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How do Students Explain Their Errors in Free Body Diagrams?

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She has also incorporated theories on social cognitive career choices and student attrition mitigation to investigate the effectiveness of institutional interventions in increasing the retention and academic success of talented engineering students from economically disadvantaged families. She's also involved in a project that explores the relationship between the institutional policies at UPRM and faculty and graduate students' motivation to create good relationships between advisors and advisees.

How do Students Explain Their Errors in Free Body Diagrams?

1. Introduction and Literature Review

The ability to draw a Free Body Diagram (FBD) of a mechanical system or subsystem is a core skill and essential element of a mechanics problem-solving procedure, and is arguably useful for analogous problems in systems and network theory. Although free body diagrams are mentioned frequently in the mechanics education literature, surprisingly few studies have inquired deeply into the general question "why do students draw free body diagrams in the way that they do?" The particular focus of this article is to examine why students make errors at end conditions such as rollers, pins, and fixed ends.

To better understand what research has been done about student drawn free body diagrams, a literature review was conducted by searching for "free body diagram" conjoined with phrases such as "(think)aloud", "(written)explanation", "(verbal)explanation", "interview", "error type", "error classification", etc. Approximately 80 articles were accessed and reviewed, 66 of which are categorized (see Table 1). Of these, 22 articles provided details of error patterns, student reasoning, or recommendations directly related to drawing free body diagrams, though several do this in the context of a larger problem solving context. An annotated bibliography of these 22 articles is provided in Appendix 1.

Table 1. Summary of Articles Related to the Student Process of Drawing Free Body Diagrams.

Articles	Comments
[1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]	22 articles provide qualitative insight into student thinking about free body diagrams and/or error classifications
[23], [24], [25], [26]	5 articles provide quantitative information about error rates and/or student performance metrics at least in part related to ability to draw free body diagrams.
[27], [28], [29], [30], [31], [32], [33], [34], [35], [36], [37], [38], [39], [40], [41], [42], [43], [44], [45]	20 articles include study of free body diagrams as part of an overall mechanics problem solving procedure.
[46], [47], [48], [49], [50], [51], [52], [53]	8 articles relate to free body diagrams as part of online tutoring systems.
[54], [55], [56], [57], [58], [59], [60], [61], [62], [63], [64], [65], [66]	13 articles did not provide direct information about student performance on drawing free body diagrams.

To begin, three articles presented lists of error classifications for free body diagrams. Steif [1] articulated 11 common errors in Statics, with E1-E9 directly related to construction of free body diagrams (E10 and E11 incorporate the notion of equilibrium). Steif proposed that each error is associated with at least one of four core concepts (C1-C4) and one of four core skills (S1-S4) Lee, Stahovich & Calfee independently articulated 16 rules for free body diagram errors in conjunction with an online tutoring system that was designed to accept student input, provide feedback, and suggest corrections [2]. Litzinger et al. [9] provided lists of "justification statements" for students to select when drawing reaction forces in free body diagrams. These rules are summarized in Table 2, slightly edited from the original texts (the mapping of the rules of Steif onto the rules of Lee et al. was performed by the authors).

Table 2. Summary of Free Body Diagram Errors Classifications

Common errors identified by Steif (2004) [1]	**Rules for FBDs identified by Lee et al. (2011)** [2]; the corresponding error from Steif (2004) is added by the authors (in parentheses).
E1: Failure to be clear as to which body is being considered for equilibrium: (C4). E2: Failure to take advantage of the options of treating a collection of parts as a single body, dis-membering a system into individual parts, or dividing a part into two: (C4, S3). E3: Leaving a force off the free body diagram (FBD) which should be acting: (C1), (S1). E4: Drawing a force as acting on the body of the FBD, even though that force is exerted by a part which is included in the body of the FBD: (C4), (C1), (S1). E5: Drawing a force as acting on the body of the FBD, even though that force does not act directly on the body: (C4), (C1), (S1). E6: Failing to account for the mutual (equal and opposite) nature of forces between connected bodies that are separated for analysis: (C4), (C1), (S1). E7: Ignoring a couple that could act between two bodies or falsely presuming its presence: (C2), (C3), (S2). E8: Not allowing for the full range of possible forces, or not sufficiently restricting the possible forces: (C2), (C3), (S2), (S4). E9: Presuming a friction force is at the slipping limit (µN), even though equilibrium is maintained with a friction force of lesser magnitude: (C3) E10: Failure to impose balance of forces in all directions and moments about all axes: (C4). E11: Having a couple contribute to a force	1. Incomplete formulation, single free body diagram problem: does not include all of the forces that must be solved for. (E3) 2. Statically indeterminate, single free body diagram problem: contains too many unknowns and thus is unsolvable. (E4, E5)* 3. Statically indeterminate composite free body diagram: has drawn only the free body diagram for the entire system and it is statically indeterminate. (E2)* 4. Incomplete decomposition: has decomposed the problem into multiple free body diagrams, but one or more of them is statically indeterminate. (E2)* 5. Missing free body diagrams: has decomposed the problem into multiple free body diagrams, but additional free body diagrams are needed. (E2) 6. Pivot support modeled improperly: One or more of the two force components is missing or the components are not orthogonal. (E3) 7. Roller modeled incorrectly: The normal force is missing, the normal force is not actually normal to the surface, or a friction force is included. (E4, E5, E8) 8. Incorrect applied force: An applied force (vs a reaction force) is missing, in the wrong direction, or has the wrong label. (E5) 9. Flexible element modeled incorrectly: The force is missing, is not aligned with the element, or is not in tension. (E8) 10. Rough surface contact modeled incorrectly: Either the friction force, normal force, or both are missing or in the wrong direction. (E9) 11. Internal Forces: The free body diagram includes forces

