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Efforts to Improve Free Body Diagrams

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Abstract

The goal of this paper is to present two novel approaches to teaching the components of and use of free body diagrams (FBDs) in core mechanical engineering courses at the Rochester Institute of Technology (RIT). The first technique is a mnemonic device to remember the key components of FBDs. This device is referred to as “The ABC’s of FBDs”. It uses the first four letters of the alphabet to identify required FBD components. The second pedagogical method developed and implemented is a game based off of “Paper Telephone”. The game emphasizes the connection between the FBD and the equations of equilibrium. At this point, these devices have only been utilized for 3 semesters however, anecdotal evidence indicates that the inclusion of these devices has aided in the retention of FBD components in follow on courses.

Introduction

It is frequently remarked within the mechanical engineering department that students in Statics, and in follow on courses, are underperforming in their ability to create well-crafted free body diagrams (FBDs). The instructional faculty were charged to identify pedagogical methods to improve student performance in Statics and the retention of key concepts. Two novel approaches were implemented over the 2016 academic year in the Statics course and continue to be used. A mnemonic device to remember the key components of free body diagrams was developed and demonstrated consistently in class. The device is referred to as “The ABC’s of FBD’s”. The first four letters of the alphabet identify an item that must be included in FBDs. The letter “A” stands for “All reactions and applied loads”, “B” stands for the “Body”, “C” stands for the “Coordinate System” and “D” stands for “Dimensions”. It is then stressed that the equilibrium equations or “E” comes after you’ve established “ABCD”. The second pedagogical method developed and implemented was a game based off of “Paper Telephone” which is used during review days. The game emphasizes the connection between the free body diagram and the equations of equilibrium and reinforces the idea that the “ABCD” components drive “E” or rather the FBD drives the equations of equilibrium. The combination of these two devices helps show the importance of the FBD in solving engineering problems.

Method 1 “ABCs of FBDs”

Statics text books are generally consistent in their descriptions of what should be included in free body diagrams. (Excerpts included in the Appendix.) They routinely describe what should and should not be included but do not do a satisfactory job of presenting the material in a way that is easily remember by students. With this in mind, the ABCD mnemonic device was developed. In class, it is presented in bullet format as shown:

- Ⓐ – All Forces
- Ⓑ – Body
- Ⓒ – Coordinates
- Ⓓ – Dimensions (Only for rigid bodies)

$\Rightarrow$ Ⓔ of Ⓔ – Equations of Equilibrium

(Stated – Your A, B, C and sometimes D drives your E of E).

While the order of the ABCD does not reflect the order generally followed when physically drawing the FBD, it does serve as a reminder to check that everything is included. Students are encouraged to always write the letters “ABCD” on their homework and exam papers.

In class, the process for drawing an FBD is outlined as follows. Initially students must identify an appropriate right handed coordinate system for the problem being solved. Next, the body is identified and isolated from its supports. The body is drawn in a location that is meaningful with respect to the coordinate system. At this point all known and unknown forces are placed on the body as vectors and are given labels. These forces may include but are not limited to applied forces, applied moments, reaction forces and reaction moments. When forces are not directed along the axes, the direction or angles must be included. The final part of the FBD is the inclusion of dimensions that are required to write the equations of equilibrium (specifically in rigid body problems).

It is emphasized to students that the FBD and equations of equilibrium are not stand alone items but are dependent on each other. If students find that they include a dimension or force in the equations of equilibrium that is not in the FBD then they must go back and add it in. Emphasizing the idea that the equations of equilibrium are driven by the free body diagram has helped students develop a clearer understanding of how and why FBDs are important to the problem solving process. In practice, instructors write ABCD $\Rightarrow$E on the board frequently when drawing free body diagrams as a constant reminder.

Let’s take a look at an example from Hibbeler’s text at how this maps to what’s already done. (Pearson has granted permission to use these images.)

To avoid confusion with the discussion of the technique, the point locations are renamed to be P, Q & R.

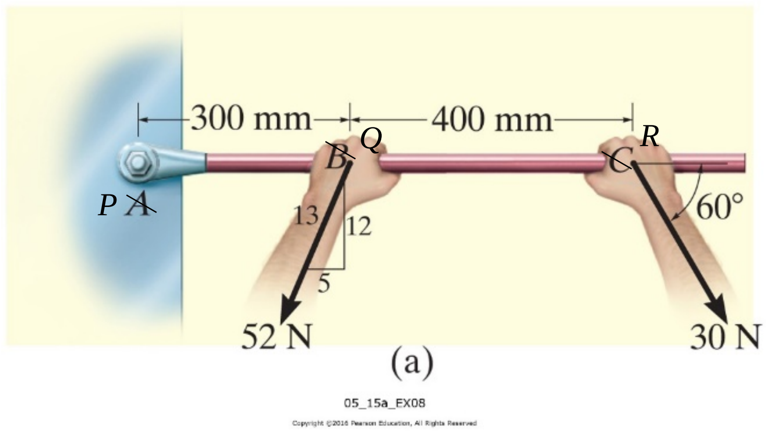


Figure 1: Example problem of a box wrench from Hibbeler[1].

