognize that they feel an inertial effect caused by the tendency of a body in motion to remain in motion in the same direction unless an external force acts upon it. If the car is isolated, the only forces acting on it are the friction force acting radially inward and the weight of the vehicle caused by gravity acting vertically downward.

• Only external forces are shown; internal forces are not included. From Newton's Third Law, the sum of the internal forces is zero. For each action there is an equal and opposite reaction. In connected-body problems, the forces in the connecting member may be treated as internal forces. If the connecting member is cut, two equal forces act in opposite directions. The sum of these two forces is equal to zero. Connected-body problems may also be solved by drawing multiple free-body diagrams.

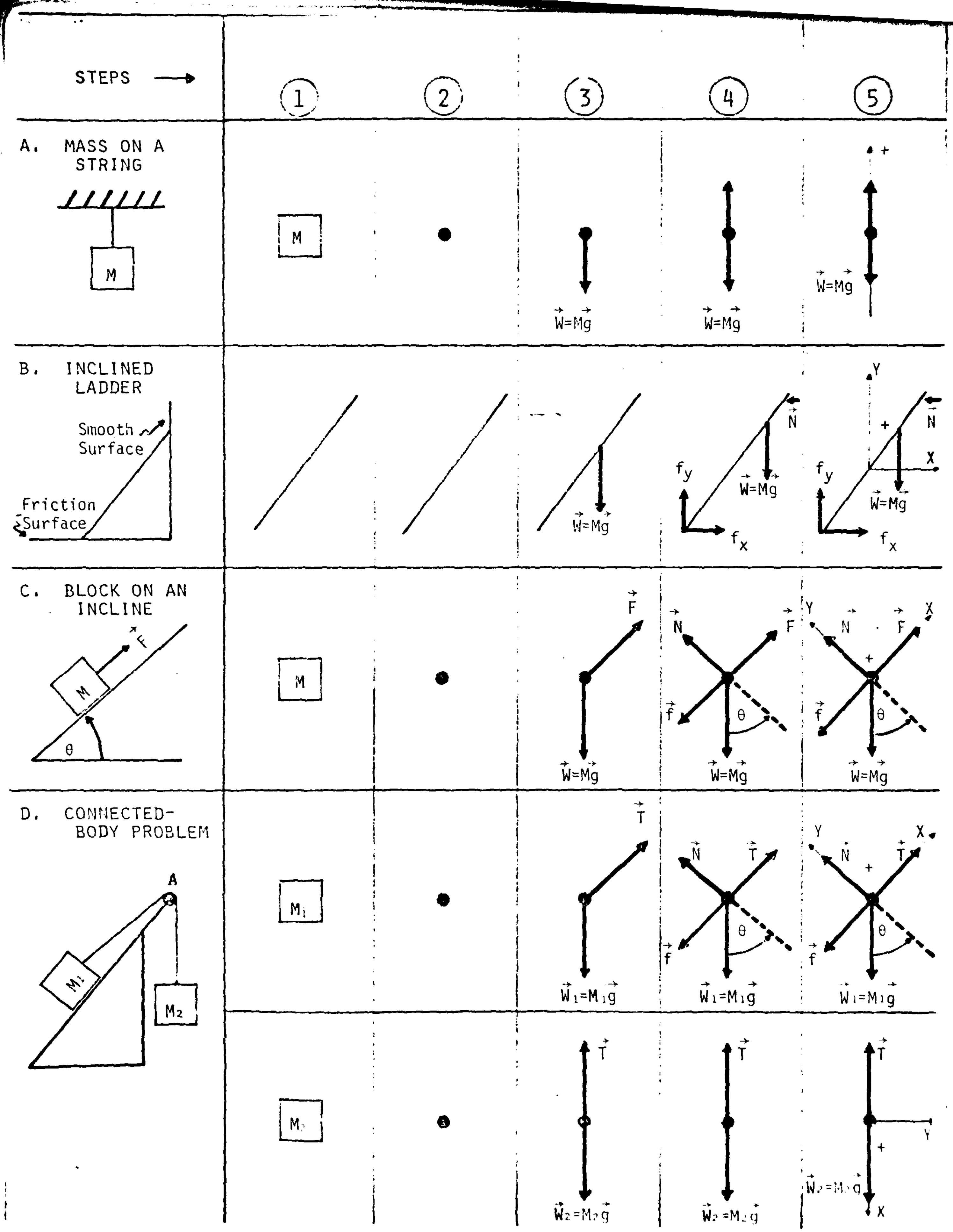
• If connected-body problems are solved by drawing multiple free-body diagrams, the coordinates must be consistent. For example, in Figure 1d, the coordinate system for m_1 is selected along, and perpendicular to, the incline. To maintain a consistent set of coordinates, one must simply slide the coordinate system along the connecting cord to m_2. This requires a rotation of the coordinate system at Point A.