summation or not having a moment summation include a couple: (C2). C1. Forces act between bodies C2. Combinations and/or distributions of forces acting on a body are statically equivalent to a force and couple C3. Conditions of contact between bodies or types of bodies imply simplification of forces C4. Equilibrium conditions are imposed on a body. S1. Discern separate parts of an assembly and where each connects the others S2. Discern the surfaces of contact between connected parts and/or the relative motions that are permitted between two connected parts S3. Group separate parts of an assembly in various ways and discern external parts that contact a chosen group S4. Translate the forces and couples which could be exerted at a connection (e.g., there is only a force in a known direction) into the variables, constants, and vectors that represent them	internal to the system. (E4) 12. Two-force member: One or both of the forces on the ends of the two-force member are missing, they are not in opposite directions, or they have different labels; or there are one or more extra forces. (E8) 13. Newton's Third Law error: A pair of reaction forces does not satisfy the third law of action and reaction: one reaction has more components than the other, the forces are not in opposite directions, or the forces have been given different labels. (E6) 14. A multi-force body confused with a two-force member, having exactly two equal and opposite forces at locations that have a bar-like shape. (E8) 15. Missing forces: Any missing forces not explained by other rules are simply reported as missing forces. (E3) 16. Extra force: Any extra forces not explained by other rules are simply reported as extra forces. (E4, E5)
"Justification Statements" examined by Litzinger at al. (2009) [9]	
Group 1 (a,b) should include an X-reaction because the connection **prevents/does not prevent** motion in that direction. (c) should include an X-reaction because applied forces must be balanced. (d,e) **should/should not** include an X-reaction because no other connection prevents motion in that direction. (f) should NOT include an X-reaction because the connection does not prevent motion in that direction. (g) should NOT include an X-reaction because there are no forces applied in the X-direction. (h) should NOT include an X-reaction because the connection prevents motion, making friction irrelevant. Group 2 (a,b) should include a reaction couple because the bar is **free/not free** to rotate about that point. (c) should include a reaction couple because forces on the body create moments that must be balanced. (d) should include a reaction couple because no other connections prevent rotation about that point. (e,f) should NOT include a reaction couple because the bar is **free/not free** to rotate about that point. (g) should NOT include a reaction couple because there are no couples applied to the body. (h) should NOT include a reaction couple because other connections prevent rotation about that point.	

There are many further developments and studies that examine errors and reasoning related to free body diagram understanding and construction. The 11 errors proposed by Steif led to his development of the Statics Concept Inventory [3], now known as the Concept Assessment Tool for Statics (CATS)[1]. Subsequent studies examined expository student responses to selected concept inventory questions [4], [5], [6], [7], not only validating the CATS, but revealing student reasoning free body diagrams, including student explanations of some errors. Further, it has been argued that a general reason for making errors in FBDs results from conceiving forces as 'substances' or objects, rather than interactions [7], [11]. Douglas et al. [7] frame these

[1] The CATS is available for deployment at the Concept Warehouse, https://conceptwarehouse.tufts.edu/cw/.

“substance-based” errors in terms of students assigning an object-based ontology to force rather than understanding it as a process of interaction. In this view, force may be treated as locational (existing “in” or “on” an object), containable, or transitional (moving from one object to another), rather than as arising from interactions between bodies. Such reasoning can lead students to describe “tension in the rope” or to treat forces as quantities that reside within components of the system and are transferred between them, instead of as relational quantities defined by interactions.

Several studies provide recommendations for procedures for drawing FBDs. Danesh-Yazdi [12] recommends using exploded FBDs, including drawing FBDs of supports or anchors. Cornwell & Danesh-Yazdi [13] further identify three “poor practices” observed in textbooks and common practice: (i) assuming cable tension is equal to the weight attached, (ii) drawing a normal force reaction directly on a pin rather than on the original support, and (iii) drawing all forces concurrently. Mongan et al. [16] and Low & Wilson [17] independently investigated the students’ confusion with normal forces and weight, exposing the possible idea that this is rooted in a confusion of Newton’s 2nd Law for the Third, and presenting instructional strategies to ameliorate the confusion. Tang [25] provides a detailed procedure to draw FBDs, including introducing the convention in which the tip of the force is drawn at the point of contact where the force acts (with the exception of tension forces, where the tail should be used).

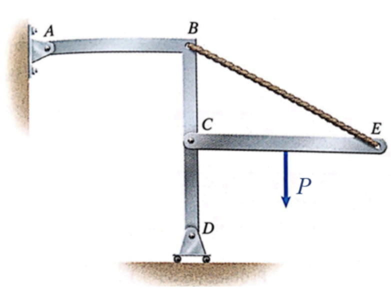
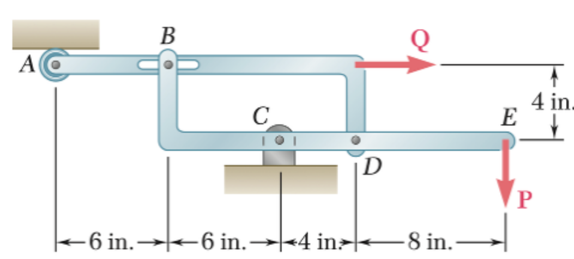
The literature provides some evidence to suggest that the ability to draw free body diagrams is associated with general success in solving mechanics problems. Litzinger reported “we learned that the weaker students were poorer performers in creating free-body diagrams and formulating the equilibrium equations, with one caveat. The two groups were about equally likely to forget to use a moment balance equation.” Rosengrant et al. [18] observed that “high achieving students used the free-body diagrams to help evaluate their work” while McCarthy & Goldfinch [26] conclude that “those who have mastered the FBD early in their engineering studies do have an advantage when it comes to engineering mechanics.” Complementing these results, Mahmutović et al. [23] demonstrated that drawing FBDs is more useful than having them provided.

2. Research Question and Methods

As demonstrated, the literature contains several studies that provide insight into student reasoning related to drawing Free Body Diagrams, including some in which students provide explanations regarding why they drew the FBD in a certain way. However, a complementary question appears not to have been directly investigated: *How do students explain their errors in free body diagrams?* With this in mind, this study poses the following restricted version of this question: *How do students explain their errors in drawing external reaction forces in free body diagrams?*

The motivation for pursuing this question is somewhat anecdotal, but is based on the authors' reflective listening to student comments during office hours when working on free body diagrams. What began as an insight about why students draw extraneous forces (paraphrasing, "I thought I needed to add a force here to balance that load over there") developed into a more general study. The first two authors (who are at two different institutions) maintain a regular communication about teaching Statics, in part due to their use of similarly designed short test questions throughout the semester, which provide a natural basis for a collaborative study. In the Fall 2025 semester, they decided to research this question together with the third author (who has ample prior experience with qualitative studies about mechanics reasoning), taking advantage of the fact that they each routinely give similar short test questions that exclusively focus on drawing free body diagrams, but without equilibrium analysis or other calculations.