The box wrench in the Figure 1 is used to tighten the bolt at *P*. If the wrench does not turn when the load is applied to the handle, determine the torque or moment applied to the bolt and the force of the wrench on the bolt [1].

Based on the problem statement, we'll treat *P* as a fixed support. We start with identifying the body – Ⓑ. Neither the hands nor bolt and included, just the bar. See Figure 2.

Figure 2: Body of the box wrench

Then we work on Ⓐ – all forces. This includes the applied forces from the hands, the magnitudes, the directions, and the arrowheads to indicate sense. Reaction forces are included, with labels and arrows indicating sense. Reaction moments are also included here with labels and the arrow indicating counter clockwise. See Figure 3.

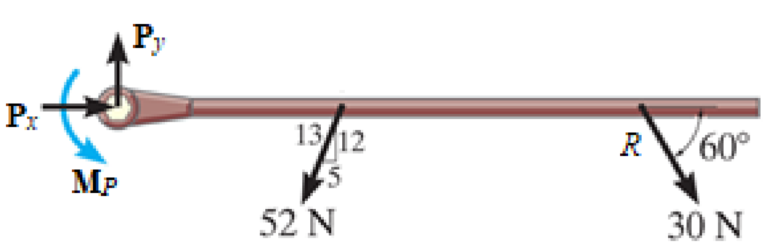


Figure 3: Body with applied forces

Figure 4 includes the coordinate system - Ⓒ.

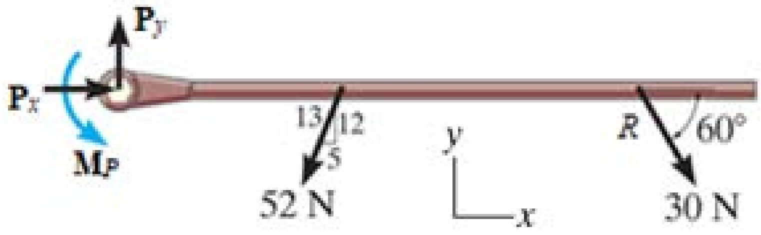


Figure 4: Body with applied forces and coordinate system

Finally, in Figure 5 we add the dimensions for moment calculations, Ⓓ.

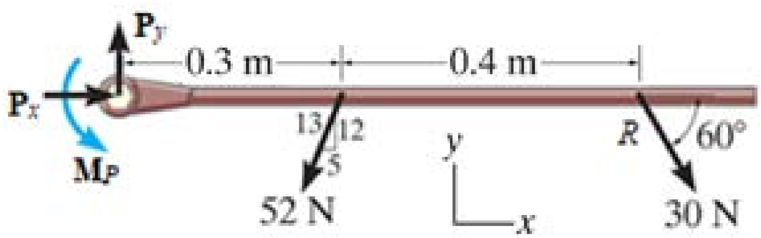


Figure 5: Complete free body diagram with applied forces, body, coordinate system and necessary dimensions.

This FBD is complete and ready for Ⓔ of Ⓔ, equations of equilibrium. A key area of reinforcement is that all items that appear in the equations of equilibrium need to be shown on the FBD. Upon writing the equations of equilibrium, if it's noticed that something is missing from the FBD, you should circle back and add it in.

The example shown is a simple 2D rigid body example, but the concept is repeated throughout the semester. Problems for which this method is used include particle equilibrium, 3D problems, structures such as trusses and frames, and problems including friction.

One method of measuring this impact was a student survey taken in the Strengths of Materials class. The survey text is provided in the Appendix. 52 students in Strengths reported that they had been shown the ABCs of FBDs method in either their Engineering Mechanics Lab or Statics prerequisite courses. At RIT, Engineering Mechanics Lab is a prerequisite course for Statics. The Mechanics Lab faculty have also adopted the ABCD method. 86% of the respondents said that the method was helpful or a little bit helpful in remembering FBDs. 67% of those (86%)

continue to use it in Strengths of Materials at least on an occasional basis. The responses are shown in Figure 6 below.