• A judicious selection of axes can often simplify the computation of force components. Figure 1c shows an example in which the axes were selected along, and perpendicular to, the incline rather than in a horizontal and vertical direction. This reduces from three to one the number of forces that must be resolved into their components.

- The free-body diagram is integrated into the problem-solving steps to solve a simple problem shown in Figure 2. Following the problem-solving steps, the student reads the problem and notes the given data and the data to find. In the fourth step, he draws the free-body diagram according to the procedure given in the above discussion. The applicable law or physics principle is Newton's Second Law. The student need only write Newton's Second Law in its component form and solve the algebra to complete the problem. A check of numerics, units, and dimensional consistency should be made to verify the solution.

CONCLUSION

The free-body diagram should play a central role in introductory mechanics during the study of Newton's laws. Once the students have mastered the technique of drawing a proper free-body diagram, they need only write Newton's Second Law and solve the resulting equations. In his text, Physics Tipler points out that "many students' errors can be traced to a failure to identify clearly what mass is being considered and what all the forces acting on it are." This is precisely the reason for emphasizing the free-body diagram. The act of drawing detailed free-body diagrams drills students in recognizing the particular mass and forces involved. Any instructor who has required students to include a complete free-body diagram with the solution of problems involving Newton's Second Law immediately recognizes that Tipler is correct in his assessment of student difficulties. The problem, of course, stems from insufficient emphasis by instructors. The reduction of student difficulties in subsequent lessons more than compensates for the additional time spent in emphasizing the free-body diagram. Such introductory textbooks as Bueche's Introduction to Physics for Scientists and Engineers, Halliday and Resnick's Physics, and Tipler's Physics refer to the free-body diagram in problem-solving.



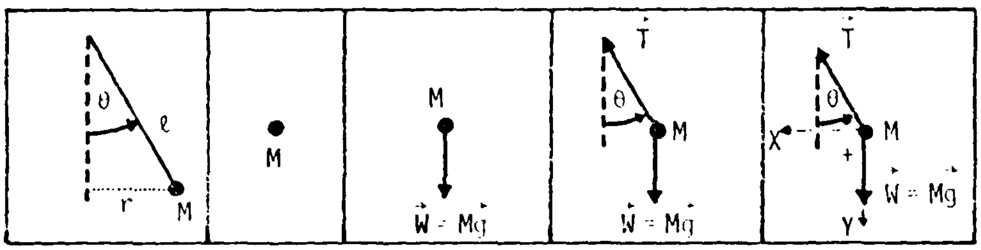
STEPS
1
2
3
4
5
A. MASS ON A STRING
M
W=Mg
+
B. INCLINED LADDER
Smooth Surface
Friction Surface
W=Mg
N
fy
fx
Y
X
+
C. BLOCK ON AN INCLINE
F
M
θ
N
f
W=Mg
Y
X
+
D. CONNECTED-BODY PROBLEM
A
M1
M2
T
W1=M1g
W2=M2g

Figure 1: Steps In Drawing A Free-Body Diagram
The Free-Body Diagram Revisited
Michael T. Toole

SAMPLE PROBLEM SOLUTION

CONSIDER A CONICAL PENDULUM THAT SWINGS IN A HORIZONTAL CIRCLE. FIND THE TENSION IN THE STRING AND THE SPEED OF THE BOB BY USING THE FOLLOWING PROBLEM SOLVING STEPS:

1. READ: Read the problem.
2. GIVEN: $\ell = 1.00\,m$; $M = 0.750\,kg$; $\theta = 30^{o}$
3. FIND: T
4. PICTURE: Free-body diagram.



5. PHYSICS: $\Sigma F = Ma$; $a_x = \frac{v^2}{r}$; $\Sigma F_x = Ma_x$; $\Sigma F_y = Ma_y$

6. SOLVE: $\Sigma F_x = Ma_x$; $\Sigma F_y = Ma_y$

$$T \sin\theta = M \frac{v^2}{r}$$

$$-T \cos\theta + Mg = 0$$

$$T \cos\theta = Mg$$

$$\tan\theta = \frac{v^2}{r}$$

$$v = \sqrt{gr \tan\theta} = \sqrt{(9.80)\,(1.00 \sin 30^{o})\,(\tan 30^{o})}$$

$$v = 1.68\ M/S$$

$$T = \frac{Mv^2}{r \sin\theta} = \frac{(0.750)\,(1.68)^2}{(.5)\,(\sin 30^{o})} = 8.47N$$ DIRECTED AS SHOWN

7. CHECK: Units, numerics, and dimensional consistency (Is the answer reasonable?).

Figure 2: Sample Problem Solution
The Free-Body Diagram Revisited
Michael T. Toole

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