The problems under study, presented in Figure 1, are related to free body diagrams of frames: Problem A (delivered and graded by the first author, "Instructor A") and Problem B (delivered and graded by the second author, "Instructor B"). As shown, the problems are substantively and stylistically similar, requiring multiple free body diagrams of elements of the given frame, including the requirement that interacting members are consistently drawn with respect to the principle of action-reaction. The differences in wording reflect the emphatic styles of the instructors rather than a controlled experimental manipulation. Whereas Problem A specifies "consistent" free body diagrams, this is implicitly expected by Instructor B (diagrams should be mutually consistent with respect to the action-reaction principle). Likewise, Problem B specifies "state your assumptions" (e.g., rigid bodies, negligible friction, planar behavior), but this is a general expectation established with Instructor A. Secondly, the authors used different grading platforms, per their preferences and available resources (coincidentally, Instructor A was testing an institutional trial for Gradescope during Fall 2025).

<table>
<tr><th>Problem A</th><th>Problem B</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Consider the frame that consists of the L-shaped bracket ABCD, horizontal arm CE and cable BE. The load P is applied at the midpoint of C and E. Assume that all elements have negligible weight. Carefully examine all connections and supports. Draw consistent Free Body Diagrams of the following:</td><td>The system shown is subjected to forces P and Q.

(a) Draw a FBD of member ABD
(b) Draw a FBD of member BCDE
(c) State your assumptions</td></tr>
</table>

(a) member *ABCD*; (b) horizontal member *CE*; (c) cable *BE*; (d) the entire system, separated from its supports at *A* and *D*. Notes: This problem was graded using Gradescope and repeated standardized comments from the rubric.	Notes: this problem was manually graded with the instructor using consistent comments.

Figure 1. Problem Statements for which Student Explanations of Errors were Surveyed.

In general, the differences in problem wording do not change the core problem solving expectations or grading standards. Although variations in problem phrasing can in some instances influence student responses, analysis of the collected data did not indicate a meaningful relationship between the requirement to state assumptions in Problem B and the targeted conceptual errors. Students in Problem B generally articulated appropriate modeling assumptions; however, they continued to include extraneous reaction forces or mischaracterize support behavior in their free-body diagrams. The types and distributions of errors were qualitatively similar across both contexts despite this difference in expectations.

To collect data, students from the Fall 2025 sections of Statics taught by Instructor A and Instructor B were asked to voluntarily respond to a written questionnaire in which they would provide images of their graded work and then provide comments to explain why they committed each error. The instructions emphasized that this was distinct from making a correction. Moreover, this process is distinct from a think-aloud process, in which students provide explanations for their decisions in real time while they are working on a problem. In this study responses from 52 participants for Problem A and 15 participants for Problem B are analyzed. A detailed profile of the students for Instructor A and Instructor B is provided in Table 3.

Table 3. Demographic Summary of Students for Instructors A and B.

	Instructor A Enrollment	Instructor A Respondents	Instructor B Enrollment	Instructor B Respondents
Overall Total	92	52	63	15
Male	59	28	49	10
Female	32	24	13	5
Non-binary	1	0	1	0
1st year	0	0	0	0
2nd year	23	9	60	15
3rd year	42	30	3	0
4th year	20	9	0	0
5th year or higher	7	4	0	0

3. Results

Four common errors were identified corresponding to the supports (occuring at points *A* and *D* in Problem A; occurring at points *A* and *C* in Problem B). Further, for each error type, several reasons were identified. Table 4 reports the list of error types ("T") and "substantive" reasons ("R") that were provided. Here "substantive" reasons are those that provide some direct insight into student reasoning and which could potentially suggest an instructional response. In contrast, other "reasons" that are excluded from this analysis are those that are self-evident (e.g., the student explained that they did not understand the problem, without providing a clearer reason as to why they made the error), "reasons that are confused with corrections", and other remarks that were not generalizable. The frequency in Table 4 reports the total number corresponding to the error type T, not the explanation R. The total number of errors exceeds the number of participants because several students made more than one error in a given problem.

Table 4. Error Types and Corresponding Substantive Reasons Provided

Error Type (Steif Error Type)	Prominent "Substantive" Reasons (explanations) provided	Frequency Prob A Prob B
T1. Missing support reactions (E3)	R1. Aligned force parallel to adjacent member	7 (9%) 3 (25%)
	R2. Presence of support/anchor already accounts for reaction	
T2. Body not isolated from supports (E1)	R3. Support/anchor is part of the body under study	26 (35%) 1 (8%)
	R4. Support/anchor is drawn to provide clarity, completeness, or specificity	
T3. Extraneous: torque drawn at pin or roller (E7)	R5. Did not distinguish a pin vs fixed support	16 (21%) 3 (25%)
	R6. Edge of pin support is fully fixed to wall	
T4. Extraneous: at roller, force drawn parallel to direction of allowed motion (E5)	R7. Did not distinguish a roller vs pin	23 (31%) 5 (42%)
	R8. Terminus of member is pin-connected to the roller support	
	R9. Force must exist in direction of allowed motion	
	R10. Force is drawn to prevent structure from moving	

3.1 Error T1: Missing Support Reactions. Several students who omitted a reaction at a support gave explanations like this student from Problem A: "I thought that at that point, since it was anchor connected, I didn't have to put the forces of that pin." A Problem B student remarked similarly, "I missed that there was a pin connection there." Such explanations are classified as "R2. Presence of support/anchor already accounts for reaction". On the other hand, one Problem A student expressed "I thought the pin only pushed sideways because the bar looked horizontal. I forgot that a pin can push both sideways and up or down. Because of that, I did not include the vertical force at point A." This explanation is classified as "R1. Aligned force parallel to adjacent member". Examples are shown in Figure 2.