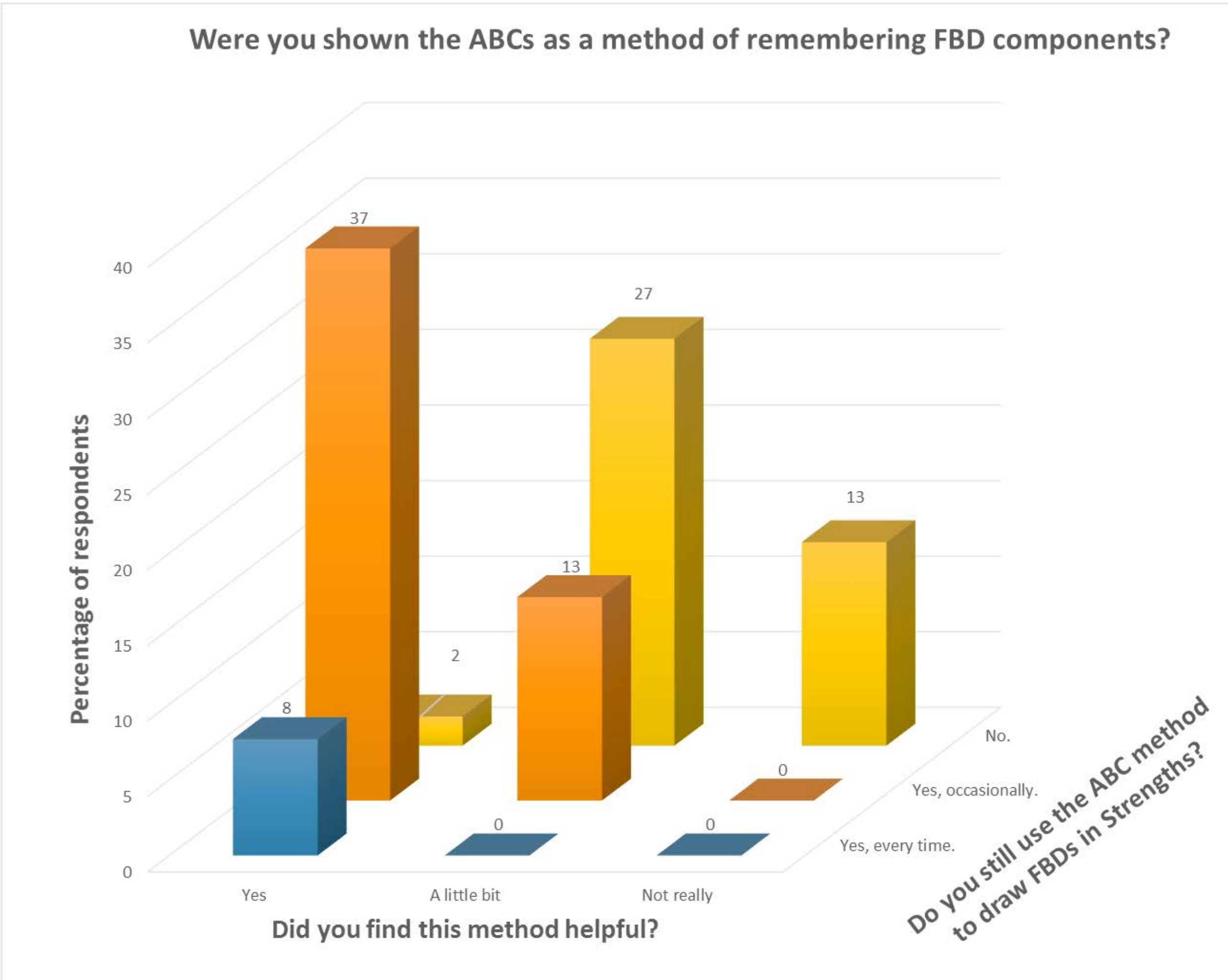


Figure 6: Survey of Strengths students regarding usage of prerequisite knowledge of free body diagrams

While specific performance data on FBDs from exams is not readily available, anecdotally the faculty teaching statics have noted that students are less likely to leave off dimensions or coordinate systems from the FBD. The ABCD device presented here is in-line with the steps outlined in popular statics text books for the formulation of FBDs. This method is not limited to applications of statics problems only but rather can be implemented and adjusted for other engineering courses. This device was presented to colleagues in the department and other courses have begun using it as well. The goal is to consistently use the mnemonic device throughout the undergraduate curriculum so students are presented with a consistent mindset for approaching engineering problems.

Method #2 - FBD telephone

Another tool was trialed to help students understand FBDs, their importance, and the connection to the equations of equilibrium. FBD telephone is a review game played in class before exams. The game is based off the game "paper telephone".

Before describing FBD telephone, here's a quick introduction to "paper telephone". Paper telephone combines the game of telephone, where you whisper a statement to someone and see how it changes, and the game of Pictionary. All you need is paper and pen for each player.

Each player starts the top of the page by writing a sentence. When everyone is done, or time is up, everyone will pass their papers clockwise. The next player reads the sentence and creates a drawing representing that sentence. After finishing the drawing, the paper is folded over so that the original sentence is not visible. (Alternately multiple pieces of paper in a stack can be used, rotating the top one to the back.) With just the drawing on top, this paper is passed clockwise again to the next player. Now players write the sentence they believe best captures what the image is showing. This alternates back and forth from sentence to image until it reaches the last player before the player who wrote the original sentence. As in telephone, the enjoyment in the game is seeing how far the original concept changed as it passed from player to player.

To utilize this technique in a class environment, some prep work is needed before hand. Typically a set of 5 review problem sheets are created and printed before class. An example of a blank review sheet is provided in the appendix. They typically look similar to the template in Figure 7. Break the class into groups. All group members should be actively engaged the entire time. Aim for 4 - 5 people in a group (Figure 8). Each student is given a sheet of paper with a different statics problem at the top. The students are instructed not to show their problem to any group members as this would ruin the game.