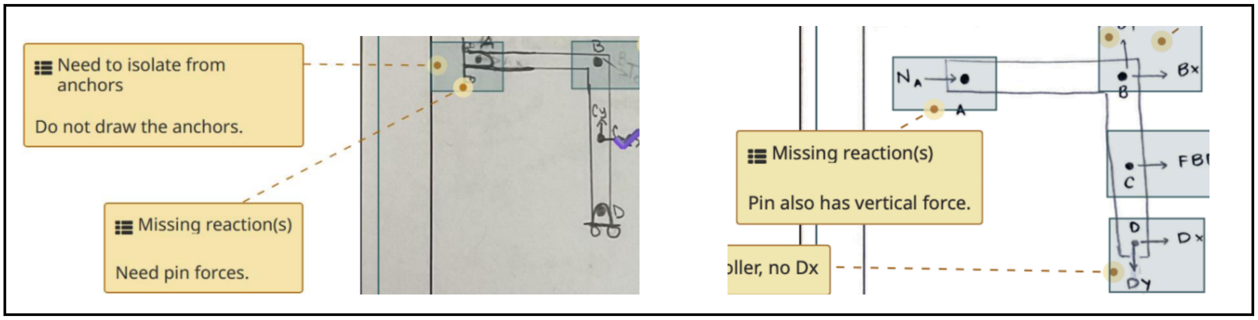


Figure 2. Examples of Error T1. Excerpts from Problem A.

3.2 Error T2: Body not Isolated from Supports. Not separating anchors from the body is often viewed as a 'nitpicking' error, with students not noticing the issue. Errors of this nature are characterized by comments from two Problem A students: "I thought that drawing the anchors didn't make a difference" and "I thought when we isolate bodies I had to draw supports too". These illustrate "R4. Support/anchor is drawn to provide clarity, completeness, or specificity" in which the student likely thought that they needed to include the support as a justification of their reasoning. In contrast, one student from Problem A remarked "When working on point *D*, I didn't fully isolate it from the anchor because I was thinking of the support as part of the structure instead of treating it as an external interaction", demonstrating "R3. Support/anchor is part of the body under study". Example drawings of these errors are provided in Figure 3.

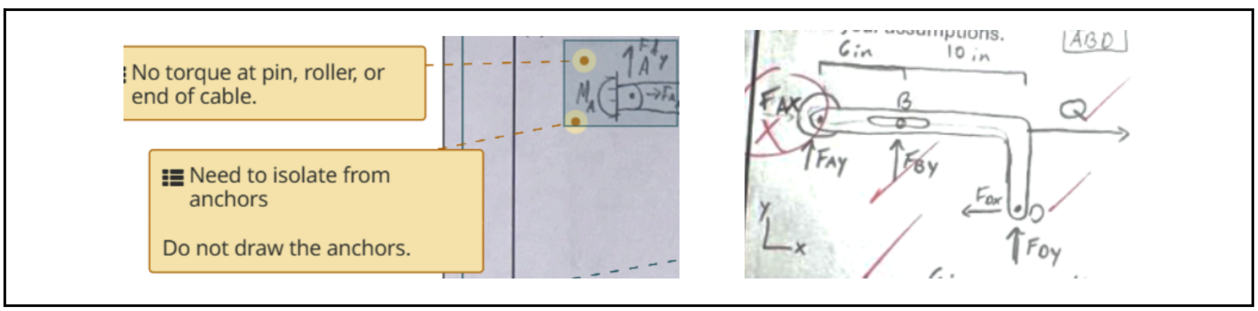


Figure 3. Examples of Error T2. Left, Problem A Excerpt. Right, Problem B Excerpt.

3.3 Error T3: Extraneous: torque drawn at pin or roller. Many students acknowledged not recognizing the difference between a pin and fixed connection, such as these students from Problem A: "I didn't recognize that was a pin and thought that all connections (pins, rollers, etc.) had torque" and "I thought that pins could resist torque, but they only provide Ax and Ay." Errors such as this were classified as "R5. Did not distinguish a pin vs fixed support."

In contrast, some students appeared to have understood the distinction between these two reaction types, but misunderstood how to apply those ideas. One student from Problem A remarked: "I was analyzing the system as if the platform bolted onto the wall was part of the system. Rather than considering the end of the system at pin *A*, and that is connected to the platform via a bolt.” Similarly, another student from Problem A stated “I understood that Point *A* included the anchored support, thus why I added torque to the FBD and why I included the support” and a student from Problem B stated “At the time, I thought… there was a connection to a surface, there must be a moment.” These remarks are classified as “R6. Edge of pin support is fully fixed to wall” and reveals an overgeneralization that any surface contact implies rotational restraint. Examples of these errors are shown in Figure 4.

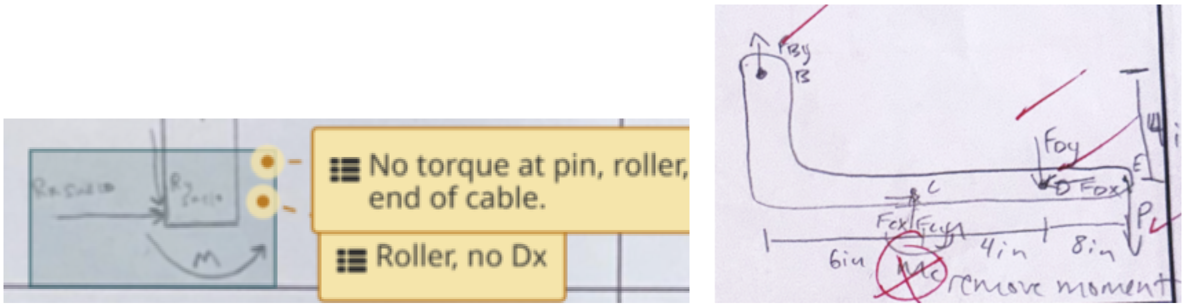


Figure 4. Examples of Error T3. Left, Problem A Excerpt. Right, Problem B Excerpt.

3.4 Error T4: Extraneous: at roller, force drawn parallel to direction of allowed motion. Of the common error to draw the “parallel” force at the roller, many students acknowledged that they did not distinguish between different kinds of reaction types, such as expressed by this student from Problem A: “I thought that it was a pin not a roller, but it was mostly a confusion and not observing very well the test.” A Problem B student gave a nearly identical remark, “Thought the connection was a pin, not a roller”, and another Problem B student said “I don’t think I realized that A was a roller, so I put two forces instead of one…”. These reasons are classified as “R7. Did not distinguish a roller vs pin”, which is analogous to R5.

Some students articulated a more distinctive reason. Some Problem A students said “Since it has a roller I thought it would have movement in the x direction but forgot we only put the forces it restrains” and “I thought that since the rollers move horizontally, they would have a Dx force.” Comments like these reflect a tendency to associate allowable motion with the need for a resisting force and are classified as “R9. Force must exist in the direction of allowed motion.” Yet interestingly, other students believe the opposite, such as “I thought that since it wasn't moving I needed a Dx”, classified as “R10. Force is drawn to prevent structure from moving.”

Finally, one Problem A student noted “I got confused and thought that in point *D* the pin exerted the force instead of the roller, making me commit the error of putting both the *Dx* and *Dy* reactions.” This is classified as “R8. Terminus of member is pin-connected to the roller support” and is analogous to R6. Examples of error T4 are provided in Figure 5.

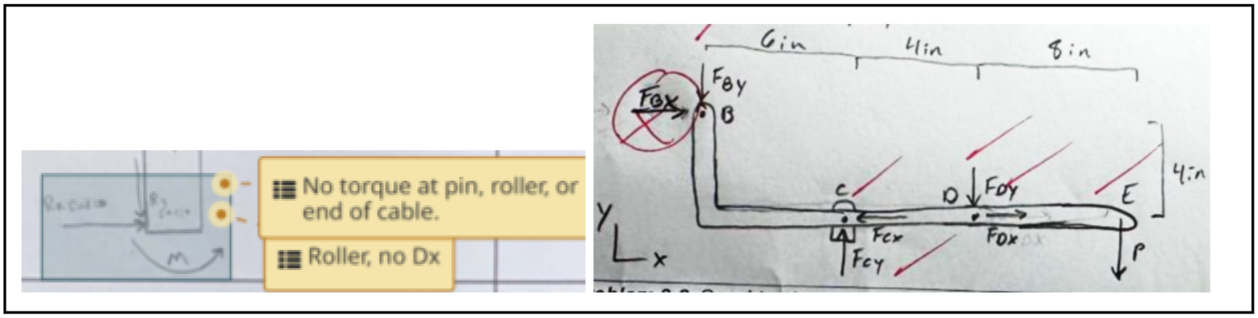


Figure 5. Examples of Error T4. Left, Problem A Excerpt. Right, Problem B Excerpt.

An important question is whether students who articulated accurate explanations of their errors continued to exhibit these misconceptions on subsequent assessments. In Instructor B's course, a mastery-based learning (MBL) framework required students to submit test corrections addressing all identified errors in order to be eligible for reassessment. Mastery was defined as earning full credit on a free-body diagram assessment, indicating a solution free of errors of any type. By the end of the semester, 59 of 63 students (94%) achieved mastery on a cumulative FBD assessment. Of the 15 students included in the present analysis, 14 (93%) ultimately demonstrated error-free free-body diagram construction on a subsequent assessment.

While this study did not track the persistence of individual error types longitudinally, these results indicate that the identified misconceptions were not uniformly persistent when students engaged in structured correction and iterative reassessment. Because reassessment was embedded within the course structure, the study does not isolate which instructional elements contributed to eventual mastery.

4. Discussion

The identified error patterns and associated substantive explanations provide actionable insights for instruction. In particular, reason codes R5 and R7 indicate difficulty distinguishing among support types, which might echo the work of Litzinger et al. in which the ability to understand and use symbolic representations might explain (at least in part) errors in free body diagrams [8], [9], [10]. Perhaps this issue is not solely about mechanics theory but also involves the meta-goal of focusing attention on recognizing established symbols versus bypassing them.

Other reason codes suggest that students are thinking about the relationship between reactions and motion, but with competing misconceptions of reactions corresponding to freedom instead of fixity (R9) versus misconstruing the overall fixity of the structure (global) instead of local constraints at the support (R10). The latter of these corresponds with other observations in the literature, such as "[a]lthough the students were provided with a free body diagram, he added his own additional support reactions, because he believed that a couple was required to prevent the rotation of the beam" [20]. Collectively, these patterns point to the need for more explicit attention to distinguishing kinematic freedom from force existence, especially for pin and roller supports, and for more deliberate contrasts between allowable motion and admissible reaction forces.

Reason codes R3, R6, and R8 further suggest that some students struggle to clearly define the boundary of the body under study, even if they seem to understand the different reaction types rotely. This could be due to a misunderstanding of how to sharply define the "end" of the body under study (that is, should an "anchor fixture" be included or excluded when considering an external support?). Perhaps sharpening question wording might clarify what is meant by "isolated" or "separated" (several students have suggested this verbally to Instructor A), but too much prescriptive detail will detract from training students to make their own assumptions and interpretations. Instruction may therefore benefit from more explicitly separating the acts of isolating the body and identifying external interactions before assigning reaction types. Because many written explanations revealed internally coherent yet incomplete reasoning, structured opportunities for articulation and correction appear particularly valuable. Requiring students to explicitly identify and revise incorrect reaction forces may help shift attention from procedural diagram completion toward conceptually grounded modeling.

5. Conclusions

This work investigated reasons why students commit errors in free body diagrams – specifically errors at external reactions – using a post-test written survey instrument. Although reliable error classifications for free body diagrams have been developed [1], [2], and some qualitative studies have provided some evidence of student explanations of errors, similar general classifications of the reasons for the errors do not appear to have emerged.

The results show that many students offer substantive error explanations (in the sense defined in the first paragraph of Section 3), while others do not. This illustrates one possible limitation of this study, which is the reliance on the student's ability to coherently explain an error. On the other hand, in cases in which students can provide a coherent, substantive explanation, instructors can glean insights that will provide insight on how to address the issues.