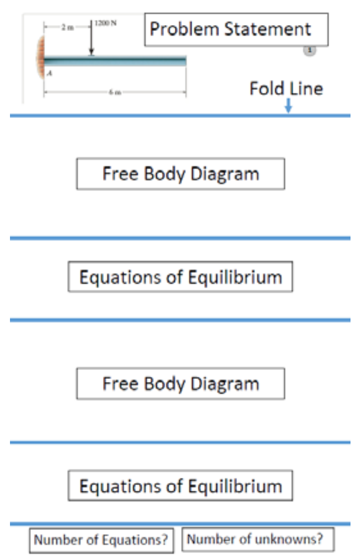


Figure 7: Example of a paper telephone starter sheet

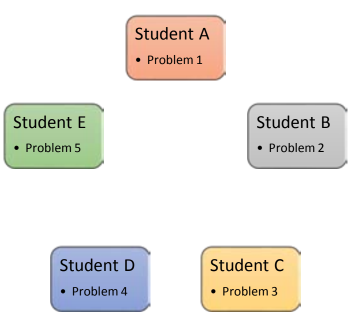


Figure 8: Original arrangment of students and problems for a game of paper telephone

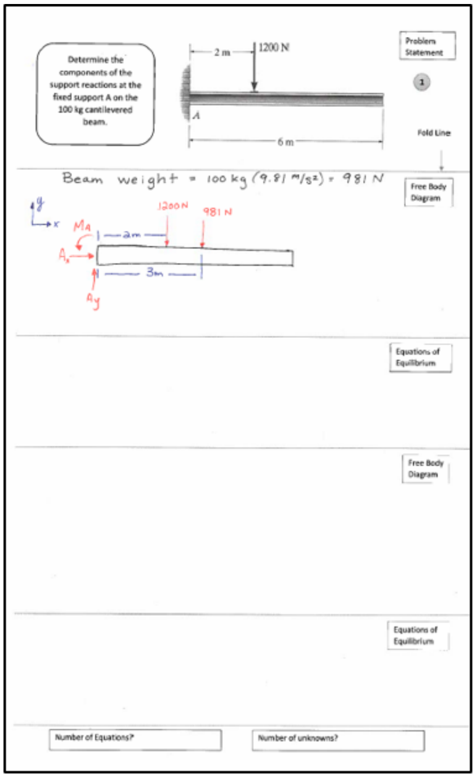


Figure 9a

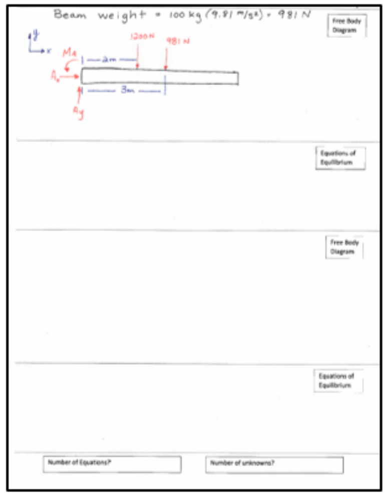


Figure 9b

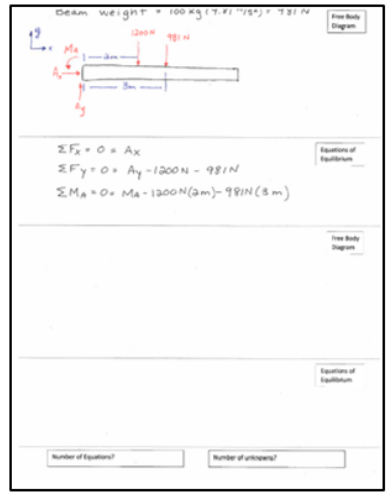


Figure 9c

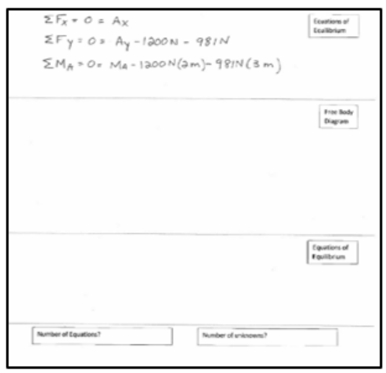


Figure 9d

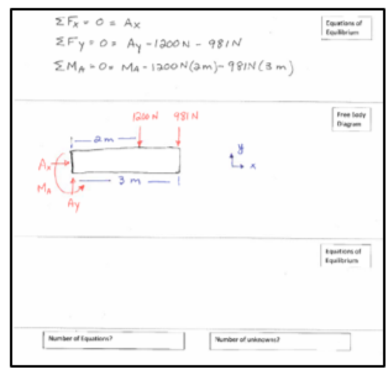


Figure 9e

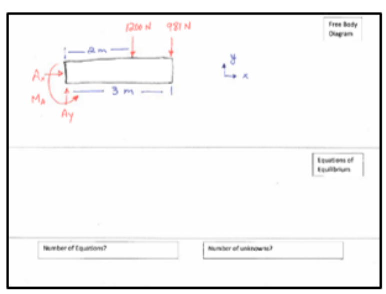


Figure 9f

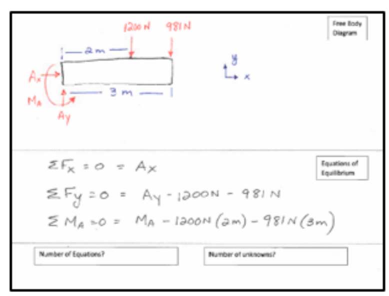


Figure 9g

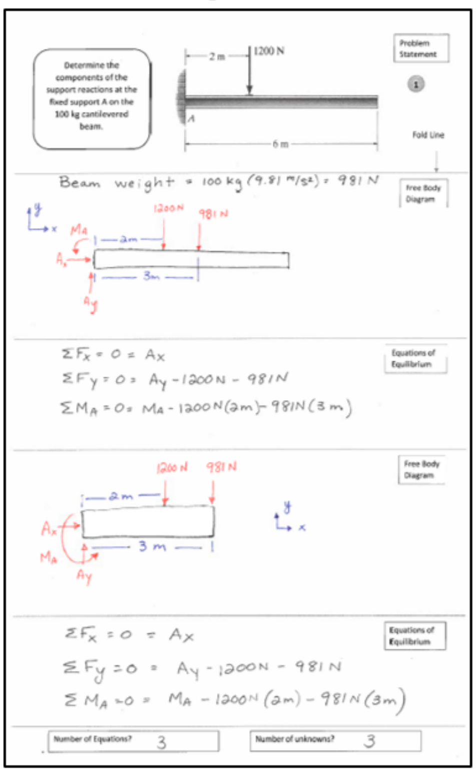


Figure 9h

Figure 9: Progression of steps moving through a game of paper telephone, featuring a statics rigid body equilibrium problem

The students are then given several minutes to draw a free body diagram of the problem described at the top of their page (Figure 9a). Once time is up, students fold the paper over, so that only their FBD is visible (Figure 9b). Students then pass their paper clockwise around the group (Figure 10). At this point, each student has a paper in front of them with their neighbors FBD. They are not allowed to unfold the paper to look at the problem description or schematic. This is done to emphasize that all information needed to solve the problem should be contained within the FBD.

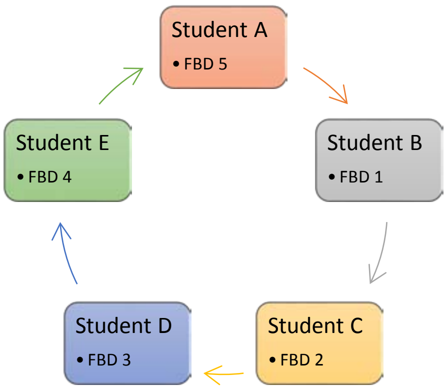


Figure 10: Flow of papers between students

With only the new free body diagram in front of them, the students then write the equations of equilibrium (Figure 9c). If the FBD they received was done correctly, then the equations should be straightforward to write. At this point there are two options. You can choose to allow students to ask the previous student for clarification. “I don’t see an angle on the FBD, where does this force point?” The other option is to enforce a no talking rule and see the “telephone” effect of incomplete information.