Much future work remains, in at least three areas. Immediately, several other errors were observed, with preliminary reason codings, but are not yet reported here. Among these is the very important and prevalent error related to the action-reaction principle, including confusing this principle with equilibrium [16], [17] and failing to correctly illustrate twin reactions with the opposite sense. Second, although the reasoning codes R1-R10 were phrased in a manner to allow generality of use, there are still questions if they are too item-specific. Further work with more problems could understand how to better generalize them. Third, further study should be undertaken to better understand how the error reasons correspond to other general possibilities, such as reliance on rote heuristics [15], inability to manipulate and recognize symbolic representations, or other deeply held preconceptions.

Ultimately, it is hoped that the current results and others from the literature will inform teaching of Free Body Diagrams, helping instructors better anticipate and address student errors, leading to improved strategies, and ultimately improved learning. While the scope of this article does not focus on how to develop or implement such strategies, the authors believe that in general, study of student explanations of both reasoning and errors can help instructors recognize phenomenological primitives that represent not merely 'errors', but opportunities to clarify and redirect prior conceptions. In Appendix 2, some preliminary thoughts and speculations about potential specific strategies are presented.

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Appendix 1. Annotated Bibliography of References [1]-[22]

Article	Description
[1] Steif 2004	Postulated 11 statics errors E1-E11; first 9 directly relate to FBDs. Suggested that errors correspond to 4 concepts and 4 skills. No qualitative study of student explanations.
[2] Lee et al. 2011	"NP2's rule base contains a total of 61 rules for free body diagram errors. Here we summarize the major conceptual errors these rules diagnose:" • Roller: The normal force is missing, the normal force is not actually normal to the surface, or a friction force is included. • Pivot: One or both force components for the pivot support is missing. • Weight force is missing or in the wrong direction. • Moment not included on the free body diagram, or is drawn in the wrong direction. • Two-force member error: missing or incorrect free body diagram for the two-force member; body is modeled with two pivots each having two unknown force components; • Third law error: A pair of reaction forces does not satisfy action-reaction: one reaction has more components than the other, the forces are not in opposite directions, or the forces have been given different names. • Forces internal to the system are erroneously included on the free body diagram. • Other extra forces: The free body diagram erroneously contains other forces not considered in the other error categories. The study of 91 students showed that most improved from pretest to post test as a result of the rule-based tool. No qualitative study of student explanations.
[3] Steif & Dantzler, 2005	Statics Concept Inventory developed. "Psychometrics based on the sample of 245 test-takers indicated that the inventory offers reliable and valid measures of conceptual knowledge in statics." No qualitative study of student explanations.
[4], [5], [6] Denick et al., 2015, 2013, 2012	Performed a think-aloud protocol of 18 students to provide detailed information about their thinking process as they solved CATS problems (each student solved 8 of 14 selected). Results indicate that student utterances can suggest the type of errors made, and provide a validation of the expected errors (from Steif) on the CATS problems. Of relevance to FBD errors specifically, without consideration of equilibrium: confusion of normal with vertical, and the confusion of adding a moment to correspond to perceived motion. Other responses involve interplay with FBD and equilibrium concepts.
[7] Douglas et al., 2010	Performed think-aloud's on 4 students completing a CATS question that relates both free body diagrams and equilibrium equations. Observed that students make "substance based" errors in which they think of forces as material objects that can be located and translated, rather than as relationships.
[8], [9], [10] Litzinger et al., 2006, 2009, 2010	[8]: Think-aloud with 4 participants drawing FBDs, no equations. Students justified their inability to handle distributed loads by claiming they could not find the force because the "height is not given," even when the information was provided in a different format. They explained their confusion by stating they were "getting confused" between the requirements of different courses. They also admitted to being "distracted by the angle" provided in the problem, which led them away from the correct physical principles.

	[10] : 39 students, using a combination of Integrated Problem Solving: verbal, diagrammatic (FBD), and mathematical (equilibrium equations) and Self-Explanation: principle-based (direct FBD principles) and anticipatory (how would certain decisions in the FBD affect writing of equilibrium equations). Provided examples of students explaining their reasoning, including that many students cite procedure (memorization or a table) in getting reactions correct. Particular errors identified: ● Omission of the friction force (barrel on ramp) ● Failure to include the normal reaction force (from the incline on barrel). ● Omission or errors of coordinate axes, dimensions, and orientation/angles. ● Incorrect isolation (included adjacent body to the one under study) ● Body not in equilibrium (because the forces in the y-direction are all negative) ● Difficulty dealing with unfamiliar reactions (reaction at B parallel to the step, not ● perpendicular at the ladder) ● Location of body forces and reaction forces caused by those body forces, e.g., body located at the point of contact rather than at the center of gravity of the body. “From the comparison of written work of the weak and strong students, we learned that the weaker students were poorer performers in creating free-body diagrams and formulating the equilibrium equations, with one caveat. The two groups were about equally likely to forget to use a moment balance equation. The types of errors in the students’ written work are not at all unusual. However, the think-aloud aspect of the work allowed us to hear what the students were thinking as they did the problems. From listening to them, we came to understand that students struggled with unfamiliar connections and that most of them could not reason physically about the reactions. Furthermore, students’ answers to the question about how they know what reactions can exist showed us that even the best students were relying heavily on memory.”
[11] Savinainen et al., 2013	335 high school physics students, quantitative results. Problems of a particle, not rigid body. No qualitative study of student explanations. “interaction diagrams (IDs) … help to identify and represent interactions between objects, thus helping students to perceive forces as the property of an interaction instead of a property of an object.” “Our first research question asked whether using IDs helps students to identify forces when constructing FBDs. The answer is positive, since the correct identification of interactions resulted in the correct identification of forces” “Our second research question asked whether the use of IDs helps students to construct correct FBDs. The results were less clear on this question. Although the majority of correct FBDs … were associated with correct identification of interacting objects, the converse was not true: The correct identification of interacting objects resulted in a correct FBD [less than half the time]. From the point of view of physics, identifying interacting objects is a necessary, but not a sufficient condition for constructing correct FBDs.”
[12] Danesh-Yazdi, 2017 [13] Cornwell and Danesh-Yazdi, 2019	[13] provides results of an instructor survey about important aspects of FBDs. [12] recommends exploded diagrams. provides several rules of thumb for drawing FBDs following the exploded-view philosophy. “... the performance of the [39] students who were taught the FBD using the exploded-view approach is significantly better in three of the four [test] problems than the [42] students [who did not have exposure to the exploded-view approach].”

<table>
<tr><td></td><td>No qualitative study of student explanations.</td></tr>
<tr><td>[14] Sloboda 2023</td><td>46 first year and 66 third year students were asked to draw FBDs of objects, based on different levels of abstraction vs realism in the way that the object was presented.
No qualitative study of student explanations. Errors encountered:

● Body Not Freed
● Missing or incorrect Two-Force Body
● Added extra normal force at Pin
● Pin Replaced by normal force
● Missing pin Forces
● Extra Forces
● Missing Interface Force
● Missing force at fixed connection
● Missing moment at fixed connection
● No Weight
● Treated body as Particle

“This paper provides evidence that the level of abstraction of the primary image of a problem description can impact student performance in drawing an FBD. For two of the three problems investigated in this paper, lower abstraction (i.e. greater realism) led to lower performance for a first-year engineering class, who had recently learned to draw rigid body FBDs. Most of the additional error accrued with less abstract representations was due to student difficulty in isolating the body and/or dealing with boundary conditions. A more experienced, third-year class facing the same problems had less difficulty transitioning between different levels of abstraction, although the trend of reduced performance with decreasing abstraction was present for one of the problems for this group as well.”</td></tr>
<tr><td>[15] Davishahl et al., 2020</td><td>27 participants. Written explanations as part of assigned activities are reviewed. Activities are qualitative, but combine reasoning about equilibrium, beyond the heuristics for drawing FBDs based on reactions from tables.

“Analysis of student explanations on the follow-up questions and work on exams indicates the majority of students are willing to engage with this approach as opposed to relying solely on heuristics as others have observed in studies of student problem solving in statics. Most students correctly applied the approach by the end of the term as evidenced by their free-body diagrams on the final exam. We did not observe any significant differences in student performance on summative assessment measures such as the final exam or CATS, indicating that increased emphasis on conceptual reasoning did not come at the expense of procedural accuracy in problem solving.”</td></tr>
<tr><td>[16]Mongan et al., 2020

[17] Low & Wilson, 2017</td><td>Both studied confusion between weight and normal force.

[16]studied written works of 40 students on drawing FBDs of simple particles that had both weight and normal forces. They identified at least five issues:
1. The direction vector of weight force w is towards the center of the earth
2. The direction vector of the normal force N is perpendicular to the plane of table
3. Position of the capture point vector w at the center of the object
4. Position of capture point vector N on the boundary touch surface
5. The vectors N and w are the same length and opposite direction

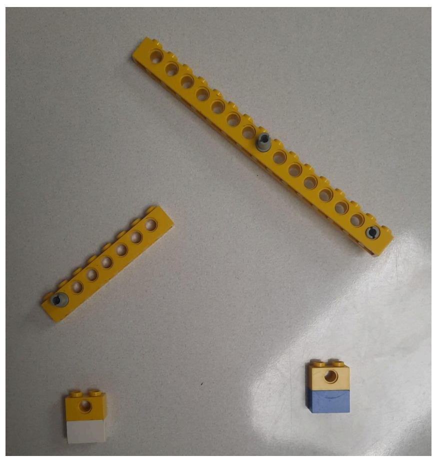
[17] performed a quantitative data from pre- and post-tests, indicating that instructional attention to this matter can lead to a robust clarification.</td></tr>
</table>

[18] Rosengrant 2009	Studied written work of 724 students" 245 from "representation rich" instruction, and 479 from "traditional instruction, on multiple choice questions in which FBDs were not required. FBDs were rated on a 4-point scale, No evidence of, Inadequate, Needs improvement, Adequate. Results showed that students in the representation-based instruction voluntarily drew FBDs at a higher rate (58%) compared to the students with traditional instruction (17%). A qualitative study of 6 students was recruited to do think-aloud experiments to explain their overall problem-solving process (FBDs and equilibrium equations). This documented more about how students used FBDs and revealed behaviors, such as tendency to check consistency and reasonableness of results, but there are no details provided about why students made certain choices or errors in the FBDs. "To summarize the interview findings we can say that the most important result is that the high achieving students used the free-body diagrams to help evaluate their work."
[19] Tarban 2011	"Other reliable indicators of skill are accurate and complete translation of the verbal and figural problem representations into a free-body diagram, correct identification of problem assumptions, accurate expansion of key equations, and monitoring the problem solving process through checking."
[20] Passmore 2020	Think-aloud of five students solving equilibrium problems that involve a moment resisting reaction. Students typically would neglect the moment reaction in the sum of moments equation. "Although the students were provided with a free body diagram, he added his own additional support reactions, because he believed that a couple was required to prevent the rotation of the beam."
[21] Kohl & Finkelstein, 2017	"Experts spent much more of their time pursuing specific goals or sub-goals even when they did not know exactly how to proceed, as with the more challenging pulley problem not presented here. Novices still spent some time in this manner (which is encouraging), but were much more likely to engage in exploration with no clear purpose, perhaps hoping to strike a more correct approach."
[22] Coughlin et al., 2025	"A rich theme is how students understand torque through one of two forms. In the first form, based on entry-level courses in physics, torque results from external forces applied to an object of interest. In the second form, based on the advanced-level course of statics, torque (sometimes called moment) results from internal forces within the object of interest."