Once the equations of equilibrium are written, the students fold the paper again, so that only the equations are visible (Figure 9d), and pass again clockwise. Now the students will draw an FBD based only on the equations of equilibrium. Typically in statics, students aren’t asked to draw an FBD based on the equations of equilibrium, so this tends to be the most challenging point of the exercise. While this task can be difficult and time consuming, it poses a fun challenge for students (Figure 9e).

After the second FBD has been drawn, papers are folded (Figure 9f) and passed and the equations of equilibrium are written again (Figure 9g). The final step can be solving the problem, or checking the number of equations and the number of unknowns. At this point, students are allowed to unfold the papers to see the entire problem start to finish (Figure 9h). It is recommended that students spend time discussing what issues came up in the various problems to help them learn from their mistakes and emphasize the impact of omitting information from the FBD or the equations of equilibrium.

2D particle equilibrium problems are the simplest implementation for this exercise. It has been trialed with 2D rigid body problems, and 2D friction problems. Due to the complex nature of 3D free body diagrams, it is not recommended for 3D problems. Some issues arise in rigid body problems going from the equations to the FBD, where exact geometry can be difficult to obtain just from equations. Fortunately, going through the steps with the 2D particle equilibrium problems can be enough to refer back to at later points in the course. “Recall our game of FBD telephone and how critical it is to get your FBD correct before writing your equations of equilibrium.”

The paper telephone game on which this is based is available as a phone app. An opportunity for future development could be creating a similar device based game. As this game has been offered as a review opportunity, it has not been formally assessed. The time when it is given is an optional class time, making assessment difficult to make a distinction between the type of student who attends optional course reviews and the effect of the review game. Discussions with students have been positive.

Conclusion

In response to faculty observations that students continue to struggle with creating complete free body diagrams, the statics instructional team at the Rochester Institute of Technology developed two novel methods to help first year students recognize the importance of FBDs and recall the critical components therein. The ABCs of FBDs approach is consistent with common textbook approaches to make inclusion into other statics courses straightforward. The FBD telephone game offers students a unique, fun, review to cement the connections between well done FBDs and their associated equations of equilibrium.

APPENDIX A – Text Book Discussions of Procedures for Drawing Free-Body Diagrams.

Engineering Mechanics: Statics by R. C. Hibbeler , 14th Edition

(Permission to use images from Hibbeler has been given.)

Particle FBD – page 89 [1]

Procedure for Drawing a Free-Body Diagram

Since we must account for *all the forces acting on the particle* when applying the equations of equilibrium, the importance of first drawing a free-body diagram cannot be overemphasized. To construct a free-body diagram, the following three steps are necessary.

Draw Outlined Shape.

Imagine the particle to be *isolated* or cut "free" from its surroundings. This requires *removing* all the supports and drawing the particle's outlined shape.

Show All Forces.

Indicate on this sketch *all* the forces that act *on the particle*. These forces can be *active forces*, which tend to set the particle in motion, or they can be *reactive forces* which are the result of the constraints or supports that tend to prevent motion. To account for all these forces, it may be helpful to trace around the particle's boundary, carefully noting each force acting on it.

Identify Each Force.

The forces that are *known* should be labeled with their proper magnitudes and directions. Letters are used to represent the magnitudes and directions of forces that are unknown.

Rigid Body FBD – page 214 [1]

Procedure for Analysis

To construct a free-body diagram for a rigid body or any group of bodies considered as a single system, the following steps should be performed:

Draw Outlined Shape.

Imagine the body to be *isolated* or cut "free" from its constraints and connections and draw (sketch) its outlined shape. Be sure to *remove all the supports* from the body.

Show All Forces and Couple Moments.

Identify all the known and unknown *external forces* and couple moments that *act on the body*. Those generally encountered are due to (1) applied loadings, (2) reactions occurring at the supports or at points of contact with other bodies (see Table 5–1), and (3) the weight of the body. To account for all these effects, it may help to trace over the boundary, carefully noting each force or couple moment acting on it.

Identify Each Loading and Give Dimensions.

The forces and couple moments that are known should be labeled with their proper magnitudes and directions. Letters are used to represent the magnitudes and direction angles of forces and couple moments that are unknown. Establish an *x*, *y* coordinate system so that these unknowns, A_x, A_y, etc., can be identified. Finally, indicate the dimensions of the body necessary for calculating the moments of forces.

Vector Mechanics for Engineers: Statics, by Ferdinand P. Beer, E. Russell Johnston Jr., and David Mazurek, 11th Edition

Particle FBD – Page 45 [2]

"Drawing a clear and accurate free-body diagram is a must in the solution of any equilibrium problem. This diagram shows the particle and all of the forces acting on it. Indicate in your free-body diagram the magnitudes of known forces, as well as any angle or dimensions that define the direction of a force. Any unknown magnitude or angle should eb denoted by an appropriate symbol. Nothing else should be included in the free-body diagram. Skipping this step might save you pencil and paper, but it is very likely to lead you to a wrong solution" [2].

Rigid Body FBD – Page 171 [2]

1. "Start with a clear decision regarding the choice of the free body to be analyzed. Mentally, you need to detach this body from the ground and separate it from all other bodies. Then you can sketch the contour of this isolated body.
2. Indicate all external forces on the free-body diagram. These forces represent the actions exerted *on* the free body *by* the ground and *by* the bodies that have been detached. In the diagram, apply these forces at the various points where the free body was supported by the

ground or was connected to the other bodies. Generally, you should include the *weight* of the free body among the external forces, since it represents the attraction exerted by the earth on the various particles forming the free body. You will see in Chapter 5 that you should draw the weight so it acts at the center of gravity of the body. If the free body is made of several parts, do *not* include the forces the various parts exert on each other among the external forces. These forces are internal forces as far as the free body is concerned.

3. Clearly mark the magnitudes and directions of the known external forces on the free-body diagram. Recall that when indicating the directions of these forces, the forces are those exerted on, and not by, the free body. Known external forces generally include the weight of the free body and forces applied for a given purpose.

4. Unknown external forces usually consist of the reactions through which the ground and other bodies oppose a possible motion of the free body. The reactions constrain the free body to remain in the same position; for that reason, they are sometimes called constraining forces. Reactions are exerted at the points where the free body is supported by or connected to other bodies; you should clearly indicate these points.

5. The free-body diagram should also include dimensions, since these may be needed for computing moments of forces. Any other detail, however, should be omitted" [2].

APPENDIX B – Student Survey Text

Student Survey

Were you shown the ABCs as a method of remembering FBD components? If so, in which class were you introduced to the method?
___ I was not shown the ABCs.
___ Eng Mech Lab (MECE-102)
___ Statics (MECE-103)
___ Other (Please indicate which class if you remember)

____

Did you find this method helpful?
___ Yes
___ A little bit
___ Not really

Do you still use the ABC method to help draw FBDs in Strengths?
___ Yes, every time
___ Yes, occasionally
___ No.