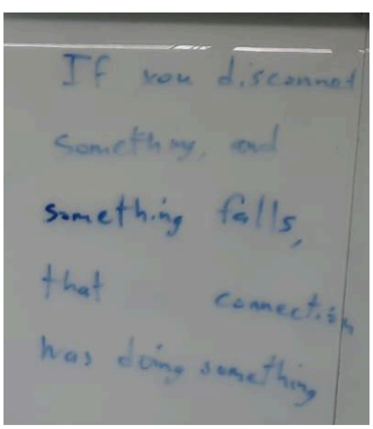
Appendix 2. Preliminary Ideas for New Strategies for Teaching Free Body Diagrams

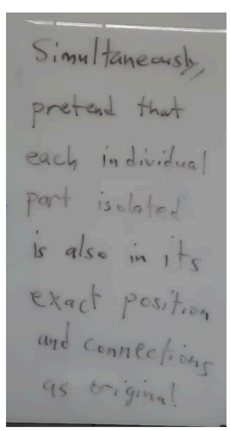
Of the three authors, only the first author (Instructor A) is teaching Statics during the Spring 2026 semester, as this article is being completed. This appendix is an informal means to share how the instructor is attempting to teach FBDs, with notes of how this work has influenced their thinking. For reference, the unit on FBDs immediately follows the unit on vector operations, and before the topic of equilibrium is formally introduced.

A lego model of a simple crane was built, allowing students to simultaneously view it as a complete, connected structure and as a set of separate parts. Students also can play with the models to feel how the connections work, suggesting the corresponding reactions and constraints. The careful inclusion of anchors and pins is motivated by the exploded FBD discussed in [12].



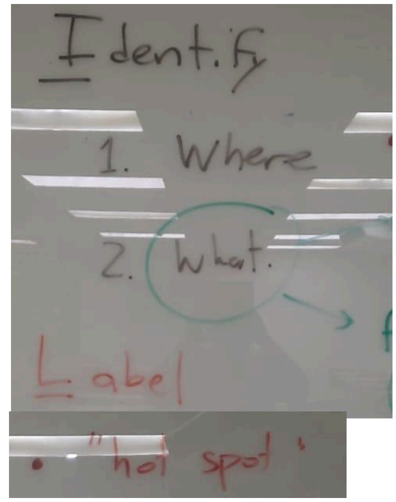
Using this as a guided example, the instructor demonstrated that by disconnecting some connections, the structure would 'fall', and wrote this idea on the board. This was followed by another comment to indicate that individually 'separated' objects must still be viewed in their original geometric and physical (connected) context.





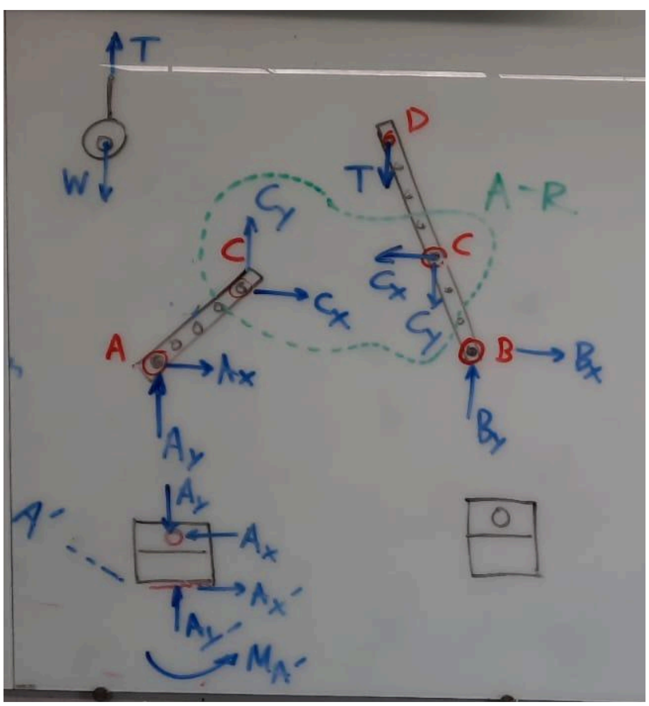
Next, a general approach "I^2" was introduced:

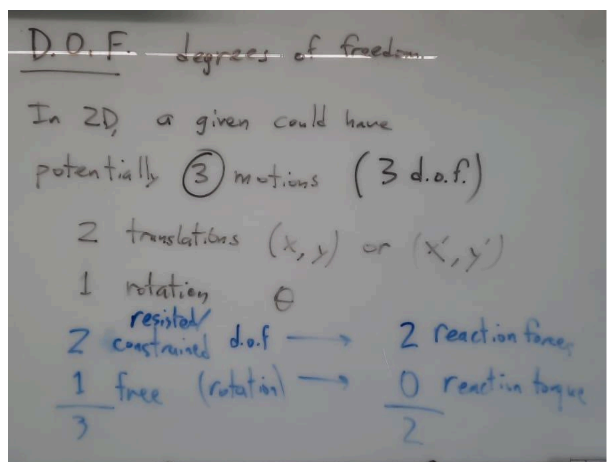
- **I**solate the objects as described
- **I**dentify
  - First, where contact or other action is occurring (corresponds to R3, R6, and R8)
  - Second, what kind of reaction results (corresponds to R5, R7, R9, and R10).

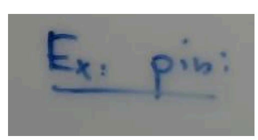


The message is that the locations of possible reactions must be located before any attempt at drawing the reactions is undertaken. The suggestion is to refer to these points as "hot spots" and draw a red dot where they occur.

In the example of the crane, the following FBDs were developed for the individual members, through a guided class discussion. It is important to note that the first two steps were to (1) Isolate the elements (black) and (2a) Identify the hotspots ("where", in red). Then (2b) the forces were drawn incrementally ("what", in blue), making use of the notion of restricting degrees of freedom. The existence of action-reaction is highlighted in green.







Finally, the “entire structure, separated from its supports was drawn, along with a ‘rule’ about never drawing internal reactions where bodies are shown connected. This is argued by imagining a ‘fusion’ or ‘collision’ of the individual FBDs, in which twin reactions ‘cancel out’. This notion is supported by the summing of equilibrium equations of the interacting bodies, to be done later in the course. (Note: in hindsight, this sketch should be updated to show points *A* and *B* as “hot spots” as well, and possibly to eliminate *C* as a hotspot in this context – a refinement of these rules is thus in order).