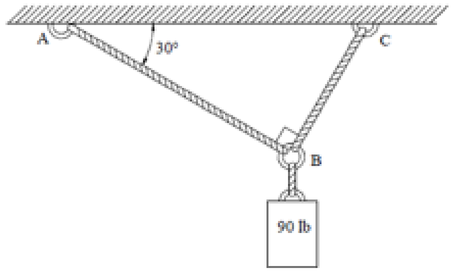
If you would like to provide more feedback via email, please provide your email address and (names omitted) will follow up with you.

____

APPENDIX C – FBD Telephone

Blank Template

Determine the tension in cables AB and AC.



Problem Statement

1

Fold Line

Free Body Diagram

Equations of Equilibrium

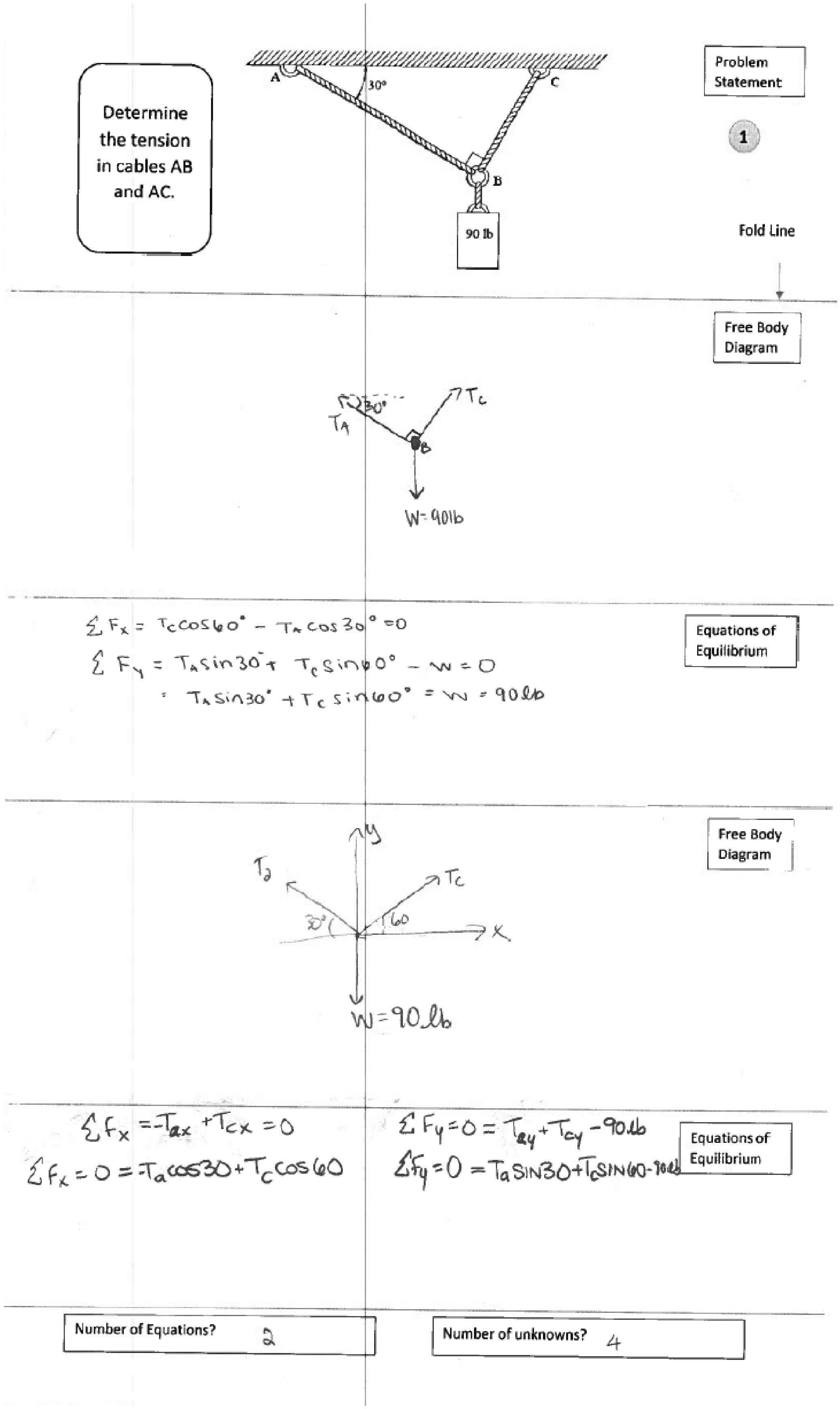
Free Body Diagram

Equations of Equilibrium

Number of Equations?

Number of unknowns?

Example of a fairly well done game.



Determine the tension in cables AB and AC.

Problem Statement

1

Fold Line

Free Body Diagram

Equations of Equilibrium

$\Sigma F_x = T_C \cos 60° - T_A \cos 30° = 0$

$\Sigma F_y = T_A \sin 30° + T_C \sin 60° - W = 0$

$\therefore T_A \sin 30° + T_C \sin 60° = W = 90 lb$

Free Body Diagram

Equations of Equilibrium

$\Sigma F_x = -T_{ax} + T_{cx} = 0$

$\Sigma F_x = 0 = -T_a \cos 30 + T_c \cos 60$

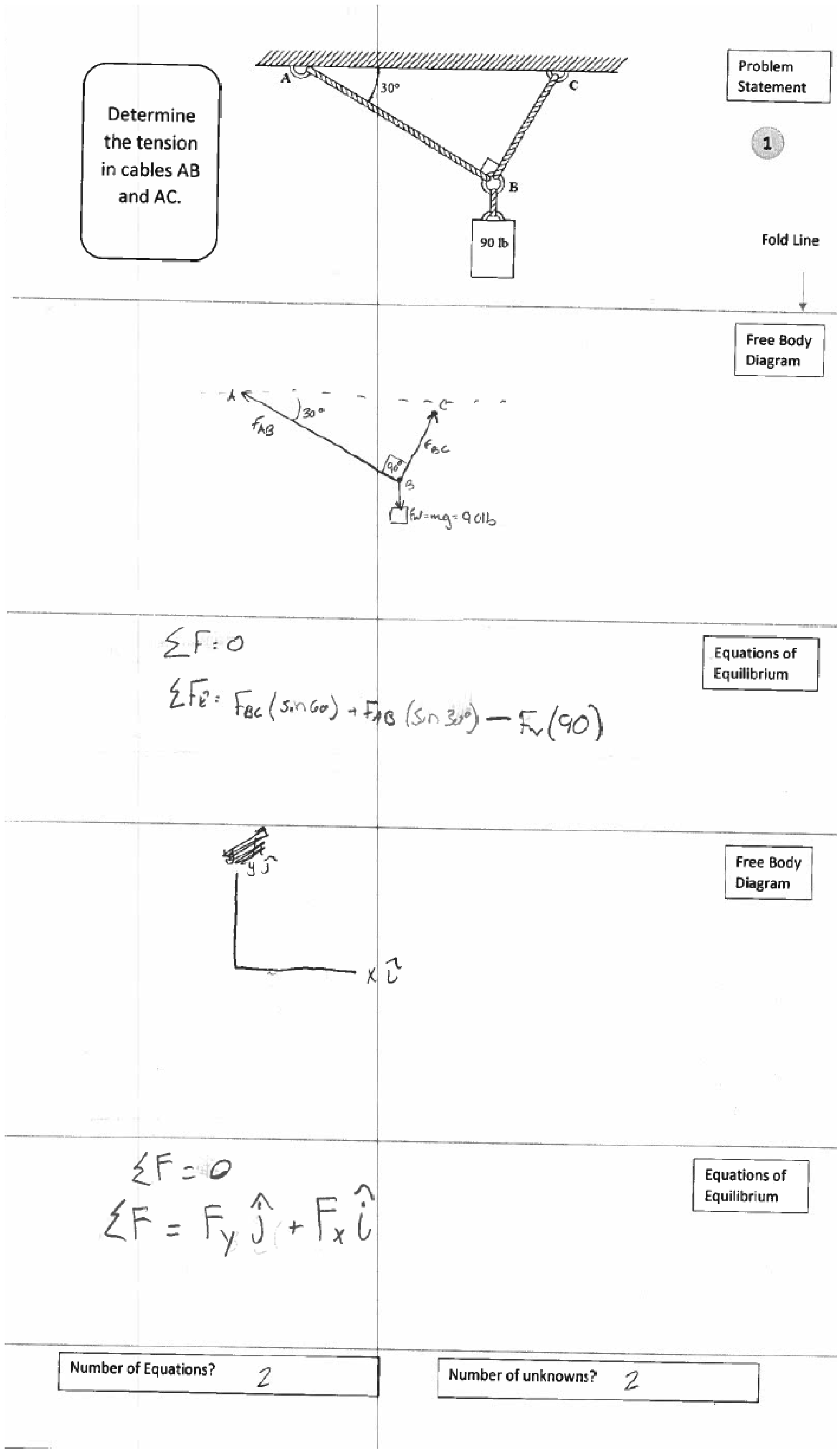
$\Sigma F_y = 0 = T_{ay} + T_{cy} - 90 lb$

$\Sigma F_y = 0 = T_a \sin 30 + T_c \sin 60 - 90 lb$

Number of Equations? 2

Number of unknowns? 4

Example of a poor game, where students struggled.



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[1] R. Hibbeler, *Engineering Mechanics: Statics*, 12th ed. Hoboken, NJ: Pearson Prentice Hall, 2016

[2] F. P. Beer, E. R. Johnston Jr., and D. Mazurek, *Vector Mechanics for Engineers: Statics*, 11th ed. New York, NY: McGraw Hill Education, 2016.